Proceedings of the 1st Residential Building Design and Construction Conference

February 20-21, 2013

Bethlehem, PA, USA

Edited by

Ali M. Memari

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PREFACE

Demand for energy efficient residential buildings has been the driving force behind many innovations in building materials and systems in recent years. This aspect in addition to the desire for high performance and sustainable construction as well as affordability or resiliency issues have encouraged government, researchers, design professionals, product manufacturers, developers, and other stakeholders to support or seek advancements in the state-of-the-art and state-of-the-practice in the field of residential construction. Significant efforts are been expended to develop new materials, products, processes, and procedures to improve the state of existing residential buildings and to incorporate in design and construction of new buildings. Because of the need for timely dissemination of the results of extensive R&D activities and new developments in the field, the Pennsylvania Housing Research Center (PHRC) at Penn State University is pleased to have started a new annual conference series to serve the housing and residential construction industry for this purpose

The 1st Annual Residential Building Design and Construction Conference was held on February 20-21, 2013 in Bethlehem, PA in conjunction with the 21st Annual Pennsylvania Housing & Land Development Conference. The latter event has been a successful PHRC program over the years with emphasis on topics of interest to developers, builders, remodelers, design professionals, planners, regulatory and code official, modular and HUD code builders, and housing product manufacturers. As a new PHRC program, the Annual Residential Building Design and Construction Conference is intended to provide a forum for researchers and design professionals to discuss their latest findings, innovations and projects related to residential buildings. The Annual Residential Building Design and Construction Conference considers papers and presentations on various types of residential buildings including single- and multi-family dwellings, mid-rise and high-rise structures, factory-built housing, dormitories, and hotels/motels.

The conference series intends to provide opportunities for contributors from academia, A/E design firms, builders, developers, manufacturers, and government and code officials to submit papers and/or make presentations on all aspects of residential buildings including the following topics:

- American Indian Housing
- Assisted Living and Elderly Housing
- Building Enclosure Waterproofing
- Building Integrated Photovoltaic Systems
- Building Science
- Design and Installation of Alternative Energy Generating Systems
- Energy Efficient Building Components
- Fire Damage and Protection
- Housing Construction Materials
- High Performance Residential Buildings
- Indoor Air Quality
- Innovations in Modular and Manufactured Housing
- Innovative Housing Construction Methods and Systems
- Innovative Wall, Floor, and Roof Systems
- Low-income Housing
- Net-Zero Energy Homes
- Panelized Building Components

- Performance of Residential Buildings under Natural Disasters
- Protection and Retrofit Methods against Natural Disasters
- Rural Housing
- Retrofit of Existing Buildings for Energy Efficiency
- Serviceability Damage Aspects of Residential Buildings
- Smart Home Technologies
- Temporary Housing for Disaster Situations
- Whole Building Design Approach

The proceedings of the 1st Annual Residential Building Design and Construction Conference contain papers or slide sets mainly related to the following topics: Building Science; High Performance Buildings; Disaster Resistant Performance, Testing and Evaluation; Energy Efficiency and Retrofit; Innovative Products and Systems; Modular Construction; Innovative Architectural Forms; and Structural Materials and System Design. Two keynote speakers were invited for this conference, Sam Rashkin, Chief Architect, Building Technology Program, DOE, and Richard Seifert, Professor Emeritus, University of Alaska, Fairbanks. The conference scheduled 36 presentations in 13 sessions over two days. There was also one session devoted to introducing the book: *Design and Construction of High-Performance Homes: Building Envelopes, Renewable Energies and Integrated Practice*. The authors of the book discussed three major aspects of the book: architectural technologies, system integrated photovoltaic, and energy and integrative design process.

I wish to thank the members of the Steering Committee and the Scientific Committee of the conference for their contributions. The support of the PHRC staff to organize this conference is gratefully acknowledged.

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Dr. Ali M. Memari
February 2013

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A keynote Presentation: "30 Years in Dogged Pursuit of the Ultimate Superinsulated Passive Solar Home"

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Abstract:

As a participant in the past three decades of Building Science Progress in North America, riding the rollercoaster's of energy cost, and enduring the tribulations of housing finance and investment woes, it is both my pleasure and duty to share with this interesting Pennsylvania conference what I have learned from living my professional life in the coldest city in North America, while trying to find a Building Science solution to how to live in the Interior of Alaska efficiently, with low carbon footprint and without being driven into poverty by fuel costs, and with a healthy indoor environment.

Starting about 1980, when Jimmy Carter suggested that energy conservation was " The Moral Equivalent of War", my fellow Alaskans and I began the long, cold, march toward the superinsulated home, discovering along the way the pitfalls of moisture, mold, ventilation, financing and the utter lack of romance to be found in the whole energy conservation world. Along this path, we created educational programs, outreach efforts, professional coursework for contractor/builders, ventilation standards, encountered new materials, attempted to use renewable energy resources such as solar energy for heat and electricity, and ultimately were recipients of an amazing state-funded weatherization and energy rebate program totaling more than 800 million dollars over the past four years. That plan is one of the finest in the nation. We found some answers, can advise our fellow building scientists on what to do and not do, for *any* heating climate, and yet there are many things still to be done.

This presentation will be mostly historical. The story of the progress and "long cold march" toward an energy efficient housing stock is valuable to share with conference participants. I want to begin in a very unexpected place: the surface of the moon. The reason to start here is to convey the importance of what I believe to be the single most important photograph ever taken in human history. It is this photo, shown in figure 1. I choose this picture because it changed how human beings viewed the world. Many of you perhaps weren't of an age of awareness when this photo was made, but it has had a huge effect on human perception. Within one year of its appearance, the first "Earth Day" was celebrated, and the administration of Richard Nixon established the Environmental Protection Agency (USEPA) less than two years later. No photograph has ever had the impact of this one, and it is certainly easy to see why. More than that, it probably utterly surprised NASA as much as it did the public. I begin here because the eventual focus on moving toward the ultimate superinsulated, energy efficient passive solar home took much longer, and was more an "evolution", than a surprise. But it is equally important for human development.

photo credit: NASA and wikipedia

Figure 1, The earth from the surface of the moon, July 1969. The first authentic view of "Spaceship Earth".

From here forward, I am going to use slides to make my points, and will refer to them, but not place them in this text.

The next historically important thing happened in 1973, and its importance was only recognized in hindsight, about ten years later. That event was the first oil embargo executed by Saudi Arabia in reaction to US support for Israel during one of the many skirmishes in which Israel and the Palestinians et al. were at each other's throats. This caused a doubling of the price of oil at the time, because as the Peak Oil curve shows, the USA had passed peak production and was no longer able to provide enough oil for its own independence. Forever more, we have been dependent on foreign oil, and now worse than ever. This is a major motivation for energy efficient building design and implementation.

At about this same time, Alaska was in the preparatory jousting for the permitting and construction of the Trans Alaska Pipeline. Contrary to what might seem the reality today, this was not a simple or compelling project, and the delays were substantial. For instance the pipeline took more than three years to pass the licensure muster, and was predicted to cost $900 million. When finally completed in 1977, the cost was nearly ten times that, about 8 billion dollars. So much for the case that the private sector handles cost overruns better than the public sector. Ho hum…

During the mid-to-late 1970s, there was some clear growth, relentless growth in fact, in import of foreign oil and the concept of energy independence kept coming up. It is during this period that I first began to hear the term "superinsulation", and the concept of the "superinsulated home". I am firmly of the conviction that an Alaskan, a fellow named Bob Roggasch, first coined the term, and it was so "on point", that it stuck. Now I can't prove this of course, but very quickly the term spread around the nation, and this was before wikipedia and the internet. At the end of the seventies, we had the second and most dramatic oil embargo, when the American embassy in Tehran was overrun by Iranians and the price of oil again doubled (1979). This caused the demise of the Carter administration and was the context for Jimmy Carter wearing a sweater during his fireside chats with America, and exhorting us to treat energy conservation as "the moral equivalent of war". The price of Saudi Marker crude oil was now up to about $24 a barrel (December, 1979-heaven forbid!) and caused a huge political and public repercussions. The US Department of Energy had only been created a few years before and now it began a long extensive effort to affect scientific research and public investment in energy efficiency and solar water heaters were placed on the roof of the White House. The effort was rather ill conceived, which is easy to say in retrospect, but not necessarily easy to grasp at the time. The really crucial misconception at the time, really a wrong-headed approach to the problem, was this: Many engineering approaches during that time never looked at the heating or electrical loads to design systems that lowered demand (the future "Demand side management approach"), but only looked at how, for instance, solar collectors could be added to existing structures to meet the present load, without reducing the present load. In Alaska, we started to notice this, and the early superinsulated houses had 18-inch thick walls filled with recycled urethane foam or fiberglass, and wood stoves for heat. We live in one of the most severe inhabited climates on earth, so the motivation is clear. This whole misperception led to some early perceived failures or at least disappointments, and then Ronald Reagan was swept into office in the early 80s, and said " Energy conservation means wearing a sweater in the winter and being uncomfortable in the summer heat", and removed the solar collectors from the roof of the White House, a symbolically devastating act for energy guys like me. I have not yet forgiven him for that. In many ways he made matters much worse and set back the learning curve for a good decade. Don't ever believe that politicians can't make a difference. They really can. The issue is more importantly, precisely what difference they do make.

The 1980s: dogged progress.

In January of 1982, I got my chance: I became the energy and housing specialist, a faculty position, for the Cooperative Extension Service at the University of Alaska Fairbanks. Alaska was now an oil production state and oil was king. We had established the Alaska Permanent Fund, a state savings account to save surplus oil income for the future, and we had an in-state refinery. The pressure seemed to be off. However, the price was controlled by the world oil market, and so, although we could not be extorted, we couldn't control prices, and energy conservation was beginning to come into its own. Examples of the success and the mistakes of early superinsulated building attempts were in the news. It was my role to be the messenger of this progress. Fairbanks has three features in this context which make it a superb place to watch the unfolding history of energy conservation and superinsulated housing. First it was cold (30% more heating degree days than Anchorage, Alaska's largest city). Second, it heated primarily with heating oil, and did not have stranded natural gas like Anchorage did, and still does, which was and still is one-half to one third the cost of heating oil on a per BTU basis. And third, Fairbanks was the seat of the land grant university, so could provide research and analytical support as well as legitimacy for the public and university attempts at demand management, superinsulated construction, and other research and health concerns of energy conservation, such as ventilation systems.

It was during the 1980s that many major insights and advances took place, and my view is that most of them were either state programs and efforts, or came out of the federal laboratories like Lawrence Berkeley (window science and general energy systems analysis), Brookhaven (for heating systems simulation and testing) Battelle PNW Lab in Richland for all sots of energy work, and Sandia and Los Alamos for passive solar design. There were also individuals like Steve Baer in New Mexico, who used his own unique creative wits to create low-tech solutions and helped establish an underground of "appropriate technology solutions which is still helping all around the world. There were many others like him who made the energy conservation world a revel of human enterprise and ingenuity, with great characters and Shakespearean dramas. Right in the middle of this decade, I was privileged to get a Fulbright Research Fellowship to the Technical University of Norway in Trondheim, and brought back with me texts and research advisory bulletins from the Scandinavians with which I sweetened the approach in Alaska. This was an uncannily good opportunity and really made a huge contribution to my career. I would thereafter know just who to ask for deeper probing into Swedish, Norwegian, and European leading-edge superinsulated design, ventilation systems for homes, (an emerging concern and technology), even the emergence of all sorts of air quality issues which came into focus once you tighten a building to prevent air leakage. The mysterious radioactive element radon came to the attention of the building scientists too, and when I got back from Norway in 1986, we even found radon problems in Interior Alaska, and began a quarter century of public awareness outreach programs on that subject as well. And I know that Pennsylvania is no stranger to radon concerns. It all began here at the Limerick Nuke plant. Along with these ever-expanding factors in the building science canon, the world was learning a great deal about how to build better energy-efficient houses, buildings and infrastructure. The Canadians had come up with the R2000 program, and we hired them in the person of Oliver Drerup (formerly of CMHC Canada) along with Ned Nisson (formerly of *Energy Design Update*) to educate us and create the first outreach education program for contractor and public education, which we called the Alaska Craftsman Home Program. The plan was very wise: we would simultaneously educate the builders on how to achieve good efficiency results, while teaching homeowners why they should go the extra mile to buy and have these homes built. It was the Canadian plan, and ever since we have become very adept at stealing the best ideas of our Canadian neighbors, and they are always generous and play well with others. They also share most of our Alaska climate concerns, an issue which we constantly confront (and always lose) in getting attention in the continental US: we are too small a population with too few people for us to get our own "Building America" manual, for instance, so we had to create our own. The Canadians helped enormously.

So in 1987, my comrade Don Markle and I won a contract from the state energy agency in Alaska and created the Alaska Craftsman Home program with the help of the building industry in Alaska. We enlisted a cadre of volunteer instructors and experienced builders to spread the word and educate the industry. Ever since, cruising on the rocky road of political survival, we have re-written and produced four ever-improved editions of the Alaska Craftsman manual through 1995, and then built another organization called the Alaska Building Science Network (see www.absn.com). This organization has now revised and improved another Alaska-specific manual in seven further editions, the latest of which is now available for downloading on the web at the sponsor's website here: http://www.ahfc.state.ak.us/reference/alaska_residential_building_manual.cfm

Also in 1995, the Alaska Building Science Network created a newsletter which I have (mostly) written and edited ever since. It is a huge archive of vast energy efficiency information, and contains over seven hundred pages of information documenting much of the history and progress of energy efficient building science, ventilation strategies, and air quality information over the past 17 years. The final edition of this newsletter was just published in June of this year (2012) when I retired as a professor from the University of Alaska Fairbanks. The archive is here: http://www.uaf.edu/ces/energy/housing_energy/

In 2008, in the midst of the incredible price increases in crude oil, which peaked at $145 per barrel in April, our State of Alaska legislature did something absolutely remarkable, and I have characterized it as the most amazing thing that ever happened in my career. Because of the oil price increase and the consequent effect it would have on much of Alaska for heating fuel, the legislature put $360 million "on the table" so to speak, in a package of weatherization funding ($200 million) and for those homeowners who were above the 50th percentile of income, a home energy rebate program was developed so that virtually all Alaskans homeowners qualified for some kind of assistance or financing to make their homes more energy efficient. The additional $160 million was for this purpose. Since the program began more than 20,000 homes have been either weatherized (which is free to qualified homeowners, by the way) or improved in some way through the rebate program.

There is much more to say about this (see references on this subject at the end of this paper), and I think it is a remarkable example for the rest of the country, as it is as generous and effective a means to improving our housing stock of any I have seen anywhere. It was also long overdue, for a rich oil state. But it finally happened.

So where have we arrived, and why am I convinced we have some of the answers to the housing optimum? Well, one reason is that I have also written four editions of another book during my 30-year career, titled the "*Solar Design Manual For Alaska"*. (see this manual online at : http://www.uaf.edu/ces/energy/alaskasun/ .) This experience has led me to comprehend fully the need to fuse superinsulation with solar and renewal energy design in homes. The resulting convergence of these varied design approaches becomes fairly obvious to someone who has followed the path that I have followed over the forty years I have been in Alaska. This "fusion" which I mention is exemplified by the German Passivhaus Solar approach, and the many designs described as " net zero energy". The ideas are really quite directly similar, and have three main tenets:

1. **First do the conservation:** Superinsulate with a climatic index as guide, and anticipate climate change, always striving to minimize the actual need for fossil fuel energy. This is essentially, the fullest application of demand side management: Save money by not needing the fuel *by design*.
2. **Seek renewable solutions to energy requirements only after you have satisfied requirement 1.** This is what I have learned from my attempts at solar optimization in housing, and in writing and studying the application of solar design to housing. Since solar and renewal energies are expensive and reliability is always dubious, the real security is in energy conservation, and additional energy supply is the expensive part. On-site energy is the most secure source, and the only means to true energy independence. Anyone telling you otherwise is selling you something you shouldn't buy.
3. **Finally, these fusions are really THE answer we have been moving toward in the twentieth century.** The oil-rich century we have just passed through was merely an era, a phase of human development which will pass, and we will be well placed if we use what we have learned in that century about passive solar, superinsulated, zero-net designs, to achieve comfort and security with low cost and health. The only caveat and detail I haven't covered well is the healthfulness requirement, which is a ventilation option that MUST be included in very air-tight conserving homes and buildings.

So we really have come to a culminating point, and do have a very optimal solution to building design for efficient comfort and minimal future costing housing. It won't be cheap, and must be durable in the face of climate change and the threat of storms and weather like Hurricane Sandy. This storm should be a harbinger of what is needed and has come at a most opportune time for this conference. Take it seriously. It can help you achieve the future we need in Building Science. I've given you what I have learned. Take it and move confidently into your future. We do have some very solid answers!

Web resources

No papers are cited in this paper as it is an informational historical review. The following is however, a list of web resources of considerable value which are related to the subject of Energy efficient building science:

http://www.uaf.edu/ces/energy/alaskasun/

A site devoted to renewable energy resources and services available for building scientists and home owners all across North America

http://www.uaf.edu/ces/energy/housing_energy/

This web site above is the major source for housing and energy information from the University of Alaska Cooperative Extension Service. It is deep and highly eclectic.

http://www.uaf.edu/ces/energy/housing_energy/absntoc/

This is the location for the archive of the 17 years of the *Alaska Building Science News*

They are all downloadable as PDFs and searchable if you include the letters ABSN in the building science topical search.

December 12, 2012

Richard D. Seifert

The Need for Building Science Education

Joseph Laquatra
Cornell University

As the demand for high-performance housing grows, so does the need for improvements in building science education. Even before the energy crisis precipitated by the 1973 Arab oil embargo, building codes in America were gradually addressing energy and moisture issues in prescriptive ways that were not evidence-based. As a result, problems ensued. Builders, engineers, architects, building code officials, and others involved in the home building industry have been learning how to avoid the problems through trial and error. This has led to widespread misconceptions that persist to this day, including beliefs that buildings should not be airtight or "overinsulated." Well-documented problems of mold-infested houses have exacerbated misunderstandings about methods for building high-performance homes.

Stricter building codes or builder licensing requirements are not necessarily the solutions to problems associated with misunderstandings about building science. Motivating professionals currently involved in the housing industry to learn through continuing education is a start, but the core problem must be addressed by including building science education in curricula related to architecture, engineering, construction management, and other fields. This paper will review early developments in the history of housing construction that led to discoveries related to building science, problems that followed, their resolutions, and current efforts to increase awareness of building science education.

Ireton (2012) provided a useful history of building science, beginning with the early years of insulating homes in the 1920s and 1930s, after which exterior paint started peeling. That resulted in painters refusing to paint insulated houses. Vapor retarders and attic insulation were prescribed by building codes; and paint continued to peel from exterior siding. Issues that were not understood included relative humidity levels inside houses and wind-driven rain that can penetrate siding. To this day, moisture movement inside houses and water intrusion into building enclosures are issues that are not well comprehended by builders, code officials, architects, and other housing professionals. Misconceptions abound and building failures continue because of moisture that can cause structural problems and create conditions that lead to pest infestations. In addition to affecting the health of structures, excess moisture affects the health of building occupants by creating conditions that are favorable to mold growth that exacerbates asthma and allergies (Institute of Medicine, 2004).

Besides moisture, other issues that affect the health of building occupants include indoor pollutants such as radon, volatile organic compounds, and combustion products. Understanding and controlling these pollutants requires a grasp of what has come to be known as building science, a growing field that takes a systems approach to understanding houses by focusing on the structure of a building, its occupants, and its contents (Florida Solar Energy Center, n.d.). In addition to a focus on pollutants, building science includes emphases on heat flows, air flows, and exterior water management. A house that is built by someone with a good understanding of building science should be durable, affordable, healthy, comfortable, and safe. But the term, building science, is not used consistently.

Rose (2012) noted a use of the term, "building science," in the *Proceedings of the University of Illinois Conference on Architectural Education* from 1949. Max Abramovitz is quoted as:

"I wonder if you realize how very few men are left today who are expert in building science." (Rose, 2012: 7)

Rose (2012) described the field as "science applied to buildings," and provides both broad and narrow definitions, with the former applying to all "physical, chemical and biological process affecting buildings," and the latter applying to "heat, air and moisture transport in buildings." He also noted that the term corresponds to what is called "building physics" in Europe. (Rose, 2012: 8)

Best Training School provides the following definition:

"Building science is the collection of scientific knowledge that focuses on the analysis and control of the physical phenomena affecting buildings. This includes the detailed analysis of building materials and building envelope systems. The purpose of building science and understanding the training that supports it is to provide predictive capability to optimize building performance and understand or prevent building failures. Those failures may include not only structural weaknesses but also failures in securing the building envelope against moisture intrusion that may result in wood rot, mold, or, in most severe cases, destruction of the structural integrity of the building." http://www.besttrainingschool.com/building-science.php (Retrieved October 10, 2010)

One thing missing from the above definition is the role of mechanical systems in a building's performance.

Lstiburek (2005) wrote that building science is an immature discipline with little visibility at universities. He compared it to structural engineering when it was a young discipline. But structural engineering did mature and brought about an understanding of loads, load resistance, and other concepts. As structural engineering matured, so too can building science.

At the university and community college levels in the United States, building science is becoming integrated into academic programs. Carnegie Mellon University's School of Architecture, for example offers graduate degrees in Building Performance & Diagnostics. The Department of Architecture at the University of California, Berkeley includes a minor in sustainable design that features courses in building sciences and sustainability. Onondaga Community College's programs in architecture and interior design include instruction in building science. An issue with current academic programs in architecture is that they are focused on large buildings, not houses. One academic program that does focus on housing is construction management, which is also known as construction science, construction technology, and construction engineering technology. What is the extent to which building science is becoming integrated into this program?

The American Council for Construction Education (ACCE) is the accrediting body for construction management academic programs in the United States. The ACCE manual, *Standards and Criteria for Accreditation of Postsecondary Construction Education Degree Programs,* lists courses that must be taught in Construction Management programs in order for them to be accredited. Building Science is not mentioned in the manual.

The Department of Technology and Environmental Design at Appalachian State University offers a Bachelor of Science Degree in Building Science with concentrations in Construction Management and Architectural Technology and Design. A specific course in Building Science in this program covers ways that buildings interact with the environment, moisture issues, indoor air quality, the use of diagnostic devices including blower doors, duct leakage testing devices, air flow detection equipment, and indoor air pollutant testing tools. This program is not accredited by ACCE.

The Department of Building Science at Auburn University offers Bachelor and Masters degrees in Building Construction and is accredited by ACCE. But building science as described above is not covered in the undergraduate or graduate program. The Del E. Webb School of Construction at Arizona State University offers Bachelor, Masters, and Ph.D. programs in Construction Management and is accredited by ACCE. Building science is not covered in any of these programs.

These are only a few examples of the current state of building science education, but they serve to demonstrate that widespread awareness of building science does not yet exist. In an article that is now 13 years old, Uniacke (1994) wrote that he expects to see serious defects in the thermal performance of newly constructed houses. He cited a lack of access to good information on the part of builders and architects as being largely responsible for the situation. He argued that integrating building science into construction management academic programs at the community college level would be an effective remedy to the problem because of ease of access and value. When Uniacke wrote the article, his institution was called Yavapai Community College. It is now Yavapai College. A check of its website on the Associate of Applied Science Degree in Residential Building Technology revealed that energy efficiency is emphasized in some program areas (http://www.yc.edu/academics/degrees-and-certificates/associate-of-applied-science---residential-building-technology/28).

Uniacke (1994) stressed other advantages of integrating building science in community college curricula. One is that building in the local climate can be emphasized. Another is that building professionals, at least at this college, could take courses without being graded. The particular course that Uniacke (1994) described a two-tiered approach to teaching building science. The first tier relates to the goal: to build a house that is energy efficient, affordable, healthy, safe, comfortable, and durable. The second tier covers evidence and theory including definitions, procedures, product information, and construction details. In his class he made use of the blower door and other diagnostic tools, used over 600 visual aids, expert guest lecturers, construction site tours, and other enhancements that made his class so popular that attendees began sending their employees to it.

A 2005 collaboration between the U.S. Department of Energy (DOE) and the Association of Public and Land-grant Universities (APLU) produced an outline for a university-level, semester-long course in building science, "Building Science 101." This course outline contains the following modules:

- Energy issues and building solutions
- Introduction to sustainable design & building performance
- Flows: air, heat, water, vapor
- Building materials and their properties
- Climate and designing with nature
- Building design, systems engineering and commissioning
- Site: drainage, pest control, landscaping
- Foundation: moisture control and energy performance
- Building envelope: moisture control and energy performance
- Windows, doors and other penetrations
- Mechanicals/electrical/plumbing: systems engineering, energy performance, occupant health, safety, comfort, and envelope/mechanicals management, part I
- Mechanicals/electrical/plumbing: systems engineering, energy performance, occupant health, safety, comfort, and envelope/mechanicals management, part II
- Electricity payload
- On-site generation
- Field issues: construction management, codes, and other regulatory matters (optional)
- Benchmarking performance: meeting and exceeding the norm
- Community scale
- Putting it all together: experiential learning in the field/office
- Homeowner education (communicating with the consumer)

The full course outline can be viewed here:
http://www1.eere.energy.gov/buildings/residential/ba_science_education.html#curricula

Numerous resources on building science exist and include books, peer-reviewed journals, websites, and organizations. The DOE Building America program has set a goal of supporting the transformation of the design/construction industry to one that routinely designs and builds quality, high performance homes that are safe, healthy, durable, comfortable, and energy efficient. To achieve this goal DOE recently developed a Building America Building Science Education committee. One activity of this group is to work with a joint committee of the Associated Schools of Construction (ASC) and the National Consortium of Housing Research Centers (NCHRC). A long-term goal of this

project is to facilitate the inclusion of building science courses as part of the accreditation process of construction management academic programs by ACCE.
In 2011 DOE worked with the NCHRC to establish an annual Excellence in Building Science Education Award program to recognize efforts of university, college, or community college faculty in this area.

Although progress is being made in building science education, it is not happening fast enough. System failures, including water leaks and mold growth in houses, are prevalent. Forty-seven percent of homes in the U.S. are reported to have problems related to dampness and mold (LBNL, 2012). Mullens, Hoekstra, Nahmens, and Marinez (2006) reported that 20% of homes built in 2003 in Central Florida experienced water leaks from the exterior during Hurricane Jeanne in 2004.

The construction of high performance energy efficient homes now requires specialized knowledge and skills that were not required of builders 40 years ago. Properly installed housewrap, window flashing, and air-tightening measures all contribute to a house that performs well. But the nature of the housing industry in the U.S. makes it difficult to ensure that everyone involved in building homes understands these issues well. Many different trades, including carpentry, plumbing, electricity, and others are involved in construction. Straube (2012) is quoted as saying that the construction site supervisor should be the first person to receive training in building science.

Changing building codes to reflect the latest knowledge in the field is not the answer to this problem, because the code process is a political one and because codes lag science by 10 to 15 years (Ireton, 2012). Requiring licenses for building contractors, coupled with continuing education would only work partially, because of all the trades involved in building. Licensing is another political issue. Not all states require this. Some that have tried to impose it as a requirement have met stiff resistance from home builder associations. The current generation of home builders requires continuing education in building science, but not all builders are motivated to pursue this. In theory, home buyers could exert a push factor on the process by becoming informed about building science themselves, but this is not very likely to happen. The long-term solution is to include building science education in academic construction management programs.

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REDUCING EXPOSURE TO THERMAL STRESS IN CUYAHOGA COUNTY, OHIO THROUGH RESIDENTIAL WEATHERIZATION

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Each year in the United States more people die from heat waves than from any other type of natural disaster (CDC 2006). While research in the environmental health sciences has shown that increasing access to air-conditioning is a strong protective measure for reducing heat-related mortality (Luber and Hess 2007; Luber and McGeehin 2008; Semenza et al. 1996), weatherizing a residence's thermal envelope may be preferable because it has the potential to improve indoor thermal environmental conditions while reducing electrical demand (Huang 1996, 1996; Nicol and Roaf 2007; Roaf 2010; Roaf, Crichton, and Nicol 2009).

Most weatherization programs in the United States only provide wintertime energy efficiency services. Research indicates that these services can improve wintertime indoor thermal comfort indoors while reducing energy costs (Chapman et al. 2009); what remains relatively unknown is the effect of these wintertime weatherization measures on summertime interior thermal environmental conditions.

To begin to close this knowledge gap, house configuration data from the Ohio Department of Development and several weatherization program assessments were used to create a set of average "low-income" homes representative of houses weatherized in Cuyahoga County, Ohio. Greater Cleveland is the focus of the study because a national-level assessment of heat vulnerability identified the county as being extremely susceptible to high temperatures (Reid et al. 2012; Reid et al. 2009).

These average home typologies were then input into the EnergyPlus simulation engine to determine if wintertime weatherization measures reduced exposure to extreme temperatures indoors. The results indicate that some of the measures typically selected for weatherization programs may increase exposure to high temperatures indoors. Additional, simple measures to reduce interior temperatures are discussed along with suggested changes to program design to maximize both summer and winter performance of low-income residences.

Topic Areas:

1. Retrofit of Existing Buildings for Energy Efficiency
2. Performance of Residential Buildings under Natural Disasters
3. Protection and Retrofit Methods against Natural Disasters
4. Low-income Housing

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Overheating in Multifamily Residential Buildings

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In this project data have been collected for eighteen multifamily buildings from the archives of multiple companies that provide energy management systems (EMS). Overheating was found in all eighteen buildings: the overall average temperature of all buildings was well above 70°F when the EMSs were not in operation.[1] In fifteen of the eighteen buildings, average temperatures in 100% of the apartments when EMSs were not in operation were above 70°F (ranging from 70.7°F to 87.4°F). In the remaining three buildings, average temperatures in 88% of apartments were also above 70°F (ranging from 70.3°F to 85.2°F). Likewise, when the EMSs were on, in seven of eighteen buildings, average temperatures in 100% of the apartments were above 70°F (ranging from 70.3°F to 81.1°F). In the remaining eleven buildings, average temperatures in 67% of the apartments were above 70°F (ranging from 70.0°F to 81.2°F). Based on this analysis, the estimated average increase in annual space heating energy cost for these buildings due to overheating is approximately 18.6% when the EMS is off, compared to a baseline average temperature of 70°F all the time.

Introduction

Due to a need to minimize energy consumption and associated greenhouse gas emissions, researchers in the U.S. are employing various techniques to avoid undesired energy consumption in residential and commercial buildings. This involves all aspects of energy consumption in a building. In the United States, approximately 41% of all energy utilized (approximately 40,000 trillion Btu [11.7 trillion kWhr]) is consumed in residential and commercial buildings (U.S. Energy Information Administration/Annual Energy Review 2010) and out of the energy consumed in residential and commercial buildings, approximately 50% is used for space heating.
As stated, a large portion of total energy is consumed in space heating and the energy consumption increases rapidly if the buildings are overheated. In the Northeast and Midwest regions of the US, there is a large stock of multifamily buildings with space heating provided by common systems using hot water or steam. According to the 2005 American Housing Survey, there are about 3.2 million occupied hydronically-heated, low-rise housing units in the US (U.S. Census Bureau 2005). Nearly 90% of these homes are in the Northeast or Midwest; with a large portion being rental units (40%), or occupied by the elderly (24%) (U.S. Census Bureau 2005). Most hydronically-heated residences are older, with only 1% being classified as New Construction (built within the past four years) in the 2005 AHS data (U.S. Census

[1] When the EMS is deactivated the boilers operate on outdoor reset control, the dominant boiler control type for multifamily buildings. EMS operation is intended to depress overheating. Using data from periods when the EMS is not operational is more representative of typical buildings because most buildings do not have an EMS.

2006). Typically, residents of these buildings do not pay for heat directly (i.e. heat is not sub-metered). Heating fuel use for these systems is reputed to be higher than necessary, given the thermal properties of the buildings. Anecdotally, a significant number of apartments are overheated much of the time (the window-as-a-thermostat syndrome) (Urban Green Council). Overheating results in an increase in annual energy consumption of approximately 1% per °F over the desired temperature in a dwelling for each eight hours of the day (the percentage of savings is greater in milder climates than in severe climates) (U.S. DOE). In the US, controlling of hydronic heating systems typically involves outdoor reset control algorithm, different day and night time space temperature set-points etc. The extent of overheating, and the variance of it in different parts of the building and on different days during the heating season, affects the strategy used to combat it. Generally, apartments must be heated to at least 68°F (20°C) by law during the heating season. Recently, at the 2011 expert meeting conducted by the ARIES Building America team[2] titled Multifamily Hydronic and Steam Heating Controls and Distribution Retrofits, the subject of just how significant a factor overheating is (and how large a potential exists for energy savings by eliminating it) was debated (Dentz 2011) and it was acknowledged that no rigorous analysis of the phenomenon is published.

Problem Description

Overheating is defined as heating to a temperature greater than that required by local ordinance or desired by building management. In New York City, for example, local law requires multifamily building operators to maintain the indoor air temperature at a minimum of 68°F if the outside temperature is below 55°F during the day (10:00 pm to 6:00 am) and a minimum of 55°F if the outside temperature is below 40°F during the night. However, it was found that indoor temperatures in many buildings were significantly higher than the required indoor air temperature. Overheating can cause discomfort for residents due to the heat and excessively low humidity levels, which can have negative health consequences. Overheating also results in higher fuel consumption than necessary and increases building fuel expenses. Moreover, if residents find it too hot, they may open windows, which further exacerbates the problem.

To quantify overheating, data were obtained from the archives of companies that provide EMS to multifamily buildings in the Northeast U.S. Data were collected for time periods when the EMS control system was disabled and for time periods when it was enabled. This procedure enabled us to quantify overheating in these buildings when the EMSs were not in operation as well as effectiveness of the EMSs when they were in operation. Data were analyzed for eighteen multifamily buildings for deviation from the locally required minimum heating requirements. Data have been analyzed for enough apartments (a minimum of 11%, and an average of 20% per building) so that the data are representative of the entire building. Table 1 shows characteristics of the buildings considered in this study.

[2] Building America is a U.S. Department of Energy research program focusing on residential energy efficiency.

Results and Discussion

In this study, data from at least 10% apartments in each building were analyzed for eighteen buildings located in New York City (Table 2). New York City law requires building owners to provide heat to the building only if the outdoor air temperature is below 55°F. Most of the boilers in this region of the US function based on outdoor air reset control in which the boiler supply temperature or firing cycle varies with respect to the outdoor air temperature and if the outdoor air temperature is above 55°F the boiler shuts off automatically. Ideally, the outdoor reset settings are formulated to maintain at least 68°F indoor air temperature. Figure 1 through Figure 3 show data from a typical building (building 15) in the study for the 2011-12 heating season. The figures show the variation of indoor air temperature, average indoor air temperatures, and the variation of indoor air temperature as a function of outdoor air temperature. For nearly the entire time, indoor air temperatures in all apartments were above 70°F.

Table 1. Characteristics of the multifamily residential buildings

No	Number of Floors	Total No. of Apartments	Heating System	Ownership Type
1	3	60	Steam	Rental
2	3	48	Hot water	Rental
3	4	36	1-pipe Steam	Rental
4	4	16	1-pipe Steam	Rental
5	4	12	1-pipe Steam	Rental
6	4	39	1-pipe Steam	Rental
7	5	21	Hot water, Staged boilers	Rental
8	5	77	1-pipe steam	Rental
9	5	77	1-pipe steam	Co-op
10	5	202	1-pipe Steam	Rental/Co-op
11	6	71	Hot water	Rental
12	6	74	1-pipe steam	Rental
13	6	56	Hot water	Rental/SRO
14	6	48	1-pipe steam	Rental
15	6	26	1-pipe steam	Rental
16	6	22	1-pipe steam	Rental
17	6	34	1-pipe steam	Rental
18	6	44	1-pipe steam	Rental

Table 2. Building summary data

Bldg. no.	No. floors	No. apts.	Sensor location (by floor)	No. apts. with sensors	EMS Status	Range of T (F)	Avg T in all apts. (F)	Apts. found overheated (>70°F)	Average T in overheated apts. (F)
1	3	60	1, 3	16	OFF	59.0 – 82.0	71.8	88%	72.3
					ON	53.0 – 85.0	72.3	94%	72.5
2	3	48	3	16	OFF	57.2 – 90.2	74.7	100%	74.7
					N/A				
3	4	36	4	5	OFF	63.4 – 87.6	78.7	100%	78.7
					ON	66.0 – 88.4	77.3	100%	77.3
4	4	16	3, 4	12	OFF	60.0 – 91.0	73.7	100%	73.7
					ON	46.0 – 88.0	71.3	83%	72.0
5	4	12	3, 4	3	OFF	69.1 – 87.1	75.5	100%	75.5
					ON	69.1 – 95.1	76.1	100%	76.1
6	4	39	3	9	OFF	62.0 – 84.0	72.3	89%	72.7
					ON	59.0 – 82.0	70.5	67%	71.7
7	5	21	4, 5	5	OFF	69.2 – 83.7	75.5	80%	76.5
					ON	65.7 – 90.2	74.6	100%	74.6
8	5	77	6	9	OFF	65.0 – 84.0	76.2	100%	76.2
					ON	59.0 – 83.0	73.6	89%	74.2
9	5	77	1, 4	12	OFF	54.0 – 86.0	77.7	92%	78.5
					ON	61.0 – 83.0	75.2	92%	75.8
10	5	202	5	20	N/A				
					ON	64.8 – 82.8	75.0	100%	75.2
11	6	71	6	8	OFF	65.5 – 87.5	74.3	100%	74.3
					ON	62.5 – 93.5	75.9	100%	75.9
12	6	74	6	10	N/A				
					ON	59.0 - 83.0	72.9	80%	74.1
13	6	56	6	6	OFF	62.1 – 100	77.7	100%	77.7
					ON	57.0 - 91.0	75.1	83%	76.8
14	6	48	5, 6	12	OFF	62.8 – 94.7	81.0	100%	81.0
					ON	48.8 - 95.7	74.7	92%	75.2
15	6	26	2, 3, 4, 5	10	OFF	65.0 – 88.0	76.3	100%	76.3
					ON	54.0 – 82.0	70.9	70%	72.1
16	6	22	1, 2, 3, 5	13	OFF	59.4 – 89.6	79.2	100%	79.2
					ON	62.8 – 95.4	75.0	100%	75.0
17	6	34	6	11	OFF	61.0 – 87.0	76.6	100%	76.6
					ON	55.0 – 87.0	72.0	73%	73.4
18	6	44	1, 2, 3, 5, 6	15	OFF	66.5 – 86.5	77.6	100%	77.6
					ON	63.3 – 90.5	74.1	100%	74.1

Figure 1. Building 15 indoor air temperatures and outdoor air temperature

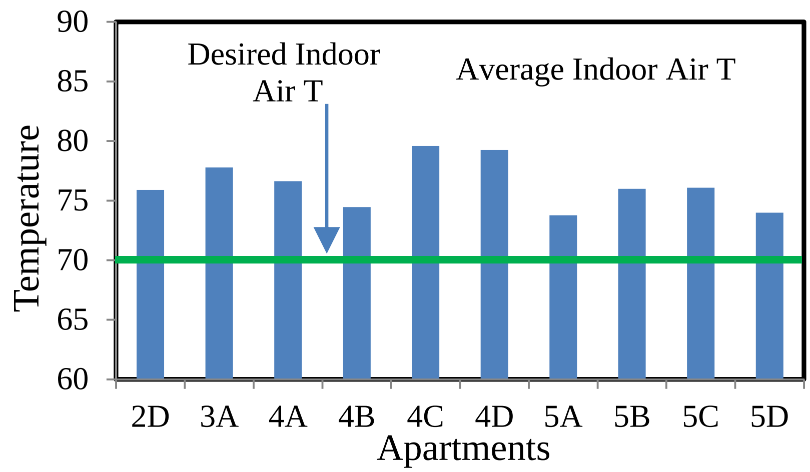

Figure 2. Building 15 average indoor air temperatures during the 2011-2012 heating season

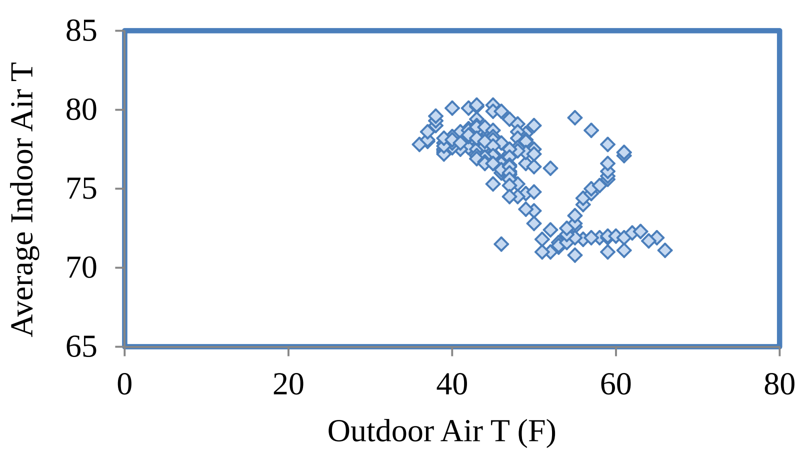

Figure 3. Building 15 indoor air temperature as a function of outdoor air temperature (2010-2011 heating season)

In this building, the sensors were located in ten different apartments on various floors. The average temperatures in all the apartments were above 70°F ranging from 73.8°F to 79.6°F (average of 76.3°F). Apartments located on the 4th floor were overheated the most (Figure 2). The average temperature of the top floor apartments was 75.0°F which was lower than the average temperature of the entire building. It can also be seen in Figure 3 that indoor temperature increases as outdoor air temperature decreases. Table 2 shows the overheating results for each building. Overheating is significant in nearly every building, even with the use of an EMS. Note that minimum temperatures in few buildings were significantly low but for a short duration, perhaps due to open windows or vacancies. The average temperature was more than 70°F in all the buildings when the EMSs were OFF. In fifteen of the eighteen buildings, average temperatures in all the apartments when EMSs were not in operation ranged from 70.7°F to 87.4°F and in three buildings, average temperature in more than 88% of apartments ranged from 70.3°F to 85.2°F. Likewise, when the EMSs were on, in seven of eighteen buildings, average temperatures in all the apartments were above 70°F, ranging 70.3°F to 81.1°F. In the remaining eleven buildings, average temperature in more than 67% of apartments were also above 70°F ranging 70.0°F to 81.2°F. The average temperature in overheated apartments was more than 75°F in 61% of the buildings when EMSs were off and more than 75°F in 33% of the building when EMS were on.

Temperature variation by floor was examined in four buildings. Figure 2, Figure 4, Figure 5 and Figure 6 show average temperature by apartment for apartments on various floors. It can be seen in these figures that average temperature is not a function of floor level. The buildings considered in this work were low-rise buildings and therefore stack effect did not play a significant role. Based on these results, it is concluded that for buildings in which sensors were located only at the top floors, the average of top floor temperature sensors closely represents the average temperature of the entire building.

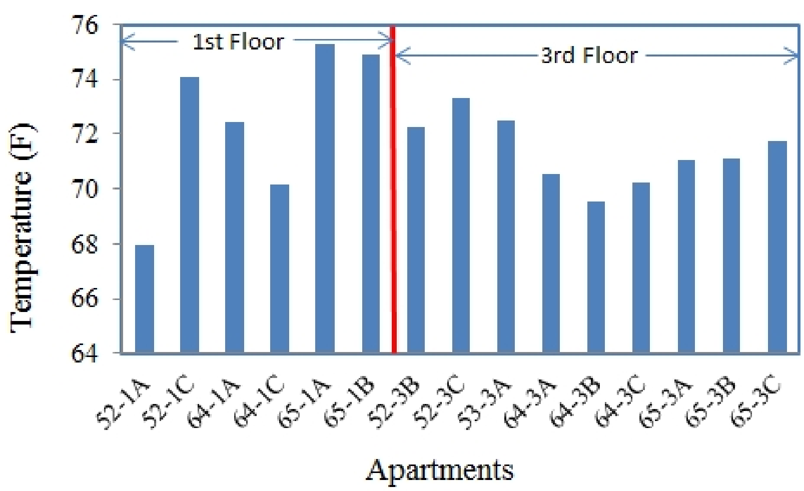

Figure 4. Building 1 average temperatures for apartments on two floor

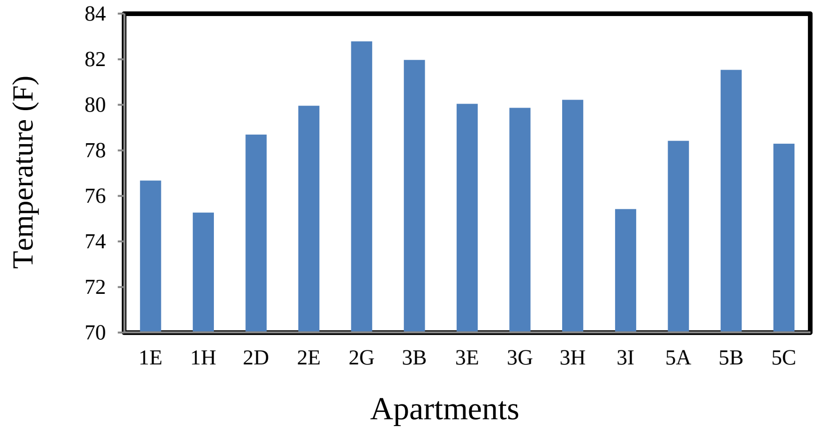

Figure 5. Building 16 average temperatures for apartments on four different floors (1st digit is floor number)

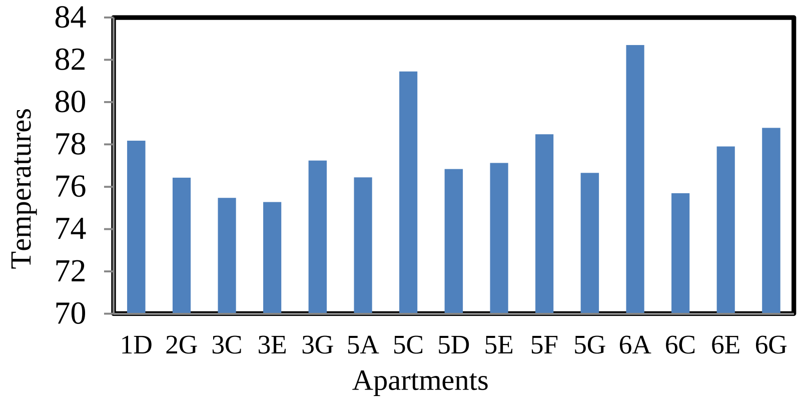

Figure 6. Building 18 average temperatures for apartments on five different floors

Figure 1 shows the variation of indoor air temperature in various apartments in building 15 and the outdoor air temperature. It can be seen that for nearly the entire time and for a wide range of outdoor air temperatures, indoor air temperatures in all apartments were above 70°F. In this building, temperature sensors were located in apartments at four different floors. In all the apartments, indoor air temperatures were above 70°F. Results show similar graphs for all remaining buildings. The pattern is similar: nearly all apartments are heated to more than 70°F for nearly the entire time when the EMS is off. However, there is a wide spread of apartment temperatures with the warmest and coolest apartments being separated by about ten degrees F on average and the coolest apartment being close to 70°F much of the time. This indicates that while there is some room to reduce heating building wide, individual zone (by apartment or by section of building) is necessary to achieve the full extent of available savings. Table 3 shows the effect of different types of heating distribution systems on overheating. Of the eighteen buildings, four were heated by hot water and the remainder by 1-pipe steam. When the EMSs were off, average temperature in the hot water heated buildings was slightly lower than the steam buildings. When the EMSs were on, the average temperature in the hot water buildings were nearly 2°F higher than that of the steam buildings. Figure 7 (a and b) compares the overall average indoor temperature of the buildings and average indoor temperatures of overheated apartments when the EMSs were off and on. As stated, the data were collected for the 2011-2012 winter season except building 9 for which data was collected from the 2010-2011 season. Note that the temperature data presented in Table 2 only represent temperatures in the buildings for a portion of the 2011-12 winter because the EMSs were installed part way through the heating season. The green line in Figure 1 and Figure 2 shows the desired indoor air temperature of 70°F. As can be seen in Table 2 average space temperatures in all the buildings were significantly higher than desired space temperatures, especially when the EMSs were disabled. Table 3 and Table 4 present a statistical analysis of the temperature data collected in the buildings. The average lowest temperature of all apartments was 72.6°F when the EMS was off.

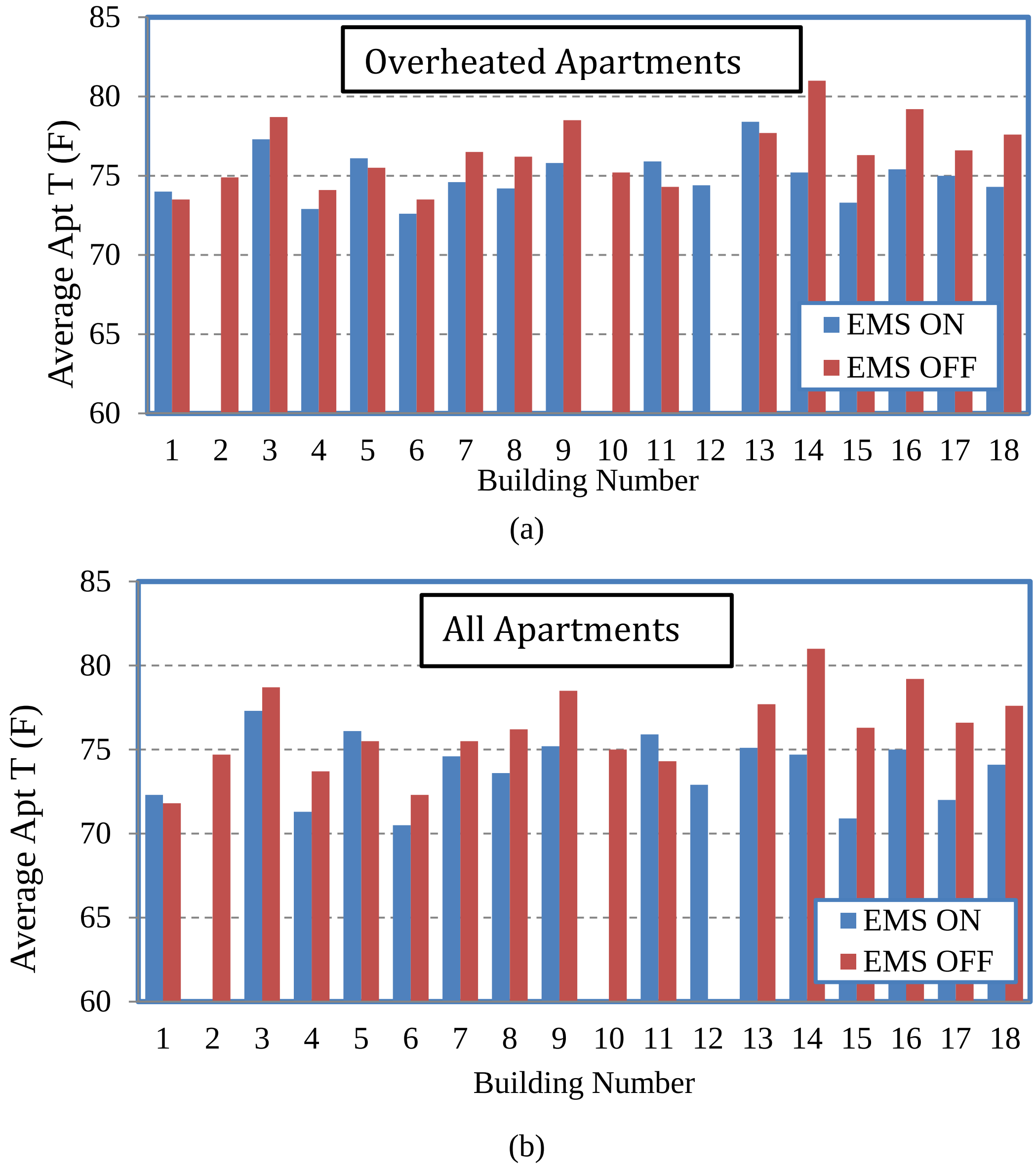

Figure 7. Comparison between the overall average indoor temperature of the buildings and average indoor temperatures of overheated apartments when the EMSs were off and on.

Based on a U.S. Department of Energy report, (U.S. DOE), overheating results in an increase in annual energy consumption of approximately 1% per °F over the desired temperature in a dwelling for each eight hours of the day (US DOE). In all the buildings studied, the average temperatures were well above 70°F, ranging from 75.2°F to 81.0°F. It was also found that most apartments' average temperature was well above 70°F. Average temperature of all the buildings when the EMS system was off was 76.2°F whereas when the control systems were on, the average temperature of all the buildings was 74.4°F. Based on this analysis, the estimated average increase in annual space heating energy cost for these buildings (assuming no EMS) due to overheating is approximately 18.6% based on 70°F target temperature, or 24.6% based on the 68°F legal daytime temperature. In addition, night time set back can be used, reducing the legally required temperature to 55°F during night (in New York City). Under these conditions, the estimated average increase in annual energy cost for these buildings (assuming no EMS) due to overheating is as high as 37.6% based on 68°F target day time temperature and an eight-hour 55°F target night time temperature.[3] These overheating saving assumptions will vary with envelope characteristics and climate conditions.

In a year with average winter temperatures, fuel bills for a typical 80-100 unit apartment building can run $50,000-60,000. Therefore annual overheating waste for this typical building and overheating profile is approximately $11,160 based on a desired temperature of 70°F, $14,760 based on the legal limit of 68°F without nighttime setback, and $22,560 with a 55°F nighttime set back.

Table 3. Variation in overheating by heating system type

Heating Type	No. of buildings	EMS OFF		EMS ON	
		Avg T	Avg T in Overheated (>70°F avg.) Apts.	Avg T	Avg T in Overheated (>70°F avg.) Apts.
Hot water	4	75.6	75.9	75.2	76.3
Steam	14	76.3	76.6	73.5	74.7

Table 4. Statistical analysis of the temperature data

EMS Status		Mean T (F)	Standard Deviation	Minimum T (F)	Maximum T (F)	Range T (F)
ON	Overall average T in Apts	72.5	1.2	70.9	75.0	4.1
	Average T in the Overheating Apts	74.4	1.6	72.9	78.6	5.7
OFF	Overall average T in Apts	75.6	1.6	72.8	78.2	5.4
	Average T in the Overheating Apts	76.1	1.5	74.1	79.0	4.9

[3] Note that because of morning boost heat, actual savings will be lower than this theoretical maximum.

Conclusion

Eighteen sites were selected where EMS systems were already installed and the data were analyzed for several apartments in each building. The primary research question addressed by this report was: How significant is overheating in this building type? Overheating was found in all eighteen buildings. In all eighteen buildings, average temperature was well above 70°F when the EMSs were not in operation (Table 2). In fifteen of the eighteen buildings, average temperatures in all the apartments when EMSs were not in operation ranged from 70.7°F to 87.4°F and in three buildings, average temperature in more than 88% of apartments ranged from 70.3°F to 85.2°F. Likewise, when the EMSs were on, in seven of eighteen buildings, average temperatures in all the apartments were above 70°F, ranging 70.3°F to 81.1°F. In the remaining eleven buildings, average temperature in more than 67% of apartments were also above 70°F ranging 70.0°F to 81.2°F. Based on this analysis, estimated average increase in annual energy cost for these buildings due to overheating was approximately 18.6% based on a 70°F target temperature or 37.6% based on the legal temperature with night time setback to 55 °F for eight hours per day.

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Air Distribution Retrofit Strategies for Affordable Housing

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ABSTRACT

In multi-unit buildings, traditional duct sealing methods are often impractical, costly and/or disruptive because of the difficulty in accessing leakage sites. In this project, supported by the U.S. Department of Energy's Building America™ program, two retrofit duct sealing techniques—manually-applied sealants and injecting a spray sealant (Aeroseal®[1]) in combination with manual sealing, were implemented in several duplex buildings in North Carolina. Each method was used in twenty housing units. Duct leakage to the outside was reduced by an average of 59% through the use of manual methods, and by 90% in the units where a combination of aerosol and hand sealing was used. The cost of manually-applying sealant ranged from $275 to $511 per unit and for the Aeroseal®-treated ducts the cost was $700 per unit. Modeling suggests a short simple payback of 1.2 years for manual sealing and 1.5 years for the Aeroseal® system.

INTRODUCTION

Retrofit duct sealing techniques for low-rise multi-unit housing are not as well documented or developed as those for single family detached construction. Multi-unit housing is complicated by the inaccessibility of the ducts, the disturbance to numerous occupants when work is being performed, and the range of construction methods, styles of buildings, and construction details unique to these structures.

Duct leakage is recognized by the Department of Energy as a significant problem in many older residential buildings (U.S. Department of Energy Building Technologies Program 2011). It can contribute to energy waste, poor comfort, poor indoor environmental quality (IEQ) and moisture problems (U.S. Department of Energy Building Technologies Program 2011). Duct sealing alone can save up to 20% of home heating and cooling energy expenditure (U.S. Department of Energy 2009). Sealing ducts, therefore, is important to improve building performance. Unfortunately, ducts can be difficult to access (e.g. when

[1] Aeroseal is a registered trademark of Aeroseal, LLC, a division of JMD Corporation.

located in floors, cramped crawlspaces or under low sloped roofs), making the repairs expensive or impossible with traditional manual methods.

Traditional duct sealing involves manually inspecting and sealing holes in the ductwork with mastic adhesive and tape from the outside. A new duct sealing method is available that allows sealing of inaccessible ducts (that have an interior air barrier[2]) from the inside using an aerosol sealant injected into the airstream with a special blowing apparatus. The aerosol system, known as Aeroseal®, is a proprietary system that was developed at the Lawrence Berkeley National Laboratory in 1994 and has been commercially available since 1997 (Aeroseal, LLC 2011). Additional field data is needed to verify its performance, cost and suitability in a variety of building types

FIELD STUDY

In a project supported by the U.S. Department of Energy's Building America program, air distribution systems were repaired in 40 apartments in two affordable housing developments (Terrace Park and Berkshire Village) owned and managed by the Raleigh Housing Authority (RHA) in North Carolina. Two repair approaches were used to compare their respective costs and effectiveness: hand sealing with mastic and fiberglass mesh (for larger gaps), and the Aeroseal® system in combination with mastic at easily accessible locations. Duct systems were evaluated before and after the repairs. Four typical unit types were modeled to estimate the effect of the two repair techniques on energy use. The one- and two-story units are about 50 years old, about 1,000 ft^2 , have central air conditioning and natural gas fired forced air heating.

Technical Approach

Each treatment group contained a similar number of one and two story housing units. Each duct sealing method was used in half of the 40 apartments, split between the two developments (Table 1). Existing heating and cooling equipment remained in place. The only changes to the units were the duct repairs. All units were occupied at the time of the retrofit.

Table 1. Unit types

Development	Unit type	Hand sealing	Aeroseal®
Terrace Park	1 story 2 bedroom	0	2
	1 story 3 bedroom	3	2
	2 story 3 bedroom	7	6
Berkshire Village	1 story 3 bedroom	7	7
	2 story 3 bedroom	3	3

[2] The Aeroseal system may not be suitable for certain duct types such as flex ducts without an inner liner or unlined duct board.

The effects of the duct repairs were assessed by measuring duct leakage (total and to the outside), system airflow (using an Energy Conservatory TrueFlow® Air Handler Flow Meter) and air flow at each register (using an Energy Conservatory FlowBlaster) before and after the retrofit in each housing unit using recommended test protocols (The Energy Conservatory, Inc. 2006, 2011, 2012). To support the modeling effort, building enclosure leakage was measured in all units (pre and post retrofit) using an Energy Conservatory Blower Door. Three guarded blower door tests were also conducted to estimate the amount of leakage between units compared to the shell leakage directed only to the outside. Primary duct system characteristics are provided in Table 2.

Table 2. Duct configurations

	Terrace Park		Berkshire Village	
Unit type	1-story	2-story	1-story	2-story
Supply duct construction	Flex	Unknown (inaccessible)	Metal trunk with flex branches	Metal trunk with flex branches for 2nd floor; Unknown for 1st floor
Supply duct location	Attic	Floor cavity	Attic	Floor cavity and attic
Return duct construction	Metal	Metal	Metal	Metal
Return duct location	Conditioned space	Conditioned space	Conditioned space	Conditioned space
Air handler location	Conditioned space 1st floor	Conditioned space 2nd floor	Conditioned space 1st floor	Conditioned space 2nd floor
Returns	1	2 (1 on each floor)	1	2 (1 on each floor)

Hand sealing application

Hand sealing consisted primarily of sealing register boots to the ceiling with mastic or foil tape from below; sealing register boots to floors with mastic or foil tape from above; sealing returns from the inside with mastic; sealing the air handler with mastic; and sealing rigid trunk duct and trunk to flex duct connections in the attic with mastic. A set of instructions was provided to the heating and air conditioning contractor for hand sealing.

Aeroseal application

Aeroseal® is a proprietary aerosol applied sealant system that is injected into pressurized supply and return ducts. Sealant particles accumulate at leakage locations, gradually closing the leak. Gaps larger than 5/8 inch are recommended to be sealed manually with fiberglass and mastic, and the duct material must have an interior air barrier (Aeroseal, LLC 2011). The injection system continuously measures airflow and leakage throughout the sealing process, which is halted when the leakage has been reduced to the desired level.

The connections from the duct system to the air handler as well as to registers are blocked to prevent the sealant from fouling HVAC equipment or escaping into the living space. Most local codes will require a licensed HVAC contractor to perform this invasive work. The Aeroseal® system treats the ductwork but, because the registers and air handler are blocked off, it does not seal leaks in the return, air handler, or at the junction between registers and finish surfaces (wall/ceiling/floor). These areas must be sealed by hand, which is possible because they are usually accessible.

At the RHA properties, sealing of the Aeroseal® units included the Aeroseal® system (sealing to the maximum level achievable); plus sealing of the boot-to-finish gaps, returns, and air handler by hand with mastic. The register boot, return plenum and air handler hand sealing was done after the Aeroseal® process was complete and was done the same way as the sealing of those areas in the hand-sealed housing units. No additional sealing beyond Aeroseal® was carried out in the attic. Figure 1 illustrates the Aeroseal® application process.

Figure 1. Aeroseal® equipment (left) connected to supply plenum (right).

RESULTS

As expected, duct leakage was lower after the retrofit. The ducts in the Aeroseal®-treated units improved more than in the units sealed solely by hand. Return flow and supply register flows on average increased in all retrofit units with the exception of the supply register flows from the hand-sealed Berkshire Village 2-story units. One possible explanation is that certain ducts or supply boots were damaged (compressed or kinked) during the hand sealing, which restricted their post-retrofit flows.

Test results

A summary of the test results before and after duct sealing using Aeroseal® (red bars) and hand sealing (blue bars) is presented in Figure 2.

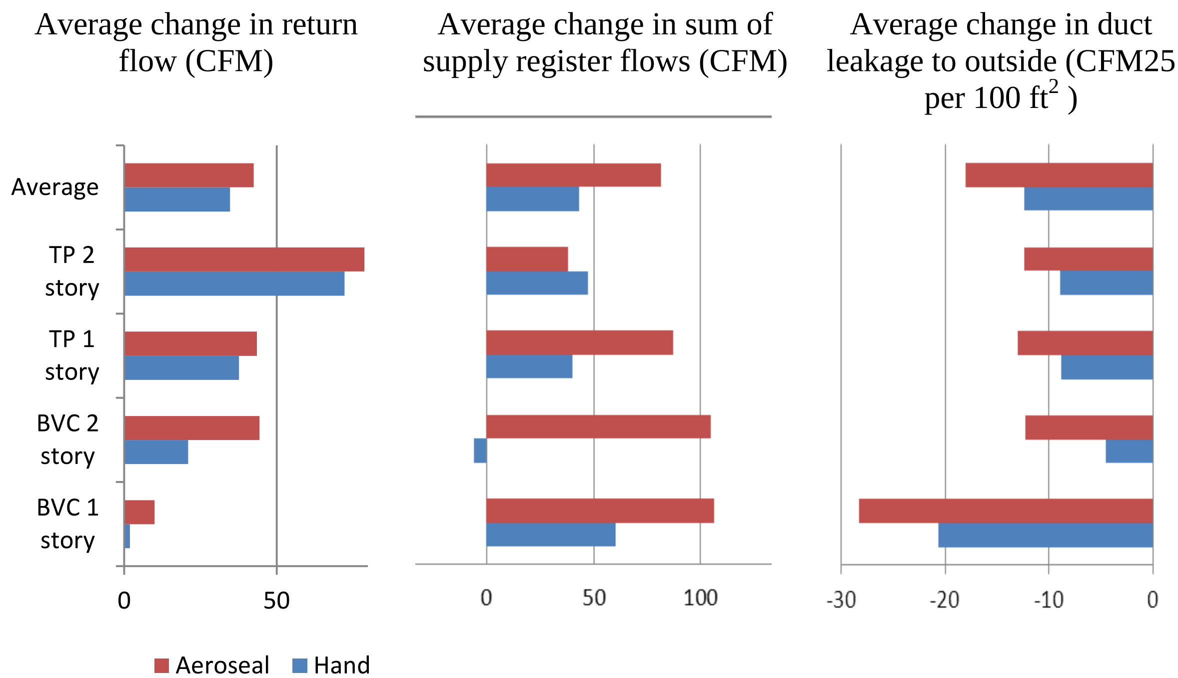

Figure 2. Duct sealing results comparing units with Aeroseal to hand sealed units by unit type (TP = Terrace Park; BVC = Berkshire Village Court)

Return flow (as measured at the return air register) increased by an average of about 40 CFM, slightly over 7% on average, with the Aeroseal units tending to have a slightly greater increase. The Berkshire Village Court one-story units showed very small flow improvement possibly due to a wide filter slot that was open when the filter was removed for testing (per the test equipment manufacturer's specified protocol). The open slot on the return side of the air handler drew in air that bypassed the return register and flow measurement device. The open slot also resulted in higher duct leakage measurements in these units.

As a result of duct sealing, supply register flows increased in most, but not all homes. On average, flow increased more for the Aeroseal® units than the hand sealed units.

A significant change in duct leakage to the outside was noted in all home types[3], with the Aeroseal® method achieving greater leakage reductions on average among all unit types. Pre-retrofit duct leakage to the outside averaged 15.8 CFM25/100 ft^2 of floor area and ranged from 7.2 to 27.2 CFM25/100 ft^2 of floor area for all units, up to four times higher than the North Carolina building code requirement of 6.0 CFM25/100 ft^2 for new construction (NC Building Code Council 2010). In post-retrofit measurements, the duct leakage was reduced to an average of 1.5 CFM25/100 ft^2 for the Aeroseal® units (with a range of 1.2 – 2.5 CFM25/100ft^2) and 7.0 CFM25/100 ft^2 for the hand sealed units (with a range of 1.3 – 21.2 CFM25/100ft^2).

[3] Measured individually (unguarded) to other units.

Reductions in total duct leakage were similar in magnitude. Pre-retrofit leakage averaged 27.5 CFM25/100ft^2 of floor area and ranged from 13.0 to 50.1 CFM25/100 ft^2 of floor area. In post-retrofit measurements, the duct leakage was reduced to an average of 7.9 CFM25/100 ft^2 for the Aeroseal® units (with a range of 4.3 to 19.5 CFM25/100 ft^2) and 16.0 CFM25/100 ft^2 for the hand sealed units (with a range of 6.3 to 38.3 CFM25/100 ft^2).

The Aeroseal® system records total duct leakage during the sealing process,[4] while the air handler, return and registers (the areas that are later sealed by hand) are blocked off. The Aeroseal® diagnostic reports reveal that on average approximately 70% of the total leakage reduction was due to hand sealing at the air handler and at the junction of the registers and the ceiling/floor, and not from the Aeroseal® product. The Aeroseal® system does not record leakage to outside, so it is not possible to determine from this data the degree to which Aeroseal® or hand sealing is responsible for its reduction.

Lessons

Researchers had the opportunity to learn from the experience of working on the duct systems in these affordable housing units relating to a variety of issues, including: the suitability of using standard testing protocols; using the two duct sealing approaches; and efficiency of production scale duct sealing in occupied units.

Approaches to duct sealing

The Aeroseal-treated units averaged 35% lower duct leakage to the outside (measured in CFM25/100 ft^2 of floor area) than the hand-sealed units. But it also has a number of other advantages over manually sealing ducts. Using Aeroseal® avoids having to work in what are often dark, hot, dirty and cramped attics. It allows sealing of otherwise inaccessible ducts inside floor cavities and low-clearance attics. It avoids the risks of workers damaging ducts, ceiling insulation or the ceiling itself as they move about the attic. Temporary flooring over the ceiling joists may mitigate this problem, but at significant added cost and time.

Difficulties with sealing ducts by hand can limit its effectiveness. To manually seal ducts wrapped with insulation, the wrap must first be removed, the duct exterior surface cleaned and then the duct connections then sealed with mastic. After 12-24 hours dry time the old wrap may be reinstalled (if undamaged) or new insulation applied. Quality control is more difficult and potentially expensive with manual sealing because of the additional labor required for an inspector to visit completed jobs and view the work in the attic. Duct testing could be conducted on a sample of units or visual inspection could be included, however, both would increase costs. Aeroseal®, on the other hand, provides a built-in test report that verifies the improvement of the supply ducts (but not the seals at register boots and return plenums).

Some challenges with the Aeroseal® system were encountered on these small homes. The Aeroseal® system is not well suited for sealing systems to less than 40-60 CFM of leakage.

[4] The Aeroseal® system includes a calibrated fan that continuously records total duct leakage during the sealing operation when the supply registers and air handler (including return) are blocked off.

A minimum airflow speed is necessary to keep the sealant suspended in the airstream. When leakage gets below 40-60 CFM, the flow becomes too low and the system may be shut down by the Aeroseal® software. The small RHA units had excessive duct leakage for their size, however much of that leakage was at the register boots, which are not treated by the Aeroseal® system and were hand-sealed. Most units had starting total leakage in the 70-80 CFM25 range (not including leakage at boots and the air handler), which is significant for apartments of less than 1,000 ft^2 , however the Aeroseal® system was constantly on the verge of shutting down due to low flow. Also, the nozzle that emits the sealant into the airstream became clogged more frequently than expected because of the many sequential low-airflow jobs that resulted in slower flow of sealant through the system.

The high ambient relative humidity during this project also served to depress flow rates. The Aeroseal® sealant needs to enter the duct system “dry”; i.e. a skin should form around each droplet of sealant. This is accomplished by a heating element in combination with an 8-10 foot plastic tunnel through which the sealant passes prior to entry into the duct system. Under humid conditions, the sealant needs more time in the tunnel to dry out, requiring slower airflow or a longer tunnel.

Connecting the Aeroseal® system to the supply duct proved challenging for these units. The lack of clearance between the top of the air handler heating coil and the ceiling required workers to custom fabricate fittings to make this transition. Arranging the equipment to provide an 8-10 foot straight run (the aforementioned tunnel) from the Aeroseal® nozzle to the duct entry point was also challenging in these small apartments. Often some portion of the equipment needed to be placed out of doors, which would not be possible in inclement weather conditions.

Production scale retrofits

To achieve greater market penetration in the affordable multi-housing segment, it will be beneficial to devise techniques that maximize the efficiency of sealing ducts in multiple similar co-located units in succession.

The run-time of the Aeroseal® equipment was approximately one hour per apartment; however, in an eight hour day, only two apartments could be completed. The equipment was idle, being moved or set-up 75% of the time. The Aeroseal® crew consisted of 2-3 people; one operating the equipment and 1-2 others doing set-up, clean-up and hand sealing of the returns and register boots. Adding another 2-person crew to prepare the next unit and restore the completed unit (re-install supply registers, repair the hole cut for the Aeroseal® entry point and general clean up) may enable the completion of three and perhaps even four units in one day with a single Aeroseal® system. Multiple spray nozzles would be required in case one became clogged due to the low sealant flow rate. The additional crew would increase labor costs, but perhaps be offset by the added productivity of the entire team (i.e. they may be able to complete twice the units per day with twice the labor but still with a single Aeroseal® system).

Another option for improving Aeroseal® productivity would be to connect two duct systems simultaneously using a “Y” connector. This would not provide an individual test result or certificate for each living unit, but it could reduce the time and cost of sealing systems in close proximity to each other. Finally, a smaller Aeroseal® system, perhaps suitable for lower levels of absolute duct leakage, would have made work in these units simpler and quicker.

MODELING

Four representative units (a one and a two story unit at each development) were modeled using BEopt, the Building America simulation tool. Pre- and post- retrofit conditions were modeled to predict energy cost savings based on measured duct leakage reductions. Average duct leakage to outside as a percentage of total flow, per unit type and per sealing type, were used for modeling the test results.

Table 3. Duct leakage characteristics from field tests for BEopt models

Method	Number floors	Average pre-retrofit duct leakage to outside (cfm/100 ft2)	Average post-retrofit duct leakage to outside (cfm/100 ft2)	Leakage to outside reduction (%)
Hand sealing	1 story	16.0	5.1	68%
	2 story	15.6	8.0	49%
Aeroseal®	1 story	17.5	1.6	91%
	2 story	13.6	1.3	91%

The results of the BEopt modeling for each of the four unit types are provided in Table 4. The Aeroseal method results in higher energy savings than hand sealing. Greater savings are predicted in the one story units than the two story units because a greater portion of the ductwork is in unconditioned space in the one story homes. Hand sealed units and units sealed with Aeroseal had similar pre-retrofit characteristics on average. The units treated with Aeroseal have lower (7% average) post retrofit duct leakage and slightly lower source energy use compared to the hand sealed units.

Table 4. BEopt analysis results – Annual whole house MBtu savings from duct sealing

Method	Number floors	Terrace Park	Berkshire
Hand sealing	1 story	24%	28%
	2 story	16%	8%
Aeroseal	1 story	34%	31%
	2 story	19%	19%

COST EFFECTIVENESS

Costs from the contractor for hand sealing were $511 per unit for the one story units where work included accessing the attics and sealing metal trunk ducts; and $275 per unit for the two story homes where ducts were inaccessible in the floor and work only included sealing boots, the air handler and the return. Contractor costs for the Aeroseal®-treated units were $700 per unit regardless of unit type, and include the hand sealing that was done in these units at the boots, returns and air handler. Most of the time spent on the Aeroseal® process is in the setup and cleanup so unit size is less important. Table 5 provides the estimated annualized energy expense[5] based on a 15-year lifespan for each retrofit method as calculated using BEopt. Based on these results, a simple payback was calculated of 1.2 years for hand sealing, and 1.5 years for the Aeroseal® process with the aforementioned hand sealing. The marginal payback for Aeroseal over hand sealing ranged from less than one year to 15 years depending on unit type.

Table 5 BEopt analysis results – annualized energy expense and savings

Method	Plan	Pre-retrofit annualized energy expense	Post-retrofit annualized energy expense	Annual savings	% Change	Marginal payback for Aeroseal® (years)
Hand sealing	TP1	$1,820	$1,415	$405	-22%	NA
	TP2	$1,837	$1,563	$274	-15%	NA
	BV1	$2,052	$1,505	$547	-27%	NA
	BV2	$1,747	$1,615	$132	-8%	NA
Aeroseal®	TP1	$2,055	$1,404	$651	-32%	0.8
	TP2	$1,772	$1,470	$302	-17%	15.2
	BV1	$2,008	$1,423	$585	-29%	5.0
	BV2	$1,729	$1,419	$310	-18%	2.4

CONCLUSION

[5] BEopt calculates the *annualized energy related costs* by annualizing the energy related cash flows over the analysis period. Cash flows consist of mortgage/loan payments, replacement costs, utility bill payments, mortgage tax deductions (for new construction), and residual values. Costs, excluding mortgage/loan payments, are inflated based on the time they occur in the analysis period. The cash flows are annualized by determining the present worth of the cash flow by converting the total cost for each year to the value at the beginning of the analysis period (National Renewable Energy Laboratory 2012).

A field evaluation was conducted in forty attached public housing units comparing hand sealing of ducts with mastic to a combination of aerosol duct sealing (Aeroseal®) with hand sealing at some easily accessible locations. Both methods were effective in reducing total duct leakage and duct leakage to the outside. Leakage reduction was greater for the ducts sealed with Aeroseal®, especially for ducts in inaccessible locations. Some of this difference is likely due to the fact that aerosol sealing reached portions of the duct system that were inaccessible to manual methods. Significant manual sealing was required even for the units treated with Aeroseal® because that system does not address air handler leakage nor the connection between duct register boots and the ceiling or floor.

Modeling indicated that both duct sealing techniques will result in lower annualized energy expenditures (accounting for the cost of the retrofit) than not sealing the ducts. Despite being more expensive to implement, the annualized energy expenditure for the Aeroseal® system was 1-16% lower than for hand sealing, depending on unit type. The marginal payback for Aeroseal over hand sealing ranged from 10 months to 15 years. Annual savings (based on BEopt annualized costs) ranged from $302 to $651 for Aeroseal® and $132 to $547 for hand sealing. The one story apartments are predicted to achieve greater savings than the two-story units because a majority of their ducts are in unconditioned attic space. While Aeroseal® is available in the market today and offered by many local applicators (Aeroseal, LLC 2011), room exists to streamline the technology, especially for production scale work and for smaller spaces such as conducted in this project.

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Whole Building Design Approach to Achieve High Performance Buildings

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The goal of the "Whole Building Design Approach" is to create a successful high performance building by applying an integrated design and team approach to the project during planning and programming phases (Whole Building Design). In residential buildings, to achieve success in building a high performance building, the project must consider sustainability.

Sustainability is defined as the "quality of not being harmful to the environment or depleting natural resources, and thereby supporting long-term ecological balance" (Dictionary.com). Practicing sustainability means being conscious of our actions and taking responsibility of maintaining our natural resources to protect the harmonious balance with our surroundings while taking into consideration our environmental, economic, and social values — the triple bottom line of sustainability.

Environment

Our environment (a physical system consisting of exchanged mass, energy, or other properties) is changing and demanding that we adapt to the changes we are experiencing, i.e., climate change. What is at risk if we choose not to preserve the environment? See below the major trends of the environment, its natural resources and the impacts of building development on people:

> The global average temperature has increased by 0.76°C (0.57°C to 0.95°C) between 1850 to 1899 and 2001 to 2005, and the warming trend has increased significantly over the last 50 years. While this report focuses on the energy sector, forest clearing and burning and land use change, and the release of non-CO2 gases from industry, commerce and agriculture also contribute to global warming (IPCC, 2007b). In the absence of additional climate policies, the IPCC (2007a; see Figure 1.4) projected that global average temperature will rise over this century by between 1.1°C and 6.4°C over the 1980 to 1999 average, depending on socioeconomic scenarios (IPCC, 2000).

> GHG [greenhouse gases] emissions associated with the provision of energy services are a major cause of climate change. The AR4 concluded that "Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations". (IPCC, 2007)

> Heat is already the leading cause of weather-related deaths in the United States, with more than 6,300 deaths resulting from exposure to extremely hot weather between 1979 and 2006. Rising temperatures, however, might result in fewer deaths from extreme cold.

> On average, we spend about 90 percent of our time indoors, where pollutant levels are often higher than those outside. Indoor pollution is estimated to cause thousands of cancer deaths and hundreds of thousands of respiratory health problems each year. In addition, hundreds of thousands of children have experienced elevated blood lead levels resulting from their exposure to indoor pollutants. An estimated 17 million Americans suffer from asthma (U.S. EPA 1999). In addition, about 5,000 deaths occur yearly from asthma—an increase of 33 percent in the last decade (Mannino et al. 1998).

The U.S. Environmental Protection Agency (EPA) found that indoor air pollution, commonly called sick building syndrome, costs businesses $60 billion annually.

In the mid-1990s, one in five U.S. schools reported unsatisfactory indoor air quality, and one in four schools reported ventilation as unsatisfactory.

Buildings in the United States contribute 38.9 percent of the nation's total carbon dioxide emissions, including 20.8 percent from the residential sector and 18.0 percent from the commercial sector (2008). (U.S. Department of Energy, 2008)

Buildings accounted for 72 percent of total U.S. electricity consumption in 2006 and this number will rise to 75% by 2025. 51 percent of that total was attributed to residential building use, while 49 percent was attributed to commercial building usage. (U.S. Department of Energy, 2008)

Of the 26 billion gallons of water consumed daily in the United States, approximately 7.8 billion gallons, or 30 percent, is devoted to outdoor uses. The majority of this is used for landscaping. The typical suburban lawn consumes 10,000 gallons of water above and beyond rainwater each year. (U.S. EPA)

The information provided is presented only to make aware the relationship between the built and the natural environment; and the importance of addressing these issues in residential building. When these factors are considered during each stage of development (planning, integrated building design & construction, commissioning, building systems, management and operations) the value on improved health, natural settings and productivity is substantial. Ian McHarg's book, *Design with Nature* encouraged Americans to map and understand wetlands, floodplains, soils, hillsides, erosion-prone areas, and vegetation patterns before starting to lay out buildings and roads (Duerksen, 2009). We can make the choice to enhance our quality of life and serve the needs of residents without compromising our natural environment (our means of survival).

Society

In recent years communities have incorporated sustainable comprehensive plans and developers are supporting green building; identifying the correlation between our natural and built environment. A Comprehensive Plan is a guide used by land use planners to determine the goals or vision of a community development. The guide can be used to dictate public policy in housing, utilities, land use, recreation, etc. A Sustainable Comprehensive Plan takes into consideration the built environment on the surrounding natural environment and larger community, seeking to balance the quality of life, resource conservation and economic vitality. For example, communities such as Greensburg, KS, and the City of Northampton, MA have adopted a sustainable comprehensive plan seeking to be humble stewards of the earth's resources to offer higher quality of life for future generations. The citizens of Greensburg, KS, and the City of Northampton, MA have taken a sustainable approach in guiding the building of their communities; it includes aligning city programs, public/private projects, and government initiatives in developing the sustainability plan. Their plans lay out their goals, guiding principles, and measurements of progress.

The demand and cost of energy is rising as building owners are seeking creative ways to offset growing operating cost. Buildings accounted for 72 percent of total U.S. electricity consumption in 2006 and this number will rise to 75% by 2025; 51 percent of that total was attributed to residential building use, while 49 percent was attributed to commercial building usage (U.S. Department of Energy, 2008). The construction and operation of buildings account for about forty percent of worldwide consumption of raw materials and energy (The Economics of Green Building, 2005). Occupants, building managers, and investors are affected by the impacts of energy cost as well. Residents today are faced with difficulties in maintaining the American dream of home ownership. Community involvement in development has increased due to these concerns. For example, the community residents and stakeholders are recommending the project development proposal of a D.C. lot located in the Shaw Neighborhood to consider architectural excellence, planned unit development [PUD], affordable housing units, variety of unit mixes, LEED certification, retail space, improvement of streetscape, and local presence and hiring. The partnership between the District government, Advisory Neighborhood Commission (ANC) and local community organizers are seeking to revitalize the District's neighborhood business districts through a preservation-based strategy for attraction of preferred neighborhood uses. The District of Columbia is known for community participation in policies and programs affecting their neighborhoods, including traffic, parking, recreation, street improvements, zoning, economic development, police protection, sanitation and trash collection, and the District's annual budget.

Economics

The U.S. green building market continues to accelerate, according to McGraw-Hill Construction's 2013 Dodge Construction Green Outlook report. The value of green building has seen growth from $10 billion in 2005 to $78 billion in 2011. In 2012, the total market — non-residential and residential — is expected to be worth $85 billion, and by 2013, overall new green building is projected to rise to between $98 billion and $106 billion. It is expected that by the end of 2012, green homes will comprise 20 percent of the market, and in 2013 a 22-25 percent share by value is expected, equating to a $34-$38 billion opportunity (Greensburg Sustainable Comprehensive Plan). As the U.S. economy continues to grow while population and energy use increases there will be greater need for housing. For example, according to the statistics provided by the Office of Planning, the District of Columbia is adding about 1,100 residents per month and 70 percent of those new residents are under the age of 35. This creates a demand for smaller and furnished units especially since it is likely that newer residents will be moving in with less furniture and materials. Delta Associates CEO Greg Leisch believes a rise in rents would keep multifamily a healthy investment for years to come. Dr. Stephen Fuller, George Mason University's Center for Regional Analysis, also projects that housing will bounce back in 2014 and 2015.

There are several proposed and active decision making opportunities that support the economics of high performance residential buildings such as policies and planning tools. As presented in the Sustainable Comprehensive Plans of Greensburg, KS, and the City of Northampton, MA, decisions are made from community planning efforts. The outcome of planning usually dictates public policy and may lead to the formation of private/public partnerships. There are also regulations that guide residential building decisions such as zoning. Just as coordination of environmental review (includes natural, cultural and historic resources) involve interagency and public participation to be efficient and effective in federal planning and project development, the same is needed for residential building planning. The coordination of regulations such as green building codes to involve interdisciplinary design fields and public participation to develop high performing residential building projects are needed.

Today, government action encourages and support sustainable planning and building. For example, there are public policies referencing various LEED initiatives including legislation, executive orders, resolutions, ordinances, policies, and incentives found in 45 states, including 442 localities (384 cities/towns and 58 counties), 35 state governments (including the Commonwealth of Puerto Rico), 14 federal agencies or departments, and numerous public school jurisdictions and institutions of higher education across the United States. (U.S. Green Building Council, 2010) In comparison to the average commercial building, green buildings consume 26% less energy, have 13% lower maintenance costs, 27% higher occupant satisfaction, and 33% less greenhouse gas emissions. (USGBC, 2008)

The challenges we find in the availability of research information on energy efficient buildings to offset energy consumption, green features and technology such as environmentally sensitive construction techniques and materials are an opportunity for economic revitalization. The U.S. Department of Energy's Energy Innovation HUBs attempt to cultivate innovation in areas of energy science and engineering. The primary focus of the HUB is to provide tools for integrated design, identify sub-system components and controls, diversify workforce development, develop public policy, and promote education and management of knowledge. Finding contractors with sustainable design experience and locally manufactured sustainable materials are scarce. There is also a mistaken belief that green building is costly and excessive compared to standard building. Research shows that green building will support 7.9 million U.S. jobs and pump $554 million into the American economy over the next four years (2009-2013). (USGBC , 2009) Energy efficiency retrofits in Philadelphia could spur $618 million in local spending and support 23,500 area jobs according to a recently released report conducted by Philadelphia-based Econsult Corporation and commissioned by the Greater Philadelphia Innovation Cluster (GPIC) for Energy-Efficient Buildings. (Energy, 2011) Perceived cost benefits of green building according to building owners are; operating costs decrease 13.6% for new construction and 8.5% for existing building projects, building value increases 10.9% for new construction and 6.8% in existing building projects, return on investment improves 9.9% for new construction and 19.2% in existing building projects, occupancy increases 6.4% for new construction and 2.5% in existing building projects, and rent increases 6.1% for new construction and 1% in existing building projects. (USGBC, 2008) This information shows that green features enhance marketability, justify higher rents and asset value, and are in demand.

Whole Building Design Approach Process

In order to understand the need for high performance residential buildings one must understand the relationship between people, the built environment, and the natural environment. Once these factors are considered, specific to a residential building's location, the integrated design team can be effective in creating a sustainable high performing building. High Performance Buildings are energy efficient, have limited environmental impact, and operate with the lowest possible life-cycle costs. (Whole Building Design) Green building, green architecture, sustainable building, high-performance building, and low-impact development are among the terms used to denote practices that reduce the environmental impact of components of the built environment. (FPC State Government)

The characteristics of green building may consist of:

SUSTAINBLE SITE

- ✓ Bicycle parking to encourage bicycling to work and a healthy lifestyle
- ✓ Designated preferred parking spaces are available for hybrids and fuel efficient/low emitting cars
- ✓ Abundant green open space; green roof, roof top deck and open green space at ground level
- ✓ Located within walking distance of transit; Metro, bus stops, and bike share

WATER USAGE

- ✓ Water efficient fixtures and low flow urinals in restrooms which will reduce water use creating savings in operating expenses

ENERGY EFFICIENCY

- ✓ Thermal efficient building envelope integrated with mechanical requirements; reducing perimeter heating and size of HVAC unit
- ✓ Contract to purchase green power from clean and renewable sources
- ✓ High- efficiency lighting design and enhanced penetration of daylight
- ✓ Efficient building design practices that allow for less energy consumption resulting in cost savings i.e. cross ventilation and selecting building products for durability and design for adaptability
- ✓ Program fundamental and enhanced commissioning to better the performances of the building systems over its life time
- ✓ Provide ongoing accountability of building electricity performance i.e. building management system and benchmarking program, EPA Energy Star Portfolio Manager

INDOOR AIR QUALITY

- ✓ Indoor Air Quality (IAQ) Management Plan was developed and implemented for all development phases
- ✓ Low-emitting/low-VOC materials (formaldehyde free wood products, paints and adhesives) used to reduce indoor air contaminants
- ✓ Entry systems to capture pollutants are included in the design
- ✓ HVAC system designed to meet Thermal Comfort Conditions for Human Occupancy and Acceptable Indoor Air Quality i.e. Dedicated Outdoor Air System (100% outdoor air)
- ✓ Energy Star lighting and appliances

RENEWABLE MATERIALS

- ✓ More than 50% of non-hazardous construction and demolition debris recycled and salvaged
- ✓ Certified wood used in at least 50% of wood
- ✓ Specified and procured new regional materials that contained recycled content
- ✓ At least 20% of new materials obtained from local/regional manufactures; preference given to local and regionally extracted materials when possible i.e. reclaimed wood cabinetry
- ✓ Central area dedicated to the collection and storage of materials for recycling including paper cardboard, glass, compost and plastic bottles
- ✓ Green cleaning and integrated green landscape adopted to maintain the building

This approach was used on a much smaller scale on the U.S. Department of Energy Solar Decathlon project; challenging academic teams to design and build solar-powered houses. The objective is to build an affordable, attractive and energy-efficient home while considering comfort, healthy indoor environment, sufficient hot water, and producing more energy than it consumes. The teams are judged on aesthetic features, affordability, consumer appeal, and design quality with energy efficiency. This program not only benefits the students and participants involved, but also homeowners, building professionals, developers, designers, and teachers.

Figure 1 – U.S. Solar Decathlon – Solar Home

The University of Maryland received first place for their WaterShed home on Friday, Sept. 30, 2011; pictures shown in Figure 1. The WaterShed is able to manage storm water onsite with the use of a green roof; and to monitor indoor air quality, use of water and energy by means of an automation system. Its solar panel system, mechanical system and effective building envelope were engineered to reduce the need for fossil fuel. This high performing home was designed for the Washington DC area climate.

The Whole Building Design Approach structure will allow the integrations of services from the design to operation and maintenance phase; architect, interior designer, engineers, construction manager, and building operators. Unlike traditional delivery methods, the collaborative process brings together the owner, designer, and builder at the beginning of the project and promotes participation from all parties at all project stages (Integrated Project Delivery). The construction manager will be available as early as the design phase to provide input such as value engineering, cost comparison information or guidance on performance of proposed systems. A few advantages that this structure has over traditional methods of procurement are lower project cost, ability to handle project changes more easily, and places emphasis on building relationships. The phases involved in this approach are a multifaceted process. There are initiatives that can take place at each phase to improve energy efficiency in buildings or encourage high building performance while reducing the usage of natural resources, a diagram explaining this process is shown below:

Planning

- Identify sustainable goals for the residential building project, e.g., at least 45 percent of hot water demand must come from solar hot water heating.

Whole Building Design Approach

- Design and Engineering professionals to collaborate and produce design documents incorporating sustainable goals; throughout the schematic, design development and construction documentation phases.

High Performance Building Systems and Technology

- Designers, building control, and MEP [Mechanical, Electrical and Plumbing] building contractors to identify resource efficient systems and technology to monitor and predict performance of building. Value Engineering by the selected Construction Manager is conducted during this phase.

Green Building Construction

- Construction Manager to review construction documents during design phase and implement sustainable goals, e.g., select low emitting and renewable building materials. Focus maybe on reduction of consuming raw materials and energy throughout the construction phase.

Maintenance and Management

- Building performance to be tracked and compared to Planning and Development goals. Managing building operations to maintain sustainable goals during building life span, i.e. green leasing or EPA Energy Star Portfolio Manager (Benchmarking).

The project development team can include the developer, land owner, architect/design team, construction contractor, consultants, traffic engineer, legal counsel, etc. Each field offer a wealth of knowledge where opportunities such as charrettes can provide the outlet to share expertise and building information while creating a channel to interact and execute decisions in developing a high performance building. Technology, design tools, and building information models can help facilitate the Whole Building Design Approach. For example the electrical engineer, lighting consultant and designer for the building envelope can design the performance and systems of a building during the summer months; focusing on ways to reduce overdesign and over usage of resources. The design team to be selected to carry out the sustainable design intent must be experienced with high quality green design and be familiar with latest building technology as well as have a good working relationship with private and public sector. The design team will be expected to have a qualified team of building architects, interior designers, mechanical/electrical/plumbing engineers, structural engineers, civil engineers, and landscape engineers. For example, The Advanced Commercial Buildings Research group at the National Renewable Energy Laboratory (NREL) develops and utilizes advanced energy modeling tools [Opt-E-Plus Software] to help architects, engineers, and facility managers understand the energy implications of their designs and maximize the efficiency of their buildings (Opt-E-Plus Software). This team will work closely with other disciplinary groups such as a green roof consultant, within the development team, to reduce overdesigning and over usage of resources. In constructing a green building, precautions must be taken to ensure the design intent is communicated effectively and efficiently to the construction management team. The construction contractors to be selected will be expected to have a professional working relationship with other project stakeholders, allowing flexibility in appointing individual sub-contractors and be highly skilled in advanced building technology systems. The construction team will be expected to be knowledgeable in the latest building codes that influence green building, experienced in green construction, and available for value engineering during design phase. The District of Columbia Green Building Act of 2006 defines a green building as an integrated, whole building approach to the planning, design, construction, operation, and maintenance of buildings and their surrounding landscapes that help mitigate the environmental, economic, and social impacts of buildings, so that they are energy efficient, sustainable, safe, cost-effective, accessible, healthy, and productive. The development team can use this definition as a project goal using the whole building design approach for implementation.

Incentives can stimulate the adoption of sustainable goals for residential building projects. For example, performance based fees based on the level of performance of the building can be included in the request for proposals for each discipline; architect/engineers, construction contractors, commissioning agent, etc. The U.S. Department of Energy provides a resource guide in procuring these services to ensure energy efficiency and sustainability goals are met (Office of Energy Efficiency and Renewable Energy). The Harvard University Office for Sustainability provides guidance on green building request for proposal language (Owner's Project Requirement).

Conclusion

The Whole Building Design Approach intends to synthesize economic, environmental and social impacts of residential development while protecting and ensuring the health, safety, and welfare of the people. The information provided seeks to educate, involve and support the public in sustainable residential building development and reducing resource consumption, encourage the development community to advance the practice of high performing buildings, promote the improvement of policies affecting these practices, and inspire smart growth and smart life principles.

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Concrete Building Systems: Disaster Resilient Solutions for Safer Communities

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ABSTRACT

Over the past few decades, there was an exponential increase in human and material losses from disaster events. 2011 was a record-setting year for loss of life and property in virtually every part of the country. 2012 has produced another set of tragic, record-setting convective storms and wildfires. While the green building movement has traditionally focused on the environmental aspects of buildings, communities must now address the need for resilience while rebuilding to meet the challenge of the next natural disaster. This paper presents a four step process for resilient construction including adopting a basic building code, promoting market driven resilience programs, adopting more robust resilience standards and building with more robust materials such as concrete. It provides an overview of concrete building systems that have the mass and hardness to resist high winds and flying debris of tornadoes and the devastating effects of flood, fire and earthquakes.

RESILIENCE IS THE NEW SUSTAINABILITY

At the end of 2011, the National Oceanic and Atmospheric Administration (NOAA) said the U.S. had experienced 14 separate disasters, each with an economic loss of $1 billion or more, surpassing the record set in 2008 (NOAA 2011). 2011 losses amounted to $55 billion in the U.S. Globally, insurers lost at least $108 billion on disasters in 2011. Reinsurer Swiss Re Ltd. said that 2011 was the second-worst year in the industry's history. Only 2005, with Hurricane Katrina and other major storms, were more costly (Swiss Re 2011).

In 2012, there have been 11 natural disasters costing $1 billion or more in damage, making 2012 the second highest year with billion-dollar disasters. Early season tornadoes, the widespread and intense drought that covered at least 60 percent of the contiguous U.S. and Hurricane Sandy are expected to go down in history as the most costly weather-related disasters in U.S. history.

Most of the increased disaster losses cannot be attributed to an increased occurrence of hazards but changes in population migration and wealth. In the last several decades, population in the United States has increased and migrated toward the coasts, concentrating along the earthquake-prone Pacific coast and the hurricane-prone Atlantic and Gulf coasts. Over 60% of the U.S. population lives within 50 miles of one of its coasts (including the Great Lakes) (CRSR 1997). At the same time, wealth and the value of their possessions have increased substantially. The high concentration of people in coastal regions has produced many economic benefits, but the combined effects of booming population growth and economic and technological development are threatening the ecosystems that provide these economic benefits. Moreover, many elements of these aged infrastructures are highly vulnerable to breakdowns that can be triggered by relatively minor events (Masters 2011).

Disasters result not as much from the destructive agent itself but from the way in which communities are (or are not) prepared. Disasters happen when the natural systems are encroached upon by human development. There is no such thing as a natural disaster. The extent of disruption caused by a disaster is greatly influenced by the degree to which society chooses be fortified for the event. It is apparent that there needs to be significant shift in how we address natural disasters, moving away from the traditional focus on response and recovery toward emphasis on resiliency, that is, preventive actions to reduce the effects of a natural hazard.

Resilience can be understood as the capacity to anticipate and minimize potential destructive forces through adaptation or resistance. Basically addressing changes in the environment requires actions to mitigate their negative effects. If we identify resiliency, not solely as a state of preparedness for disaster, but as a desired characteristic of a sustainable society, one more in control of its energy and food production, access to water supplies, as well as being one that enables local social capital, we can begin to see the relationship. The term ‘sustainability’ usually describes some aspect of maintaining our resources from the environment to the quality of life, over time. It can also refer to the ability to tolerate—and overcome—degradation of natural environmental services, diminished productivity and reduced quality of life inflicted by man’s relationship to the planet and each other.

Critical infrastructures and other essential services have enabled societies to thrive and grow and become increasingly interconnected and interdependent from the local to global levels. As a society, we have placed a great deal of emphasis on recycling rates and carbon footprints. We are surprisingly willing to invest considerable amount of upfront capital for a LEED (Leadership in Energy and Environmental Design) Platinum certified building to achieve a mere 14% energy efficiency, yet be completely satisfied if the structure meets only the code minimum requirements for seismic or wind load.

The California Green Building Code, the ASHRAE 189.1 Standard, and the ICC700 (National Green Building Standard) all cite life-cycle assessment (LCA) as a means to promote sustainable building practices. The latest version of LEED rating system developed by the U.S. Green Building Council (USGBC) introduced special emphasis on regionalization and LCA criteria, but does not recognize disaster resilience as one of its standard criteria. The building service life plan (BSLP) elective by the International Green Construction Code (IGCC) gives credit to proposed projects designed to have a 100 year or 200 year life span as approved by the jurisdictions.

This is good start as building service life is rarely considered but is critical to any analysis of long-term sustainability. Balancing long term development plans with the ability to adapt to the needs of a rapidly evolving society is vital to the ultimate success of a building life plan. But for green building standards to truly address sustainable construction, they will have to address the concept of disaster resilience.

For a building to be truly sustainable it should be resilient. It should consider potential for future use and re-use and have a long service life with low maintenance costs. In addition, a sustainable building should be designed to sustain minimal damage due to natural disasters such as hurricanes, tornadoes, earthquakes, flooding and fire. Otherwise, the environmental, economic and societal burden of our built environment could be overwhelming. A building that requires frequent repair and maintenance or complete replacement after disasters would result in unnecessary cost, from both private and public sources, and environmental burdens including the energy, waste and emissions due to disposal, repair and replacement.

It doesn't make sense to design a modern building, commercial or residential, to meet LEED or other green building requirements that could be easily destroyed as a result of a hurricane, earthquake or other force of nature. That would mean that all of the green technology and strategies used in the building would go to the landfill. What is the point of installing low flush toilets in a home to conserve water if it ends up in a landfill after a tornado blows through?

FOUR STEPS TO DISASTER RESILIENCE

There are essentially two ways to approach mitigation. There are voluntary programs where communities or building owners voluntarily reduce their risk of natural disaster through enhancements in structures, warning systems and education. The second approach is to install mandatory building code requirements such that communities and building owners are obligated to design buildings and infrastructure to be more disaster resilient. We propose the following four steps, combining both voluntary and mandatory mitigation strategies, to achieving disaster resilience:

- Adopt a Building Code
- Encourage Voluntary "Code Plus" Construction
- Adopt High Performance Building Standards
- Build with Robust Materials

1. Adopt a building code. About 200 years ago, in 1811 and 1812, there were earthquakes that were so powerful in the area 50 miles north of Little Rock, AR, that seismologists still talk about it today. All of the quakes were estimated to have been magnitude 7.0 or greater. It is said that those earthquakes opened deep fissures in the ground, caused the Mississippi River to run backwards and that they were felt as far away as Boston. The earthquakes along the New Madrid Seismic Zone rank as some of the largest in the United States since its settlement by Europeans. The area of strong shaking associated with these shocks were 10 times as large as that of the legendary 1906 San Francisco earthquake. Despite the significant risk, many communities living near the New Madrid fault have not enacted significant earthquake preparedness policies such as the adoption of building codes with more stringent seismic requirements.

Building codes are effective for reducing disaster risk. A building code sets standards that guide the construction of new buildings and, in some cases, the rehabilitation of existing structures. Currently, building codes set minimum construction standards for *life safety*. Maintaining the functionality of structures is important for high-risk areas, but more importantly may be critical for certain groups that are more vulnerable to natural hazards, those who do not have a choice on where they live and work.

To date, among the eight States in the New Madrid Seismic Zone, five (Arkansas, Indiana, Kentucky, Missouri and Alabama) have statewide building codes for residential construction as minimum requirements, but three (Illinois, Mississippi, Tennessee) do not and they pass the responsibility to the local jurisdictions to adopt the codes themselves. Although earthquakes are high-consequence events, seismic mitigation in Mid-America generate little public interest because earthquakes in this region are low frequency.

If we are to take people's vulnerability seriously, we must deploy—and insist on—much greater technical expertise in resilient code adoption. The design community can provide some of the expertise, but their skills are not being effectively considered on the planning and policy level. The key, missing element is awareness among practitioners, the development community, and policy makers.

2. Encourage Voluntary "Code Plus" Construction. One way to encourage communities to develop fortified structures, enforce building codes and land-use management measures is to provide insurance premium reductions to all policy-holders in the area based on the stringency of land-use regulations, building code standards, and inspection. The more effective a community program is in reducing future disaster losses, the greater the insurance premium reduction. The Federal Insurance Administration created such a community rating system in 1990 as a way to recognize and encourage community flood plain management activities. This model could be applied to other hazards as well.

Another approach, the FORTIFIED for Safer Living and Safer Business program of the Insurance Institute for Business and Home Safety (IBHS) are voluntary programs aimed at incorporating building techniques into construction to provide an optimum level of protection against a variety of natural hazards. IBHS is a not-for-profit applied research and communications organization supported by the insurance industry. Their focus is to reduce or eliminate residential and commercial property losses due to wind, water, fire, hail, earthquake, ice and snow (IBHS 2012). The programs also address other business continuity issues such as such as interior fire, burglary, lightning protection and electrical surge.

IBHS promotes the need for strong, well-enforced building codes but also realizes that building codes offer minimum life safety standards and often don't have the necessary provisions to provide disaster resilience. For that reason, IBHS developed it FORTIFIED programs that provide specific design criteria and the necessary construction and inspection oversight to ensure "code plus" structures that are truly disaster resilient.

Over 250 homes have been designated as FORTIFIED since 2001. The program was battle tested by Hurricane Ike on the Bolivar Peninsula in Texas in September 2008. Ten of 13 FORTIFIED homes survived a direct hit from Hurricane Ike, including a 20 ft. storm surge. These FORITIFED homes were the only structures left standing for miles around, precisely because they were specifically designed and built to withstand extreme wind and water damage. The three FORTIFIED homes that did not survive were collapsed when other homes in the area slammed into them.

3. Adopt High Performance Building Standards. Adopting high performance building standards involve having local, state and federal governments adopt stricter standards for construction of buildings and infrastructure with the objective of reducing losses from natural hazards. The two primary model building codes in the U.S. are the International Building Code (IBC) and the International Residential Code (IRC). Depending on location, some states and municipalities adopt the model codes for their jurisdictions.

The Portland Cement Association recently developed *High Performance Building Requirements for Sustainability* that go beyond the basic building code and enhance the key concepts of durability and disaster resilience. Essentially these provisions state that for a building to be considered green, it must not only conserve energy and water, use materials efficiently, and have a high-quality indoor environment but it must also reasonably withstand natural disasters. In other words, a sustainable building must be long-lasting and durable (PCA 2012).

In addition, high performance buildings should not be a burden on their communities. They should be sufficiently resilient to disasters to ensure continuous operation and not place excessive demand on community resources such as emergency responders including fire, police and hospitals. Communities with disaster resilient buildings are more likely to be able to continuously operate hospitals, schools, and businesses after a disaster. Stronger homes and buildings mean people will have places to live and work after a disaster. Less disruption for a community means robust commerce and consistent tax revenue.

National associations such as the National Ready Mixed Concrete Association (NRMCA) and the Portland Cement Association (PCA) continue to work at the national level to make changes to the model codes to incorporate these high performance standards. This process is difficult and could take years. However, local jurisdictions could use the standards in whole or in part to strengthen building codes to address specific hazards for their community.

4. Build with Robust Materials. The final step towards disaster resilience is to build with robust building materials. Some of the qualities of robust building materials include versatility, strength, wind and water resistance, seismic resistance, fire resistance, energy efficiency and durability. Concrete building systems are especially suited to provide resistance to natural hazards. Concrete has the necessary hardness and mass to resist the high winds and flying debris of tornadoes and hurricanes. Concrete is fire resistant and non-flammable, which means it can contain fires and will not contribute to the spreading of fire. Reinforced concrete framing systems can be designed to resist the most severe earthquakes without collapse. Concrete doesn't rot or rust even if it is subject to flooding.

CASE STUDIES

There are many examples of structures built with heavy building materials such as concrete surviving major disasters. When Hurricane Katrina slammed into the coastal counties of Mississippi with sustained winds of 125 mph and a storm surge that reached 28 feet, the only house to survive along the beachfront of Pass Christian, MS, was the Sundberg home. Scott and Caroline Sundberg were 85% complete building their dream home along the Mississippi coast when the Hurricane hit. When the winds died down and the water retreated, the Sundberg home had survived the storm. All other homes on the beachfront were completely destroyed. They built their home using insulating concrete forms (ICFs) for the walls and cast-in-place concrete frame construction for the lower level, floors and roof precisely for this reason—to survive the devastating effects of a hurricane.

Figure 1. The Sundberg's concrete home survived the devastating effects of high winds and storm surge of Hurricane Katrina (FEMA/John Fleck).

Wild fires consume an average of nearly 7,000 square miles annually since 1960. In the last decade, that number has increased to over 10,000 square miles (NIFC 2012). A 1993 wildfire in Laguna Beach, CA, consumed 17,000 acres and destroyed 366 homes in a single day. Figure 4 shows the lone survivor which remained protected by an envelope of non-combustible stucco wall cladding and concrete roof tiles. Detailing such as stucco cladding on walls, eaves and trim, as well as Class A concrete tile roof prevented combustion of the exterior amidst the firestorm that swept through the community.

Figure 2. Stucco cladding and eaves along with concrete roof tile helped protect this home during a 1993 wildfire in Laguna Beach, CA (AP Photo/Douglas C. Pizac).

The EF-4 tornado that roared through Tuscaloosa, AL, on April 27, 2011, leveled block after block in the Forest Lake neighborhood. The only thing left standing was a closet at the Blakeney residence on 16th Street East. The closet was built as a safe room using 8-inch reinforced concrete masonry to withstand high winds and flying debris caused by tornadoes (Jones 2011). Small windowless rooms such as a walk in closet are ideal locations for a safe room in a home.

Figure 3. William Blakeney helped build this safe room inside his grandparents' home in Tuscaloosa, AL, before a tornado hit destroying the home and most homes in the neighborhood (The Tuscaloosa News/Michelle Lepianka Carter).

Concrete proves to be the most widely used method for constructing safe rooms**.** FEMA has funded testing programs, primarily at Texas Tech University to determine the proper design to resist windborne debris on walls, doors, and roofs. The Texas Tech research included firing a test missile – a 15- pound, 12-foot-long 2x4– at combinations of wall, ceiling, and door construction materials. The missile was fired at speeds of 67 mph and 100 mph to simulate the speeds of similar-sized debris driven vertically downward and horizontally, respectively, by 250 mph storm winds. According to the research, concrete systems including cast-in-place concrete, insulating concrete forming systems, precast concrete and concrete masonry pass the test.

ADDITIONAL COST OF FORTIFIED CONSTRUCTION

Building to a disaster resilience standard does cost more but typically result in cost savings over the long run. One report conducted by Blue Sky Foundation of North Carolina found that the additional cost of building a home to the FORTIFIED for Safer Living standard cost an additional $3,936 or about 5% more an a home with a retail value of $80,000. Amortized at 6% simple interest over a 30 year mortgage, the additional monthly cost would be about $24 per month. According to the report, this additional cost is easily offset by likely repairs of the home after the 5-10 hurricanes anticipated over the mortgage period (BSE 2005).

In another example, IBHS reported that a 3-bedroom, 2-bath 1,132 square foot home built to the FORTIFIED standards in Baldwin County, Alabama, only cost $1,000 to $1,500 more than a home built to the standard code (IBHS 2012). Often, the additional cost is offset by lower insurance costs. For example, Flora and Anita Cannon's Spanish Fort, AL, house needed a new roof so they decided to retrofit their home to the FORTIFIED standard for existing buildings. The Cannons paid nearly $3,500 per year for insurance before the upgrades but the policy was reduced to less than $1,800 once the house is retrofitted to the FORTIFIED hurricane standards (Jumper 2011).

BENEFITS OF NATURAL HAZARD MITIGATION

Natural hazard mitigation is a resilience strategy that saves lives and money. In 2005, the Multihazard Mitigation Council (MMC) of the National Institute of Building Sciences conducted an independent study for Congress funded by the Federal Emergency Management Agency (FEMA) to study the effectiveness of disaster mitigation. The report, *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*, quantified the future savings, in terms of losses avoided, from government grant hazard mitigation activities from 1993 to 2003 (NIBS 2005). The benefits of mitigation were defined as the potential losses to society that were avoided as a result of investment in mitigation. Those benefits include:

- Reduction in property damage
- Reduction in business disruption
- Reduction in nonmarket damage (environmental damage to wetlands, parks, wildlife and historic structures)

- Reduction in deaths, injuries and homelessness
- Reduction in cost of emergency response (ambulance and fire service)

The study indicates that the natural hazard mitigation grant programs funded by FEMA were cost effective and did in fact reduce future losses from earthquakes, wind and floods. The mitigation programs resulted in significant net benefit to society and potential savings to the federal treasury in terms of future increased tax revenue and reduced hazard related expenditures. The FEMA grant programs cost the federal government $3.5 billion from 1993 to 2003 but yielded a societal benefit of $14 billion. That is, for every dollar spent on mitigation saved four dollars in avoided future losses.

CONCLUSION

Resilience planning offers communities an opportunity to play a major role in determining the essential services and infrastructure needs that underpin their economic vitality, the health and safety of its citizens, and support sustainability. Voluntary methods such as IBHS's FORTIFIED programs are valuable, but the most effective method would be to change model building codes at the national level. By participating in code development so that all model codes include hazard mitigation for water, energy, conservation, and land use, a community makes the conscious choice to invest in their own future regardless of socioeconomic status.

The building codes are not a panacea for all problems. Nevertheless, to subject our vulnerable population to the all too often, shortsighted political or economic decisions that trump safety considerations is unconscionable when the technology and economic returns of disaster resilience are well understood.

Disaster mitigation works and is cost effective. Spending time and money up front to reduce the likelihood of loss during a natural disaster can bring significant benefits to building owners and communities including lower insurance costs, higher property values, security to residents, maintaining a consistent tax base, and minimizing the cost of disaster response and recovery.

In the end, no community can ever be completely safe from all hazards. Generally, it would be uneconomical to design commercial or residential buildings to survive a direct blow from a tornado with 300 mph wind speeds or magnitude 9.0 earthquake. But resilience promotes greater emphasis on what communities can do for themselves before a disaster hits, and how to strengthen their local capacities, rather than be dependent on our ineffectual governmental agencies and aging centralized infrastructure. Disasters are inevitable, but their consequences need not be.

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A New Paradigm for Residential Construction in Regions of High Seismicity

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ABSTRACT

21st Century construction will be deeply connected to the concepts of sustainability. To date, sustainable design has mostly focused on the carbon emissions associated with the operation of buildings; however the total life-cycle carbon associated with the construction is rarely, if ever, considered. Additionally, in regions of high seismicity, the carbon associated with seismic damage resulting in demolition, repair and reconstruction can be significant. Cost-benefit comparisons, probable seismic damage, and consideration of operational downtime are especially important in considering building system selection for all disciplines.

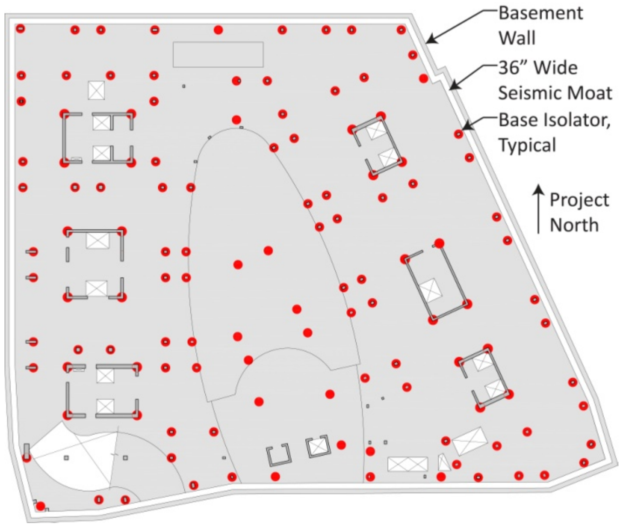
In what follows, a case study on a future condominium development to be located in downtown San Francisco, California, which includes two residential buildings base isolated on a common ground level with a Triple Friction Pendulum™ system is discussed. The Environmental Analysis Tool™ is used to calculate life-cycle environmental and fiscal impacts.

OVERVIEW

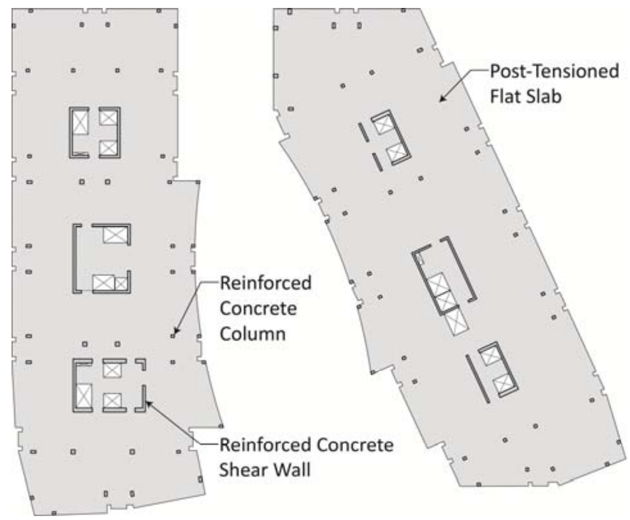
Initiatives such as the California Energy Efficiency Strategic Plan (CPUC, 2011), which establishes as a goal that new construction "will reach zero net energy performance for all new single and multi-family homes by 2020", is a clear examples that connect 21st Century residential construction to sustainability. Undoubtedly, new residential developments should be targeted towards an integrated and sustainable design of all the systems which form the building, establishing performance-based objectives beyond the traditional design approaches.

From a structural engineering perspective, sustainable solutions focus on innovation in the use of materials and systems, and on the development of appropriate assessment tools which inform the decision-making process at the early stages of the design. This becomes of critical importance in regions of high-seismicity where structural and non-structural damage, and associated repair costs, can be a considerable factor when the life-cycle costs of building are studied. In such cases, enhanced seismic force resisting systems and performance-based engineering assessments are of particular interest.

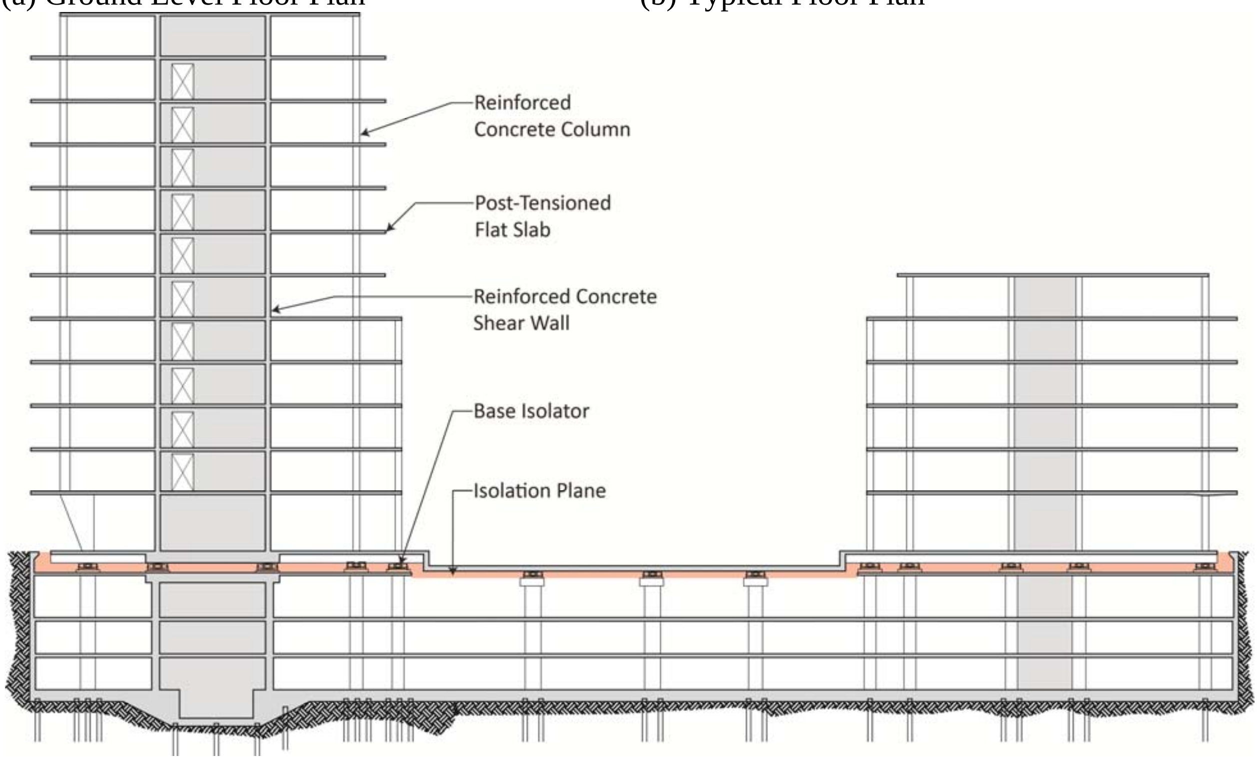
As a result of a collaborative design process in accordance with oncoming green building design goals, Skidmore, Owings & Merrill LLP (SOM) has applied a series of innovative methodologies and design solutions to a future condominium development to be located in downtown San Francisco, California. The project, presents a new paradigm in residential construction, and includes two apartment buildings, 12 and 6 stories high, separated by a private courtyard at ground level, where communal spaces are combined with retails and restaurants. Both residential buildings share a seismic base isolation system under the first floor, and three basement levels below with resident and public parking. The main superstructure elements are entirely built with concrete, presenting a post-tensioned flat slab system, reinforced concrete columns and reinforced concrete shear wall cores. See Figure 1 for typical floor plans and a building section.



(a) Ground Level Floor Plan



(b) Typical Floor Plan



(c) Overall Building Section and Isolation Detail

Figure 1. Building Plans and Section

This paper presents two of the most significant sustainable design considerations of this project. First, the Environmental Analysis Tool^{TM} (EA Tool) is presented; software developed by SOM which calculates the carbon footprint of the structural system based on basic design information, seismic hazard, etc. By means of tools such as the EA Tool, the benefits of an enhanced seismic system could be quantitatively analyzed and presented to the developer for discussion during the schematic design phase, leading to a high-performance structure with Triple Friction Pendulum^{TM} seismic isolators (developed by Earthquake Protection Systems, Inc. (EPS)) with a minimal increase on project budget (approx. 2% of construction cost) and robust protection of investment. An overview of the isolation system and some relevant design coordination topics are discussed.

SUSTAINABLE DESIGN PROCESS

In recent years, much attention has been given to sustainable buildings through organizations such as LEED (USGBC, 2012) which consider, among other components, operational systems such as mechanical, electrical, and plumbing systems. These operational factors are important to the carbon footprint of a building, but do not fully represent the total life-cycle impact a building has on the environment. Recent reports by Sturgis Carbon Profiling (2010) suggest that as much as 45% of the total life-cycle carbon footprint of office buildings and 30% of residential buildings is embodied in the materials which compose the building. There are numerous materials which are needed to conceive a building and include the foundations, structural system, exterior enclosure, roofing, and finishes. One area of great impact which has received little attention is the carbon embodied in the structural system. Additionally, in regions prone to seismic risk, significant carbon once embodied in a building can be lost due to damage in earthquakes. Seismic damage levels can range from modest repairs of finishes to complete demolition and reconstruction.

With these challenges and opportunities in mind, an informed design process is undertaken for the considered residential buildings. Along with traditional metrics of cost, saleable area, and client intent, quantified metrics for carbon are included in the design decision making process. Synergies among building systems are identified and utilized for a new level of high performance design in residential buildings.

Environmental Analysis Tool™

The Environmental Analysis Tool™ has been developed by SOM for the quantification of equivalent carbon emissions embodied in structural materials for a variety of buildings with options for estimation of probable seismic damage and enhanced seismic force resisting systems. This approach to carbon footprint assessment is needed in all phases of design to inform designers of anticipated impacts design options may have.

When a bill of material quantities are known, they can be specified in the carbon footprint analysis, but this information is often only known in later phases of design after significant design decisions have already been made. When key decisions are made at early phases of design, engineers and architects need accurate estimations of material and carbon quantities to guide the design process. To facilitate this need, the EA Tool is capable of calculating the structural system's carbon footprint with knowing only:

1. The number of stories (superstructure and basement).
2. The total framed area in the structure or area average area per floor.
3. The structural system type.
4. The expected design life.
5. Geographic conditions related to expected wind and seismic forces.

With this limited amount of data, the program refers to a comprehensive database containing the material quantities for hundreds of previously designed SOM buildings. Based on these data, statistical models and curve fitting techniques are used to estimate average material quantities. Estimated material quantities can be completely overwritten or partially supplemented by project-specific information. Options for superstructure structural framing materials include structural steel, reinforced concrete, composite (combination of steel and concrete), wood, masonry, and light metal framing. Foundation materials include reinforced concrete for spread / continuous footings, mats, and pile-supported mats.

From concept-level decisions to fine grain details such as travel distances associated with construction processes, the EA Tool is scalable to all phases of design. Key concepts of the EA Tool are presented in Figure 2 and program interface in Figure 3.

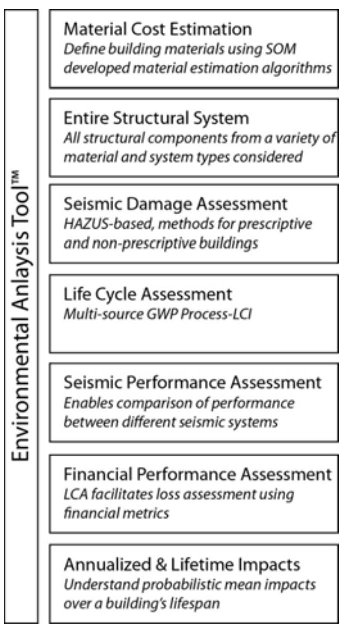


Figure 2. EA Tool

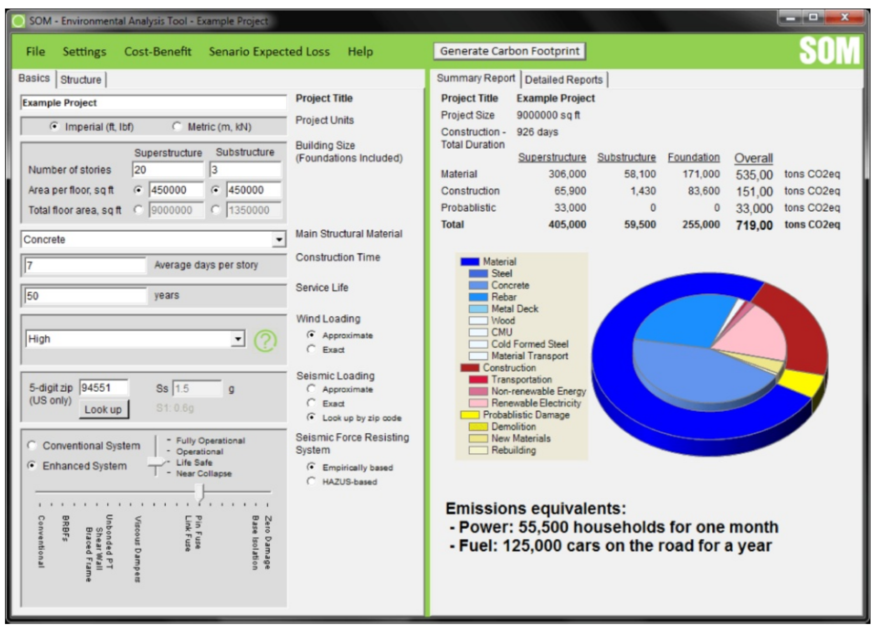


Figure 3. EA Tool User Interface

The selected seismic resisting system is important to a building's carbon footprint over the life of the structure. The contribution of carbon related to damage from a seismic event could account for 25% or more of the total carbon footprint for the structure. Furthermore, if a building is designed to code-minimum standards, then the building may need to be completely demolished after a design-basis earthquake. Conventional code-based structural systems are provided with the option to select enhanced systems such as seismic isolation, unbonded braces, viscous damping, and Pin-Fuse Seismic Systems (Sarkisian, in press). Potential seismic damage and the repair required are considered.

Design Process

From concept, through most of the schematic design phase a traditional shear wall seismic force resisting system was considered. The shear walls would wrap around the elevator and service areas with additional 'wing walls' at the north and south end of each building. These walls were needed to provide additional stiffness in the east-west direction and to mitigate significant torsional motions of the building. Although effective structurally, the wing-walls are problematic for tenant layouts, programmatic needs, future flexibility, and displaced approximately 1,000 sq. ft. of valuable lease space.

During schematic design the client and design team considered several enhanced structural seismic force resisting systems to not only achieve code-superior performance in a seismic event, but address the issues outlined above. Probable seismic damage is a metric used to estimate potential damage associated with a seismic event. Although the exact magnitude and resulting damage cannot be predicted precisely, probabilistic modeling can estimate likely seismic amplitudes and associated damages.

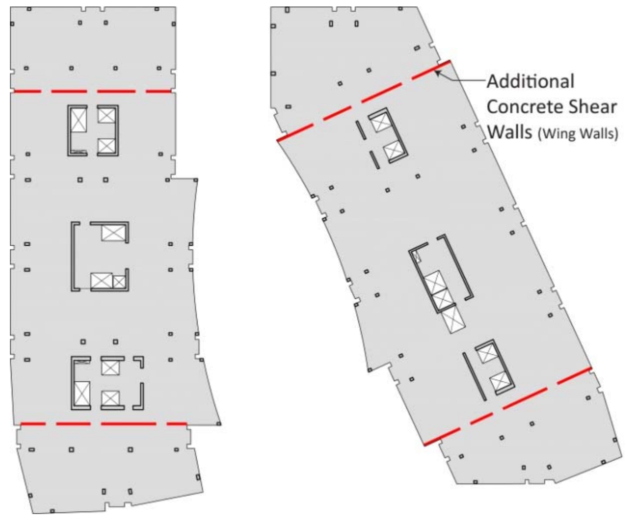


Figure 4. Floor Plan for Concpet Design

Using the schematic design fixed-based reinforced concrete shear wall scheme (Figure 4) as a baseline, several seismic force resisting systems were evaluated including viscous dampers and base isolation. By utilizing the EA Tool and its Cost/Benefit analysis component, fiscal and environmental impacts were quickly evaluated and discussed with the client and notable reductions in embodied carbon were identified with the employment of viscous damping and significantly more with base isolation (Figure 5). In fiscal terms, base isolation has a slightly better cost/benefit ratio, but the estimated savings from mean annual losses are almost ten times higher for base isolation. While viscous damper protect structural system components, they do not significantly reduce damage to non-structural components and contents. Base isolation significantly limits, and may even eliminate, damage to non-structural components and content.

Regarding tenant space, the viscous damper option would replace the wing walls with braces and dampers. Although a savings in concrete could be attained, the lease space would remain mostly unchanged. In the base isolation scheme, the wing walls would be eliminated due to the significant reduction in seismic forces and approximately 1,000 sq. ft. of valuable tenant space gained. Due to the high value of the tenant space this was a significant consideration.

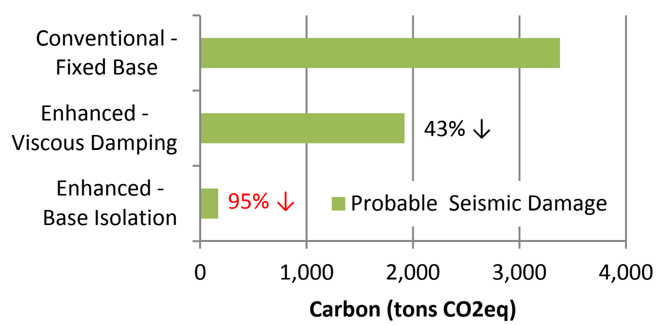


Figure 5. Carbon Footprint of Considered Seismic Systems at Schematic Design

Although base isolation may significantly reduce seismic damage and associated repair costs, the introduction of an isolation plane and ground-level seismic moat can present coordination and technical challenges as the isolated superstructure may move up to 34" relative to the basement levels for the considered residential building. The seismic plane was located just below ground level to maximize valuable parking space below grade. This introduced two challenges: one, an increase of excavation depth and basement construction, and two, mechanical, electrical, and plumbing (MEP) coordination issues with the superstructure movement. A synergy was identified in moving MEP components into the base isolation plane as shown in Figure 6. This reduced the excavation by moving MEP components out of the basement soffit into the isolation plane and permitted more freedom in MEP layout and improved basement parking aesthetics by hiding the MEP components. Furthermore, basement air intake and exhaust was moved to the seismic moat to avoid tenant areas.

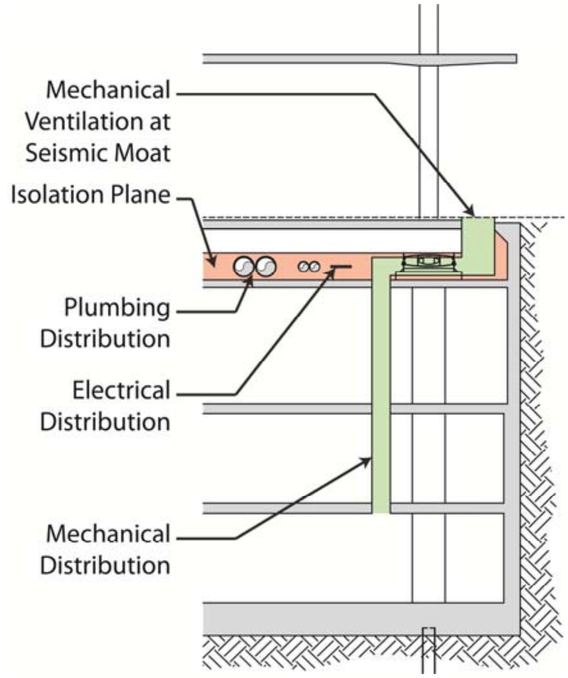


Figure 6. Basement Coordination with Isolation Plane and MEP Components

With considerations of cost, tenant space, construction, and other trades, a decision was made to incorporate base isolation into the building design through the detailed design phase. All trades were coordinated and cost assessments refined. Through the detailed design stage carbon quantities associated with structural system components were computed using the EA Tool and are presented in Figure 7.

As a refined bill of quantities was attained, the material quantity estimations of the EA Tool were replaced with as-designed quantities. As can be observed, a regular reduction in embodied carbon was achieved at each design milestone. These were achieved not only by incorporation of an enhanced seismic force resisting system, but with specification (i.e. fly ash replacement) and material quantity reductions through component design.

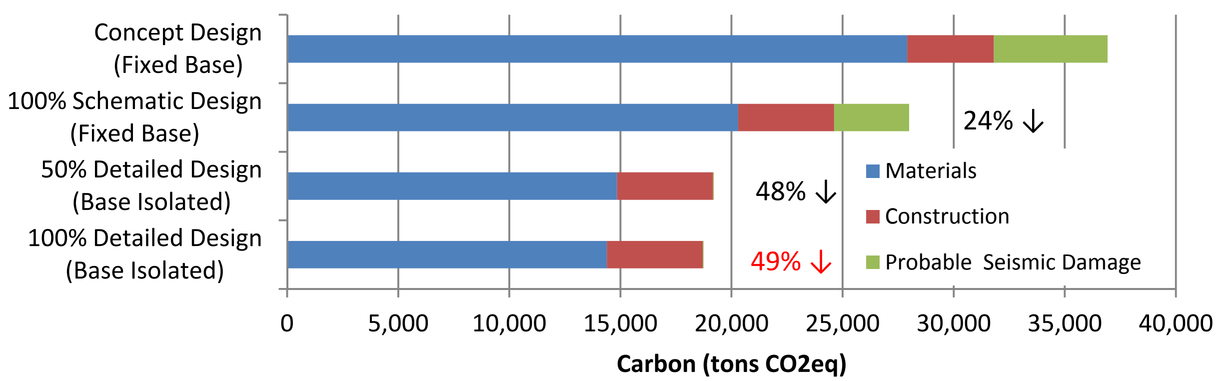


Figure 7. Carbon Footprint During Design Phases

TRIPLE FRICTION PENDULUM BASE ISOLATION

Through the last couple of decades seismic isolation techniques have become the landmark of high-performance structural systems for buildings in seismic regions. Perceptions of high initial cost and design complexity have limited their implementation in the United States to critical and public buildings required to remain functional after a major earthquake event, such as hospitals, research centers and other essential facilities. However, the recent growth of performance-based assessments and life-cycle cost analyses within the engineering community has facilitated quantifiable fiscal metrics to convey to owners and developers of residential buildings the long-term benefits that isolation systems can provide.

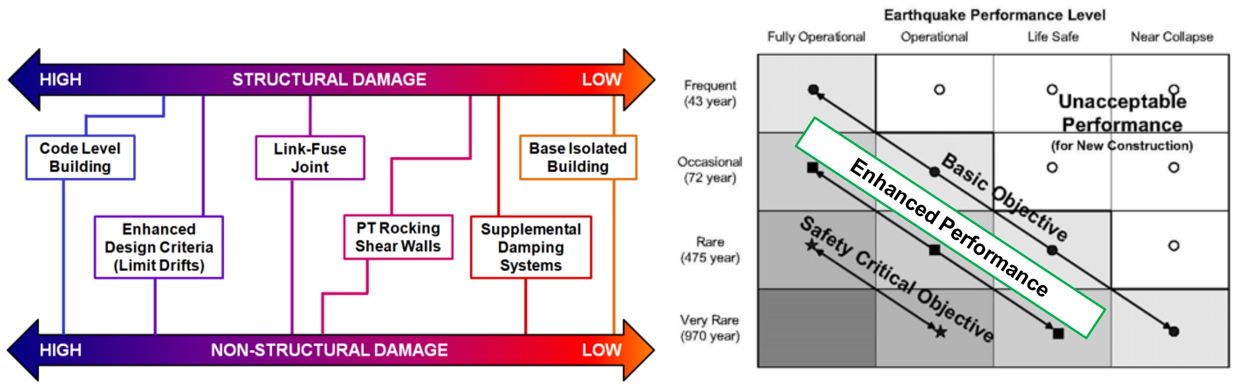


Figure 8. Enhanced Seismic Performance Systems considered for the project (Left). Basic Objective versus Enhanced Performance Level (SEAOC, 1995) (Right)

Prior to the commencement of the detailed design phase for this condominium project, several enhanced lateral seismic force resisting systems were studied (see Figure 8) and their global structural performance was compared. From them, base isolation is the only system that can assure low structural and non-structural damage for large earthquakes, and therefore leading to the lowest values of Expected Annual Loss and Probable Maximum Loss. Enhanced seismic performance not only facilitates a sustainable urban environment, but also protects the owner's investment and lowers earthquake insurance rates. These factors yield more marketable residential spaces for the client. With this premise, it was agreed with the client to design a base isolation system for the project.

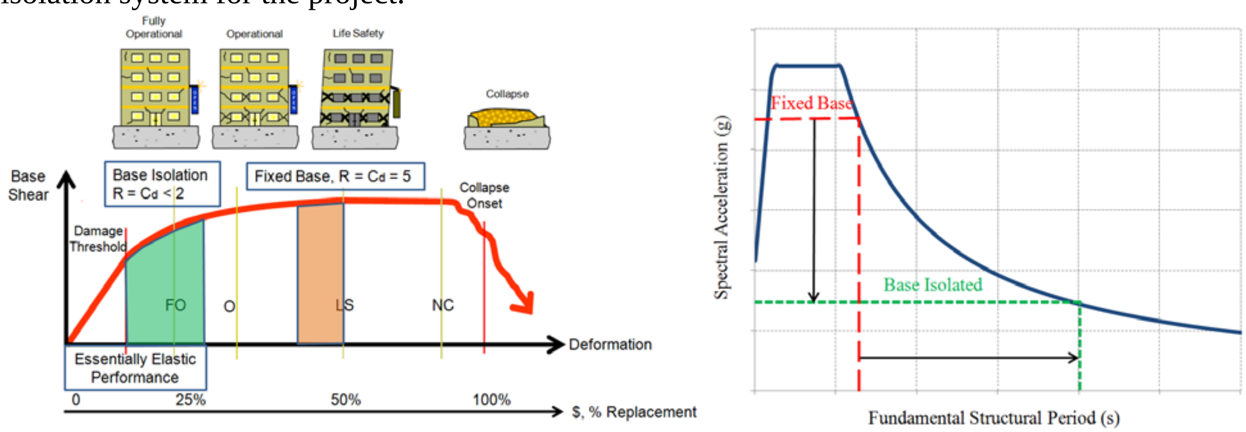


Figure 9. Qualitative performance comparison of fixed base versus base isolated building

In general terms, a base isolated building can be subdivided in three parts: superstructure, the isolation system itself, and the substructure. The superstructure is formed by all the elements of the building that sit on top of the seismic isolation bearings, which therefore will be subject to reduced structural and non-structural damage. The isolation system divides superstructure and substructure and it is typically located at the ground floor level of the building, consisting of the seismic isolation bearings, supporting pedestals, etc. The substructure is located under the isolation bearings, and it can be formed by several basement levels or just a foundation slab. None of the substructure elements are isolated, and they behave as a fixed-base structure.

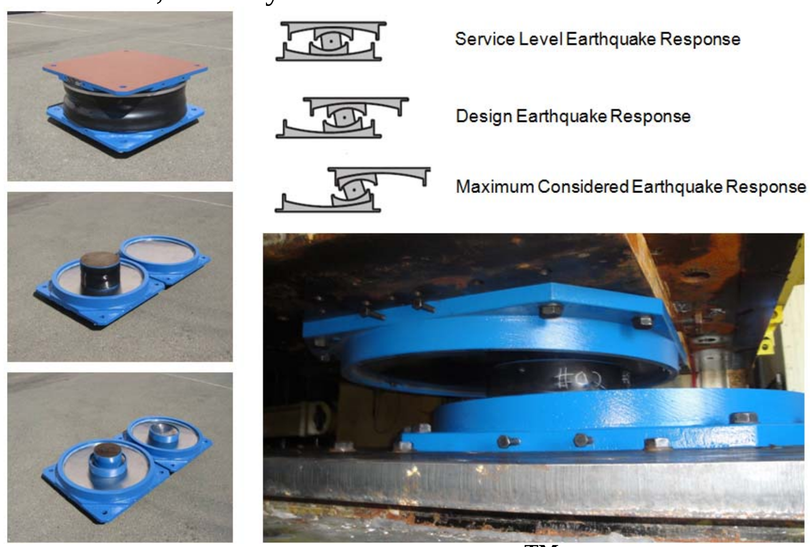


Figure 10. Triple Friction Pendulum^{TM} seismic isolation bearings

In base isolated structures, the global structural performance is fundamentally controlled by the characteristics of the isolation bearings. Bearings have very low stiffness, and therefore greatly increase the fundamental period, reducing significantly seismic forces on all components as well as superstructure drifts and accelerations (see Figure 9).

There are two types of isolation bearings typically considered, Lead-Rubber Bearing (LRB) systems and Friction Pendulum (FP) systems. Although both types can be designed to a comparable level of performance, the FP system presents several design advantages such as the independency of the fundamental isolated structural periods from the mass of the superstructure and the natural dissipation of any inherent and accidental torsion effects at the isolation plane (Zayas et al.). In addition, by utilizing the latest version of the FP assembly, the Triple Friction Pendulum^{TM} (TFP) bearings, the system can be tuned to an enhanced performance for different earthquake intensity levels, whereas the LRB system does not present this design flexibility. For this project, the asymmetric distribution of mass at the isolation plane (with the subsequent seismically-induced torsion) due to the presence of two buildings of significantly different heights, and the desire to protect drift and acceleration sensitive non-structural components for service level earthquakes (less than 100 years return period), clearly indicated the suitability of the project for a TFP system. By reducing the torsional demands, the 'wing walls' could be removed from the lateral system, hence improving the quality of the interior spaces designed for the client.

A common isolation plane located at ground level for the two residential buildings involved in the project was utilized. Under the isolation plane, a total of 125 TFP seismic isolation bearings were located under each main gravity column and under each corner of the shear wall cores. A global building structural analysis model was constructed using the commercial structural software ETABS (CSI, 2011).

For accurate estimation of drifts, forces and displacements, it is fundamental to calibrate the nonlinear element links utilized to model the isolators so that they match the physical properties provided by the manufacturer, EPS. This was done for all bearings types, by using a parallel model of ISOLATOR2 and GAP and HOOK link elements (CSI, 2011). See Figure 11 for a sample adjustment, for more information on advanced modeling of the bearing mechanics refer to Fenz et al. (2008) and Sarlis et al (2010).

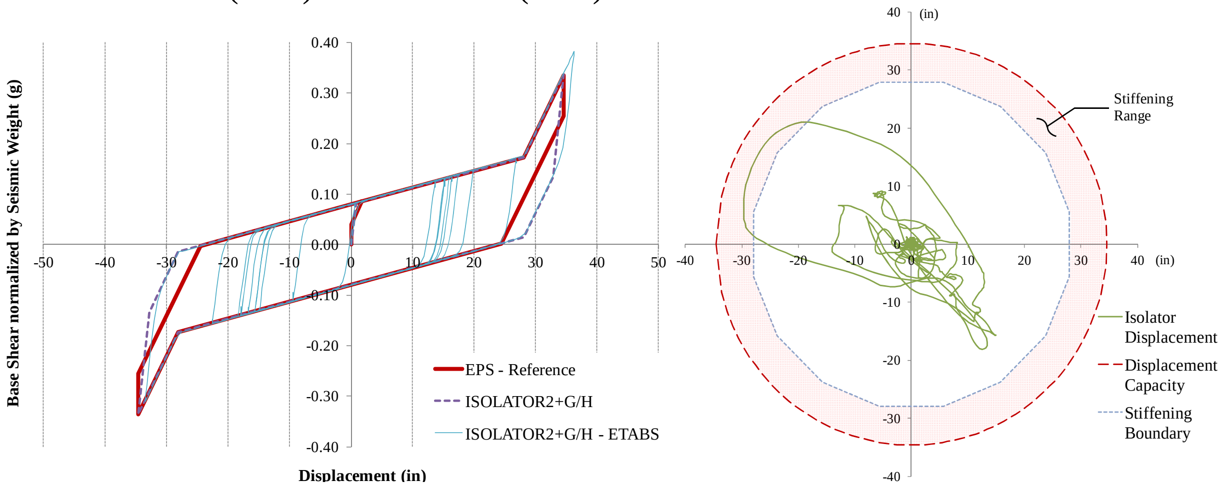


Figure 11. Example of analytical and numerical calibration of the TFP model to the prototype (left). Example Isolator Trajectory (right)

As the bearings were designed to reach the displacement capacity of the top and bottom plates (surfaces 1 and 4 on Figure 12) at the Maximum Considered Earthquake (MCE) level, it is critical to correctly envelope the boundary of the so-called “stiffening range” by adding several sets of GAP and HOOK elements at different orientations (Fenz et al.) to the analysis model. If this is not properly done, isolator displacement demands would be overestimated whereas other parameters such as uplift and superstructure drift underestimated. A total of 16 degrees of freedom were modeled for this case, which approximated the theoretical circular boundary with less than 2% overestimation (as shown on Figure 11).

Superstructure drifts obtained based on nonlinear time history analyses (average of 7 earthquake records) were limited to 0.77% for Design Earthquake (DE) level and upper bound friction properties and 1.15% for Maximum Considered Earthquake (MCE) and lower bound friction. Therefore, the essentially elastic performance criteria stated on ASCE 7-05 Chapter 17 were satisfied. The peak uplift was found to be 2.4 in at the core locations, within the allowable uplift criteria established for the project.

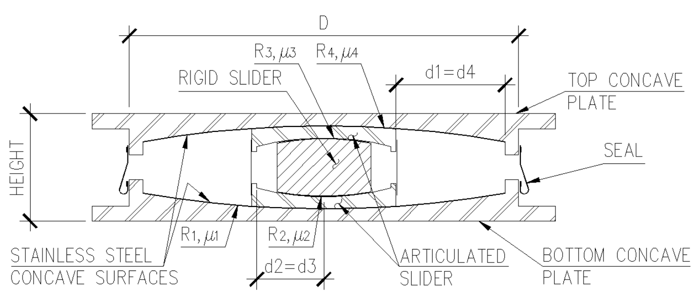


Figure 12. Typical TFP bearing section indicating main components and design parameters

The total maximum displacement of the isolators was designed to be equal to 33.4 in, as determined from analysis, being the displacement capacity of the bearings equal to 34.0 in. In order to accommodate construction tolerances the seismic moat around the isolation interface was set to 36.0 in. Complex nonlinear analyses including ground motions with rotational components were performed to assess the degree of torsional displacement amplification experienced by the system. To that regard, the “stiffening range” acts positively as a rotation-dissipating mechanism which forces the system to have mainly translational components at the isolation plane. This allowed using a 4.3% displacement amplification factor, approved by the Peer Review Panel, instead of the non-specific 10% factor stated by ASCE 7-05 Chapter 17.

A VISION FORWARD

In seismically active regions, sustainable design in residential construction and innovation in structural engineering have to be synonyms. By adopting presented approaches in future residential developments, the following benefits are provided to the society, clients and architecture and engineering communities:

1. A common quantitative and economic language provided by applications such as the Environmental Analysis Tool™, in which designers can communicate to the client, starting at the early stages of the project, the impact that different structural system selections may have in the life-cycle cost, as well as assess the carbon footprint of such decision.
2. Protection of investment, society welfare and increased reputation of the technical communities by designing enhanced structural systems beyond minimum code-level performance. The case study has presented a design with a revolutionary technology, Triple Friction Pendulum™ base isolation, to produce, with minimal alteration to the construction cost, the most sustainable structural system within the design possibilities in hand.

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Prescriptive Details for Wind Resistant Envelopes based on Observations of Newly Built Homes Damaged in 2011 Tornados

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ABSTRACT

Damage observations conducted by APA after recent tornados focused on homes built within the last 10 years. Unfortunately many of the damaged homes were built in compliance with existing building codes and were robustly constructed minus a few relatively inexpensive techniques that provide structural continuity. In non-hurricane areas, now assigned with design wind-speed as low as 85 mph, this indicates a need for building practices that take advantage of the inherent strengths of roof, wall and floor assemblies in tornado-prone areas.

To this end APA engineers compiled a set of reinforcement techniques for each of the common weak points along the load path resulting from code-minimum attachment schedules, and commonly used construction techniques. The resulting publication *Building for High Wind Resistance in Light-Frame Wood Construction*, APA form M310 was published in August 2011.

Instrumental in offering these recommendations is recent testing at APA performed to determine the design capacity of shearwalls subjected to simultaneous shear and uplift forces. Recommendations are prescriptive and apply to many homes otherwise constructed to IRC minimums. The aim was optimization of material assemblages already commonly in-use, while minimizing the effect on cost. Recommendations apply when a higher degree of safety is desired for resisting severe straight-line winds and tornados on the lower end of the EF-scale.

SUMMARY OF FIELD OBSERVATIONS.

Damage observations conducted by APA after the April 16, 2011 tornados in Eastern North Carolina and the powerful EF-4 and EF-5 storms that struck Tuscaloosa, Alabama on April 27 found that a lack of attention to detail along the uplift load-path often leads to weakness on the route through which high-wind forces must travel within the framing and into the foundation. Following a review of the findings, the Association has published a set of construction recommendations for improving tornado or hurricane resistance in light-frame wood construction.

The investigation focused on the performance of homes constructed within the last 10 years. The most common roof-to-wall framing failures were attributed to the use of toe-nailed connections, still prescriptively allowed in many non-hurricane areas. In addition, many homes observed were poorly anchored to the foundations. This was especially true in Alabama where nails were often used, instead of anchor bolts, to attach the bottom plate of walls to the concrete or masonry foundation. Not exclusive to just the top and bottom of structures, load path failures were witnessed at every connection location in between.

Another common theme observed along the tornado paths is that homes constructed with non-structural exterior wall sheathing, especially if used in conjunction with vinyl siding, failed at wind speed much lower than called for in the building codes. Walls that are fully sheathed with OSB or plywood and constructed with proper connections have stronger resistance to the damaging forces of high winds and even when siding has been lost still offer strength and weather protection.

Figure 1 –Building Envelopes Fully Sheathed with Wood Structural Panels.

In a field survey of damaged structures, APA observations indicated that structural failure along the critical load-path was often located at the roof-to-wall connection. Most of these connections were made using toe-nails through the roof framing and into the top plate of the exterior walls. Toe-nail connections are weak because they rely upon the withdrawal capacity of nails, which is limited. Light-gauge metal connectors provide good performance in wood framing because load is applied perpendicular to the nail shank, instead of pulling the nail straight out. Toe-nail rafter connections are still prescriptively allowed in most non-hurricane areas by modern building codes through “grandfathered” language. It is generally recognized that these connections do not provide the capacity to resist the range of pressure requirements of the *International Building Code*.

Figure 2. Toe-nailed Connection of Roof Framing-to-Wall.

Metal roof-to-wall connectors should be installed in-line with the load-path. Failure was observed when metal roof framing connectors were installed on the inside face of the wall top plate instead of on the exterior of the wall and in-line with the load-path in the structural wall sheathing. Roof framing connector manufacturers' specifically advise against such applications.

In each of these tornado outbreaks, regardless of the tornados intensity, anchorage of the exterior walls to the foundation was most often the difference between a structure that continued to provide some level of protection to occupants, or one that was swept clean from the foundation. Among severely damaged homes it was observed that wall-to-foundation anchorage was often woefully inadequate. In many of these cases roofs and walls were strongly built, but poor connections to the foundation resulted in sudden and catastrophic failure. In many cases hand-driven cut masonry nails were used to attach the bottom of support walls to the concrete or masonry foundations. In some cases the nails were observed to be pneumatically-driven framing nails. Modern building codes generally require anchor-bolts to be embedded into concrete or grouted concrete masonry units.

Figure 3 – Failed Nail Connection of Wall Bottom-Plate to Slab.

Breaches or openings in the building envelope, and the resulting pressurization of the building interior caused catastrophic failure of homes in many examples. Openings in walls due to failure of doors, windows, and cladding systems were common. These often resulted in heavy damage to home interiors due to rainwater infiltration and flying debris penetration. Larger breaches from loss of weak garage doors and exterior cladding systems often acted to initiate catastrophic failure and exacerbated deficiencies along the aforementioned load-path.

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Figure 4 – Envelope Failure of Foam Sheathed Exterior Walls

In homes with gable roofs, failures were most notable at the bottom of the gable-end roof and ceiling framing where they are connected to the top of the gable-end wall below. This joint is often not well connected laterally to the rest of the building and is weak to resist negative pressure on the exterior gable-end surfaces.

Figure 5 – Failure of Gable-end Framing.

The gable-end is also a vulnerable location for cladding systems since walls within the roof cavity are not backed by drywall like the exterior walls within the living space. Material failure was commonly observed when non-structural foam wall sheathing was used in conjunction with low-strength siding. Besides vulnerability to wind pressure, these products provide little resistance to the flying debris.

Figure 6 – Non-Structural Sheathing at Gable-end after minor wind event.

In most observations where buildings were at least partially intact, wood wall and roof sheathing loss could be attributed to improper attachment. When nails were used as prescribed in the building codes good performance was observed. Staples performed poorly since they generally offer less resistance to pull-out than nails and must be used in greater quantity. Greater structural failure often resulted from poor roof sheathing attachment to the last rafter or gable-end truss. Enhanced nailing of roof sheathing to the gable-end truss or rafter such as is recommended for panel edges provides necessary enhancement at minimal cost.

BUILDING FOR GREATER WIND RESISTANCE.

New recommendations are meant to optimize structural performance of prescriptively built homes while adding as little cost as possible. A different approach was taken from most design scenarios where the resisting elements are selected based on the anticipated loads. In this case the resisting elements were optimized to utilize the inherent strength of wood wall and roof systems as already constructed. The aim was to develop a single set of recommendations to ensure structural continuity and provide similar resistance levels within each of the structural links to the foundation.

In many cases observation of structural damage points to one of several common weak links as the cause of catastrophic failure in homes that are affected by hurricanes and tornados.

Figure 7 – With thoughtful layout, continuous structural sheathing can resist both shear and uplift forces, providing cost-effective continuity between the foundation and roof framing connections. Oversize panels may be used to eliminate blocking by locating horizontal panel joints at the rim joists and to match the dimensions of taller wall systems.

RECOMMENDATIONS

The following APA recommendations address these weak links and provide tips for building a wind-resistant shell:

1. **Nail roof sheathing with 8d ring shank (or deformed shank) (0.131 in. x 2-1/2 in.) nails at 4 inches on center along the edges of the wood structural wall sheathing and 6 inches on center along the intermediate framing.** *Comments: deformed-shank nails are the best option for resisting withdrawal forces on roof sheathing fasteners due to negative pressure on the exterior surface of the building envelope. It is important to maintain consistency in this operation since one missed nail can be expected to limit the pressure resistance of the roof before a breach occurs.*
   Note that the panel edge nailing of 4 inches on center for roof sheathing is appropriate for nails that penetrate the gable-end roof framing, as this is the panel diaphragm boundary.
2. **Sheath gable end walls with wood structural panels, such as plywood or oriented strand board (OSB).** *Comments: Gable end wall failures are frequently observed when non-structural sheathing is used. Most non-structural foam sheathing materials are required to be used in conjunction with gypsum wall board inside of the house. This is frequently neglected in the construction of gable end walls. The easiest way to avoid the need of installing interior gypsum at the gable end walls is to use wood structural panel sheathing on the exterior.*
3. **Tie gable end walls back to the structure using continuous lateral braces 6’-0 on center on top of the ceiling framing and connecting these to the gable-end wall using steel straps nailed on each side of the connection using (8) 10d common nails.** *Comments: One of the weakest links in residential structures during high wind events is the connection between the roof gable-end and the wall below. The prescriptive codes provide no guidance on how to properly attach these two important elements and failures at this joint are, unfortunately, quite common. Construction details that have been developed to properly secure and tie back a gable end may be used. Also common in high wind areas is to eliminate the gable through the use of hip roofs or, if the gable is an architectural necessity, use balloon framing. (Detail courtesy of Standard for Hurricane Resistant Residential Construction, SSTD 10-93 Section 306.4.2.)*
4. **For the roof framing-to-wall connection, use a hurricane anchor attached on the exterior (sheathing side) of the exterior walls.** *Comments: The roof-to-wall connection under high wind loads is subject to both uplift and shear. For this reason the best option is to use a connector that is intended to provide restraint in all 3 directions such as the H1 connector by Simpson Strong-Tie. A simple twist-strap may also be used for the uplift component in combination with toenails to provide lateral restraint.*
5. **Nail wall sheathing with 8d common (0.131 in. x 2-1/2 in.) nails at 4 inches on center at end and edges and 6 inches on center in the intermediate**

framing. *Comments: This enhanced nailing will improve the resistance of the wall sheathing panels to negative wind pressure as well as improve performance in resisting racking and uplift forces. Staples offer less resistance to blow-off than nails and so a greater number of them are required to achieve the same level of resistance.*

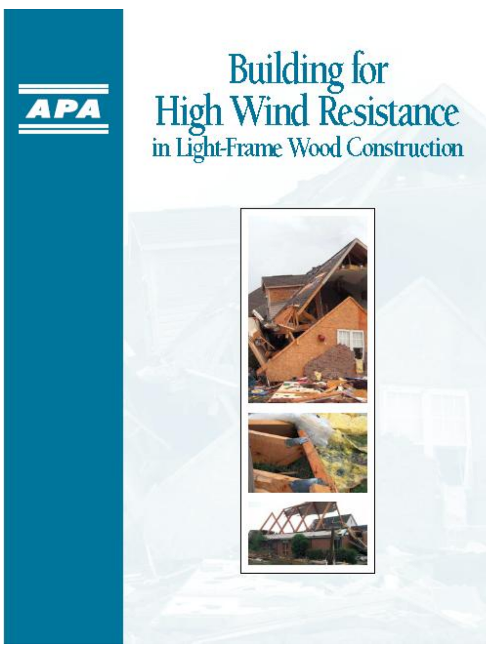
6. **Nail upper story sheathing and lower story sheathing into common wood structural panel Rim Board®.** *Comments: The most effective way to provide lateral and uplift load continuity is to enlist the use of continuous wall sheathing to bridge joints in the wall plane. Long length OSB Rim Board can be used as this common framing member to ensure shear and uplift continuity, which eliminates the need for horizontal blocking. Being at least 9-1/2" in depth and 1" in thickness, commonly available Rim Board makes an excellent "target" for mating adjacent panels. Otherwise horizontal blocking may be utilized at panel joints to enhance continuity in wall sheathing panels. For use around windows and doors or as an alternative to this detail, metal strap anchors designed for such applications may be used. For designed applications, additional information is available in* APA Data File: *Shear Transfer at Engineered Wood Floors, Form* Y250.
7. **Continuously sheath all walls with wood structural panels including areas around openings for windows and doors.** *Comments: Continuous wood structural panel wall sheathing on the entire building exterior improves redundancy and resistance to wind-borne debris during high-wind events. Since all wall, floor, and roof elements are restrained by attachment to adjacent diaphragm elements, buildings constructed in this manner behave more like a box, and less like a collection of independent plates. In addition, the use of continuous sheathing provides both strength and protection if the exterior siding is blown off or damaged by flying debris.*
8. **Extend wood structural panel sheathing to lap the sill plate which is bolted to the slab or foundation-wall.** *Comments: Nailing of the wall sheathing panels to the sill plate is important because this is where uplift forces are transferred into the foundation through the anchor bolts. Too often bottom sill-plates are observed to be the only remaining wall element still attached to the foundation. Nailing the wall sheathing to the sill plate utilizes the nails in shear and provides an economical, strong, and redundant attachment at this point along the load-path.*
9. **Space ½ in. anchor bolts 32 inches to 48 inches on center with 0.229 in. x 3 in. x 3 in. square plate washers with slotted holes.** *Comments: Plate washers of this size are able to incorporate most of the bottom-plate width and more effectively prevents cross-grain stresses and splitting from occurring in the bottom plate material. Tests performed by APA prior to the tornados scrutinized anchor bolt spacing for use in the engineering of walls sheathed with plywood or OSB and subjected to simultaneous shear (racking) and uplift wind and seismic forces. The results revealed tremendous gains in capacity of walls with more closely spaced anchors when used in conjunction with larger 3" x 3" plate washers.*

More information and illustrations of these construction details can be found in the APA guide: *Simplified Tips for Improving Tornado or Hurricane Resistance of Light-Frame Wood Construction*, Form M310, available for download at www.apawood.org .

APPLICATIONS FOR ENHANCED BUILDING CODES.

The state of Georgia Department of Community Affairs (DCA) was awarded a grant through the U.S. Department of Housing and Urban Development (HUD) to develop Disaster Resilient Building Code (DRBC) Appendices for the International Building Code (IBC) and the International Residential Code (IRC). The DRBC Appendices are optional regulations that local jurisdictions may adopt, in whole or in part, through local ordinance to improve resilience from hurricane, flood, and tornado events.

The optional appendix, ***Georgia State International Residential Code Appendix R Disaster Resilient Construction*** contains increased prescriptive requirements for non-hurricane 90 mph regions based largely on APA's new publication *Building for High Wind Resistance in Light-Frame Wood Construction.* The appendix may be adopted in whole or part by local jurisdictions in the State of Georgia beginning January 1, 2013.



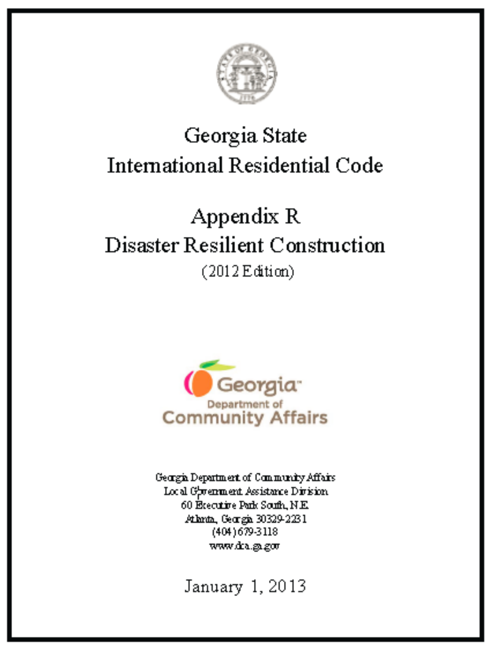


Figure 8 – APA publication M310 – *Building for High Wind Resistance in Light-Frame Construction* (August 2011,) and Georgia State IRC Appendix R, Disaster Resilient Construction, January 1, 2013.

A cost estimate was performed by Georgia DCA for these structural enhancements for a one-story 2100 square foot home with a 6:12 roof pitch with three dormers. The additional costs related to these upgrades including labor and materials were approximately $595.00.

CONCLUSION

Many homes built in compliance with existing prescriptive building codes are robustly constructed minus a few relatively inexpensive techniques that provide structural continuity. New recommendations from APA seek to optimize structural performance of prescriptively built homes while adding as little cost as possible. A collection of best practices was developed to provide a level of performance for prescriptive construction that is above code-minimums. These recommendations were subsequently codified through use in recently adopted codes aimed at providing a level of performance above the current minimum-code level. Due to the inherent strengths of building systems as already prescriptively constructed, these enhancements offer a great value for protection of life and propery.

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Residential Damage Patterns Following the 2011 Tuscaloosa, AL and Joplin, MO Tornadoes

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ABSTRACT
Two of the most powerful tornadoes in 2011, occurred in Tuscaloosa, AL on April 27th, and in Joplin, MO on May 22nd. These tornadoes caused a significant amount of damage ($13 billion), and resulted in an estimated 175 fatalities. Despite decades of damage reports on violent tornadoes, little is known regarding the structural loading imposed on buildings by these events. However, non-engineered residential property suffered the worst damage as documented by two damage survey teams. The post-tornado damage surveys documented the structural performance of houses, and spatial distribution of residential damage within the tornado wind field. The data include damage observations from over 1600 homes that were assigned degrees of damage (DOD) ratings using the EF-Scale procedure. Publicly available information such as the age, construction materials and size of the homes were also collected.

An analysis of the failure patterns was performed on the combined dataset to quantify the magnitudes and distributions of tornado loads on buildings, relating the damage to distance from the centerline of the tornado, orientation of the structure and variation along each tornado path. The study presents correlations among major failure mechanisms; i.e. between roof removal and ensuing wall collapse, and between roof sheathing loss and resulting failure of gable-end walls. The paper presents common failure patterns related to specific construction practices that increase the vulnerability of houses to tornadoes. These field studies and analyses are being used to inform the development of full-scale structural testing wall components with the goal of developing structural retrofits and improved design practices for tornado-resilient houses.

INTRODUCTION

On average over 1200 tornadoes occur in the United States causing nearly $1 billion in insured losses each year (Changnon, 2009). The year 2011 was an exceptional year for tornadoes in the US with at least 1625 confirmed tornadoes, 794 tornado-related fatalities and an estimated $46 billion in economic losses from tornadoes and thunderstorms. The total of insured losses, $25 billion, more than doubled the previous record year. Two outbreaks in particular, the April 25-28th outbreak and the May 22nd outbreak, caused catastrophic damage to a large number of communities. Some of the greatest impact was seen in Tuscaloosa, AL and Joplin, MO, where EF-4 and EF-5 tornadoes respectively impacted urban regions with dense populations. In both of these communities, newer homes are nominally built to withstand design wind speeds of 90mph through the use of prescriptive code provisions. However, the majority of the homes were built prior adoption of these codes, and even these new homes could not be expected to survive the impact of an EF4 or EF5 tornado (with wind speeds as high as 200 mph). As a result, damage was catastrophic, with an estimated 13,000 buildings damaged or destroyed in the two communities combined. With growing urban populations in tornado-prone regions, it is likely that such events will become more frequent. It is important then to identify key failure patterns present in these two storm damage databases as well as others in order to better understand the unique loads imposed by tornadoes and to provide the necessary design improvements that can improve the performance of residential homes (the majority of which in the US are wood-frame (Rosowsky, 1999)) to tornadoes.

ASSESSMENT METHODOLOGY

In the immediate aftermath of each of the Tuscaloosa and Joplin tornadoes, engineering assessments of the damage were conducted by a team that included engineering faculty, local engineers, scientists and students. Complete details of the assessments are available in the published literature (Prevatt, Van De Lindt *et al.*, 2011; Prevatt, Lindt *et al.*, 2011). Over 14,000 photos were taken of the damage, the majority of which were linked to a geographic location using either GPS-capable cameras or standard cameras in combination with hand-held GPS units and geotagging software. This complete dataset includes nearly 3,000 unique residential structures that were rated to estimate a wind speed in accordance with the EF scale provisions. The location of each of these homes is shown in Figure 1.

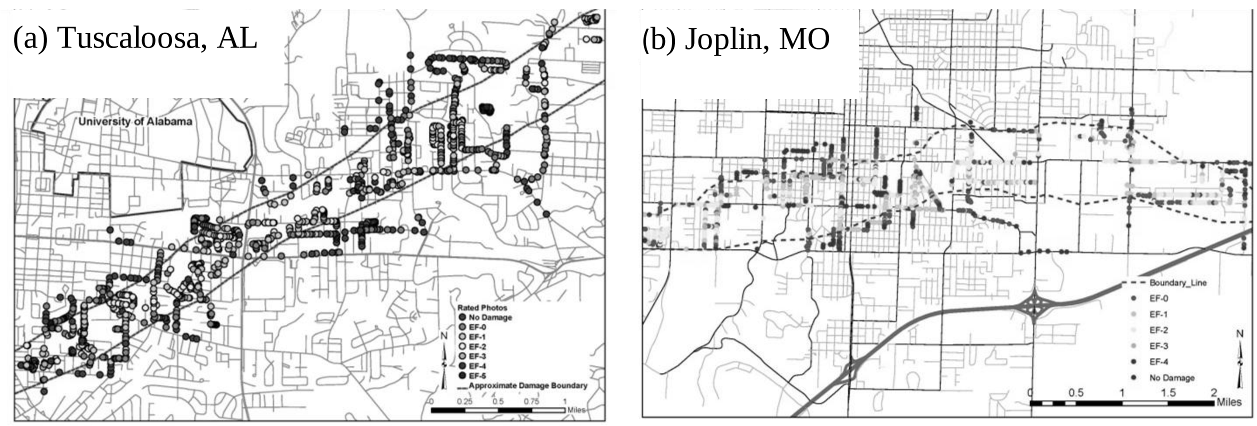


Figure 1: Locations of Rated Homes

TORNADO WIND FIELD

By relating the estimated wind speed from the damage at each home to the location of the home, a more precise estimate of the distribution of wind speeds throughout the tornado wind-fields was obtained. Contour plots of the estimated wind speeds for each tornado were developed and are shown in Figure 2.

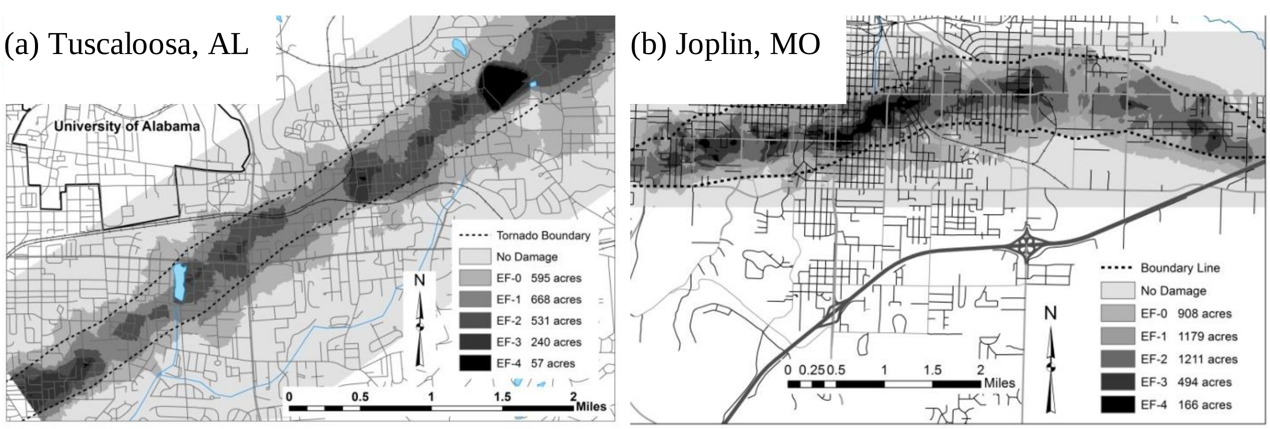


Figure 2: Wind Speed Distributions within the Tuscaloosa and Joplin Tornadoes

Further analysis of the distribution of wind speeds was performed by determining the distance from the estimated centerline of the tornado vortex to each rated building (and therefore estimated wind speed) in both Tuscaloosa and Joplin. The results of this analysis are plotted as normalized histograms in Figure 3, illustrating the distribution of wind speeds within the complete damage path. Box plots are also used In Figure 4 to depict the median, 25th and 75th percentiles of the distributions, with EF-1 representing homes with no observed damages. The "+" data marker represents data that falls outside of ±2.7 standard deviations from the mean. It is possible that such outliers represent the locations of secondary vortices, but other options such as undocumented tree damage should also be considered.

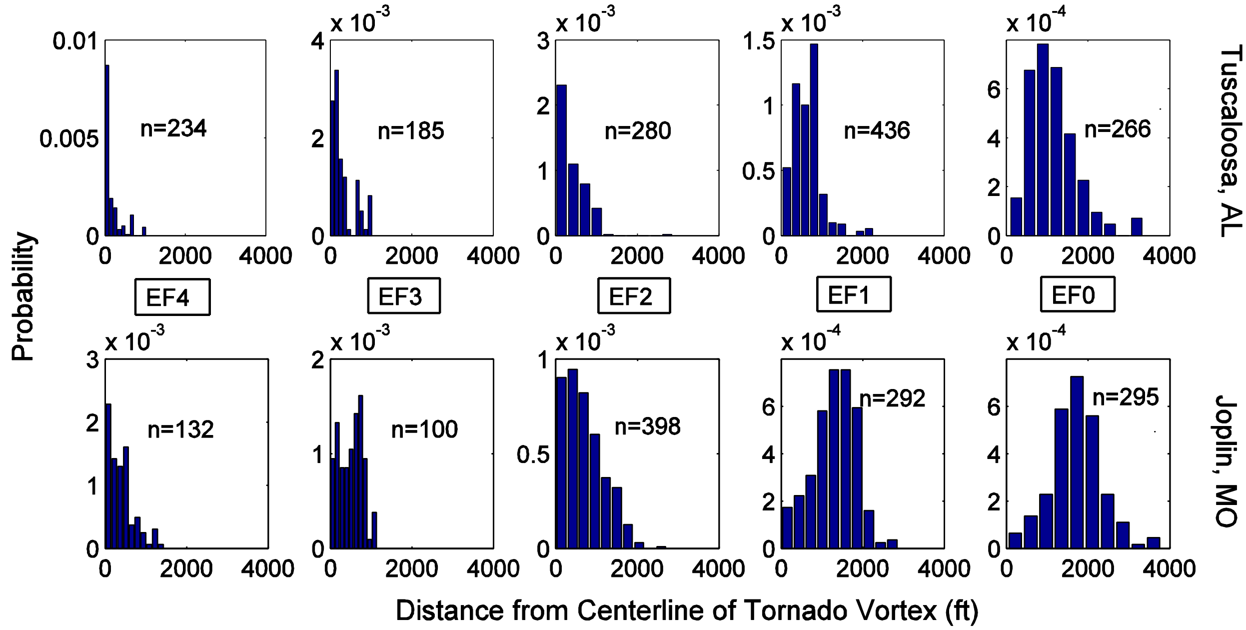
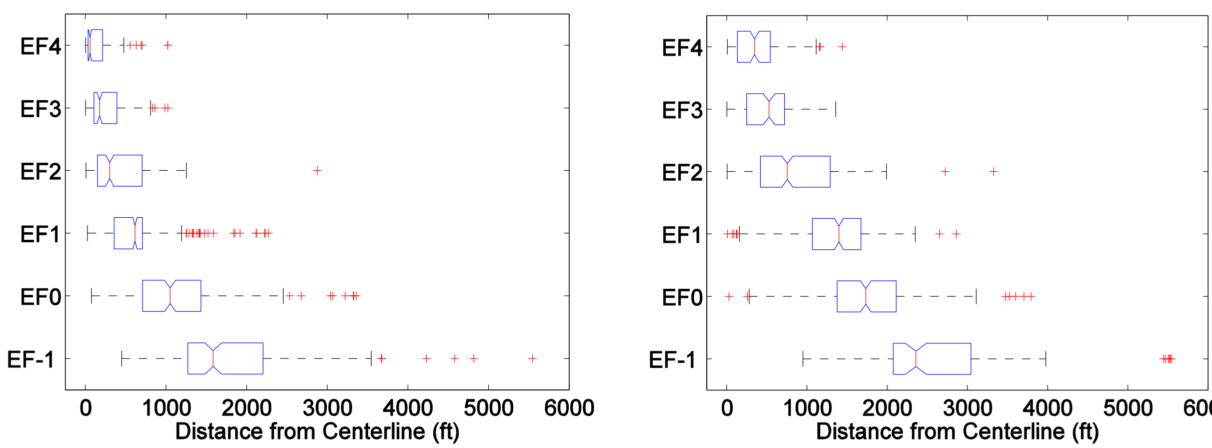


Figure 3: Distributions of Wind Speed within the Tornado Wind-field



Tuscaloosa, AL Joplin, MO

Figure 4: Distribution of Damages around Centerline

Differences in the characteristics of the two tornadoes are apparent from these plots of the observed damages. While the maximum size of both tornadoes is similar (nearly 4,000ft radius, assuming equal distances each side of the centerline), the median values for each EF-scale rating are much more compact in the Tuscaloosa tornado than in the Joplin tornado. These distributions of damages around the centerline were analyzed to empirically develop a model of the changes in wind speed with increasing distance from the vortex. The midpoint value within the range of wind speeds attributed to each EF Scale intensity was paired with the median distances from the vortex that are presented in Figure 4. Wind speed as a function of this distance from the edge of the vortex is typically modeled as a Rankine vortex, with $V(r) = (V_{max})*(R/r)^a$, where V_{max} represents the maximum tangential velocity, R the radius to maximum wind velocity, r the radial distance from the center of the vortex, and a the decay coefficient, estimated to vary from 0.5 to 1.0. Wurman et al estimated a decay coefficient of 0.67 for the F4 tornado in Spencer, South Dakota (Wurman e Curtis, 2005), and this estimate is compared in Figure 5 to the empirically developed model, assuming the same maximum wind speed for all three models. The comparison demonstrates good agreement between the model observed by Wurman et al using Doppler radar and the empirically developed models from the damage assessments, particularly for the Tuscaloosa tornado. While it is possible that the exceptional agreement between the Tuscaloosa model and the observations by Wurman et al in the Spencer tornado is entirely coincidental, it suggests that the behavior of the boundary layer wind speeds in a large tornado is similar to that observed by Doppler in the upper atmosphere.

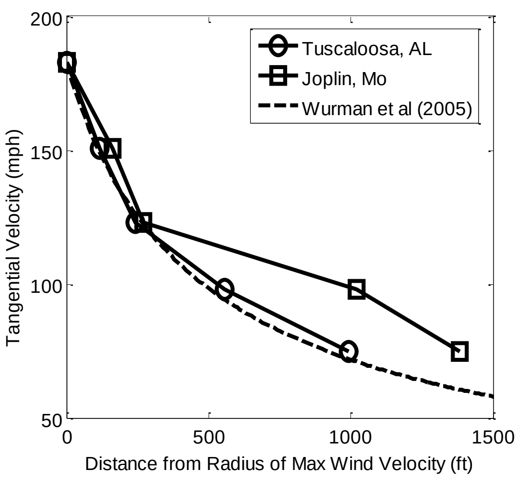


Figure 5: Comparison of Wind Speeds with Distance from Vortex

FAILURE MECHANISMS IN WOODFRAME HOMES

Of particular concern in these assessments was the performance of residential housing, the majority of which was wood-frame construction. A number of previous reports have well documented the typically poor performance of residential housing during tornadoes, particularly wood-frame homes (Minor, Mcdonald *et al.*, 1978; Fema, 1999; Urs, 2007; Bienkiewicz, 2008). The poor performance stems from the fact that the majority of the homes in these two regions were built using traditional methods or conforming to prescriptive building codes, and as a result these structures typically lack the strong connections necessary to provide an adequate vertical or lateral load path to resist tornado loads. Furthermore, as shown in Figure 6 the majority of the

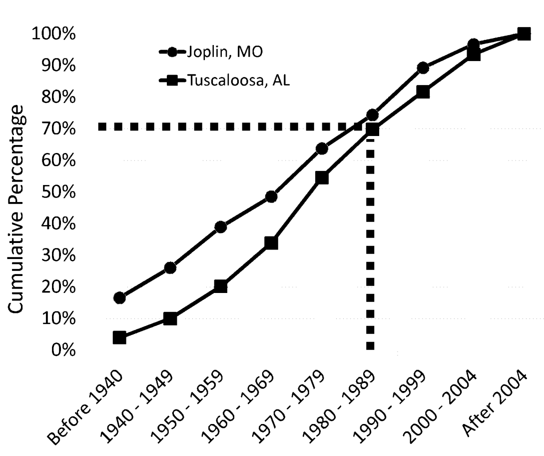
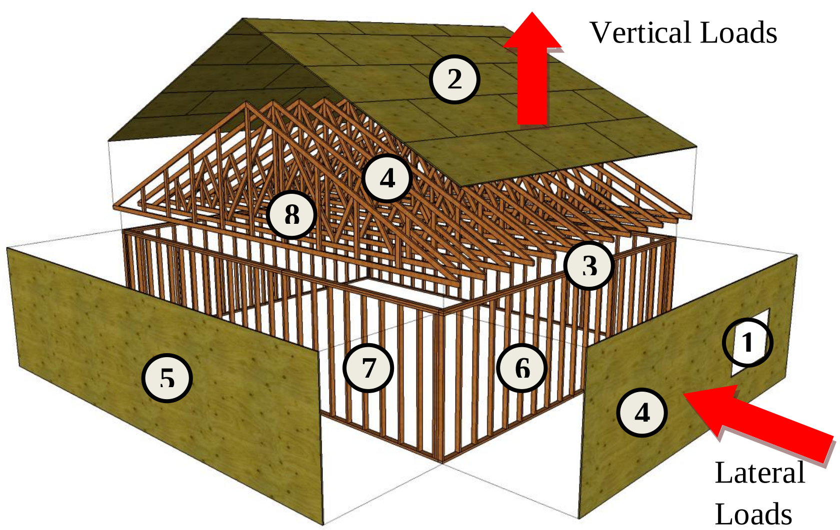


Figure 6: Age Distribution of Housing (Bureau, 2011)

homes were built over 30 years ago and the effects of aging reduce the expected performance as well. The result is a large number of homes that are particularly vulnerable to extreme wind events such as tornadoes.

Wood-frame homes are unique in that typically the components and cladding elements of the home also dictate the system response. Roof sheathing serves to tie the individual trusses together to act as a single diaphragm and similarly the wall sheathing to the stud walls as shown in Figure 7. These two diaphragms act together, with the roof diaphragm acting to support the interior portions of the transverse walls and transferring those lateral loads to the shear walls. As a result, the components of the structure are necessary to the capacity of the system, and loss of the components significantly weakens the system. The importance of the components however does not minimize the importance of the system, and particularly the various connections in the vertical and lateral load paths. Every element is needed to create a tornado-resistant home.

With this understanding, a sample set of 244 homes was selected from the dataset to perform a pilot study to examine correlations between the observed damage patterns. Seven damage patterns in all were identified in the sample set used for this pilot analysis and they are defined as given in Table 1.



1) Glazing/Openings
2) Roof Sheathing / Roof Diaphragm
3) Roof-to-Wall Connections
4) Transverse Wall Sheathing
5) Shear Wall Diaphragm
6) Transverse Wall Framing
7) Shear Wall Framing
8) Gable End Framing

Figure 7: Major Components and Systems in a Typical Wood-frame Home

Table 1: Defined Damage Mechanisms for Wood-frame Homes

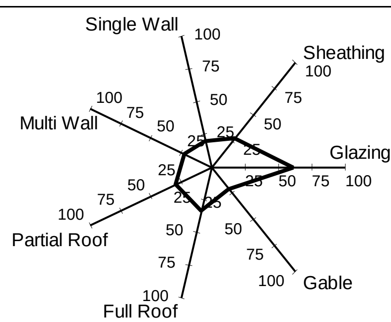
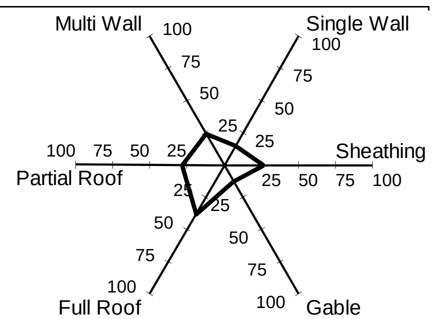
Glazing/Envelope Breach Broken glass in doors or windows or failure of a door or other opening. Broken glass is typically the result of wind-borne debris, the effects of which can be accelerated in dense residential regions or in the presence of trees, gravel or other potential projectiles. Door failures, particularly garage doors, are indicative of wind speeds near 100mph according to the EF scale provisions.	
Sheathing Failure Uplift of one or more sections of roof deck. This failure mechanism corresponds to a Degree of Damage of 4 and is indicative of significant uplift forces on the roof. Although typically not a major structural failure, it can lead to progressive failures, due to the resulting weakening of the roof diaphragm, and significant economic losses from the resulting water ingress.	
Partial Roof Removal Failure of one or more roof trusses at the roof-to-wall connection. The loss of multiple such connections weakens or eliminates the transfer of lateral load from the walls into the roof diaphragm and can lead to collapse of walls.	
Full Roof Removal Failure of all roof-to-wall connections, such that no part of the roof remains. The complete removal of the roof leaves the walls particularly vulnerable to collapse due to the loss of the roof diaphragm.	
Single or Partial Wall Collapse Collapse of an entire single wall or any significant portion of a wall	

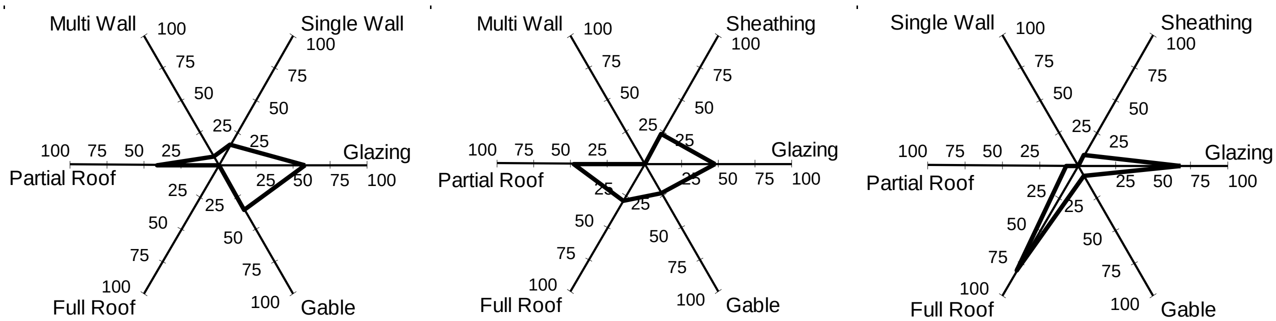
Multiple Wall Collapse Collapse of more than one wall, including complete collapse of all walls.	
Gable Failure Collapse of the gable truss or separation of the gable truss from the gable wall below. This damage mechanism was documented due to previous studies which have shown that a significant portion of the vertical load throughout the roof system is transferred to the walls through the gable end. (Datin, Mensah *et al.*, 2010)	

OBSERVED FAILURE PATTERNS

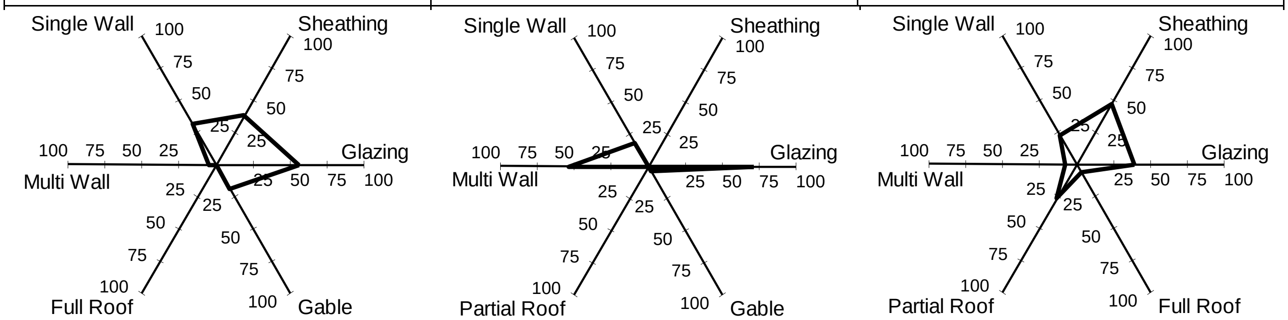
The subset of 244 wood-frame residential structures was analyzed to identify which failure mechanisms were present and the results are illustrated in Table 2 below. In the majority of the structures multiple failure mechanisms were identified. The overall distribution of failure mechanisms within this subset is illustrated by percentage in (a). Further, in each spider-web diagram (a) through (g) the association of each failure mechanism is analyzed showing their percentage frequency of occurrence, with which it was associated with the other defined failures.

Table 2: Observed Failure Patterns in Wood-frame Homes

	
(a) Distribution of Damage Mechanisms	(b) Glazing



(c) Sheathing | (d) Single Wall | (e) Multiple Walls



(f) Partial Roof | (g) Full Roof | (h) Gable

The analysis demonstrates several trends with respect to damage patterns in tornadoes that are worthy of discussion.

1) The most prevalent failure mechanism is the failure of glazing (50%) Table 2(a), which is to be expected given the large, circulating debris cloud associated with tornadoes.
2) The collapse of multiple walls was the most highly correlated (at 81%) with full removal of the roof, Table 2(d), illustrating the importance of the roof diaphragm in overall stability of the house. Of the homes that were observed to have multiple wall collapse, 81% were associated with full removal of the roof as well. This again illustrates the importance of the roof diaphragm in the support of the walls. Without the support of the roof diaphragm, the exterior walls function as inadequately fixed cantilevers and are prone to collapse. Interior walls could serve to provide additional interior support but in typical construction minimal attachment if any is used to connect the interior and exterior walls.
3) With nearly 60% of the homes experiencing envelope breaches of some kind, it is probable that internal pressures played a significant role in the final damages. Of the homes that experienced full roof removal, nearly 75% of them also had breaches in the envelope whether due to glazing fracture or door failure. Perhaps this should be expected given the large, fast-circulating debris clouds associated with tornadoes. But such breaches in buildings suffering full roof removal and multiple wall collapse occur 20% more often than in the other defined damage mechanisms. This suggests a failure pattern of glazing breach → buildup of internal pressures → full roof removal → multiple wall collapse.
4) Gable failures were associated with roof sheathing removal in nearly 50% of the observed homes. While not as strong a correlation as the others, it suggests an intuitive

failure pattern in which the loss of sheathing, typically along the gable wall in the ASCE 7 edge zones, can weaken the support of the gable truss and allow it to collapse.

DISCUSSION

The results of this analysis provide insight into what should be the primary areas of focus for tornado-resistant design. As discussed previously, the protection of the roof diaphragm is vital to maintaining the structural integrity of the home during a tornado, and this is validated by the results. In homes in which multiple walls collapsed, full roof removal occurred in 81% of the cases. The use of stronger roof-to-wall connections such as the metal ties used in hurricane-prone regions could significantly reduce the number of buildings that experience total collapse by strengthening the roof-to-wall connections and maintaining the structural integrity of the roof diaphragm.

With nearly 60% of the homes being identified with breaches in the envelope, it is obvious that unless debris-impact glazing and strengthened doors are used, the impact of internal pressures cannot be overlooked in design. Moreover with the significant debris-cloud and high winds associated with tornadoes, it may be necessary from a tornado design standpoint to design for internal pressures in addition to providing a certain level of debris-impact glazing.

To improve performance of residential structures van de Lindt et al (Van De Lindt, Pei *et al.*, 2012) proposed a dual-objective design philosophy approach seeking to mitigate damage from EF0 to EF2 tornadoes while maintaining life safety. Using this approach, buildings can be designed to minimize damage for tornadoes in the EF0 to EF2 range but also provide life safety during tornadoes of higher intensity. Our analysis suggests that were such a design approach in place in Tuscaloosa and Joplin prior to these tornadoes, it would be possible to reduce tornado damage in as much as 85% of the impacted regions, and the reduction in debris cloud would mitigate losses even further.

FUTURE RESEARCH

Several avenues are proposed for future research. A failure patterns analysis is underway using the complete dataset of nearly 3,000 houses surveyed in the two tornadoes. Further an in-depth correlation study of failure mechanisms versus building location within the tornado's wind field will be conducted. The field data provides the basis for developing empirical models of structural load distributions within the tornadoes which will be used in validation studies against small-scale experimental models of tornado loads variation with distance from the vortex (i.e. Haan et al (F. L. Haan Jr., Balarmudu *et al.*, 2010)) using tornado simulators.

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Wind Uplift Capacity of Foam-Retrofitted Roof Sheathing Subjected to Water Leaks

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ABSTRACT

A well-known source of damage to houses in hurricanes occurs when water bypasses failed roof coverings that allow water to enter the interior through joints in the wood roof decks. Closed-cell spray-applied polyurethane foam (ccSPF) sprayed to the underside of the roof functions as a secondary water barrier to mitigate this damage, in addition to its primary function as a thermal barrier. Recent studies at the University of Florida revealed that ccSPF also significantly increases the wind uplift resistance of a wood roof deck due to its strong bond to wood substrates. This presentation describes a research project that investigated the effects of incidental water leakage on the strength of the ccSPF-to-wood bond and on moisture retention characteristics in a wood roof.

The two-phased study consisted of the construction and long-term testing of full-scale roof attics exposed to outdoor environmental conditions in Gainesville, FL, and bench-type studies using small-scale roof deck samples. Each roof attic was retrofitted using ccSPF, self-adhered membrane underlayment and/or air gaps between the sheathing and ccSPF. Numerous ½ in. diameter holes (leak gaps) cut into the roofing created sources of water leaks, and we continuously monitored moisture content in the wood in real-time through a web-based application. The wind uplift capacity of roof panels (ultimate failure pressure), were determined at the end of each exposure period. Concurrently, small-scale testing was conducted to measure the tensile strength of the wood-to-ccSPF bond for samples exposed to up to 16 weeks of intermittent water sprays. The moisture distribution in 6 in. x 6 in. wood (OSB and plywood) roof deck samples was also determined, representing common construction patterns such as vertical or horizontal sheathing joints, and the configurations of full-scale retrofit systems.

While ccSPF remains highly effective as a structural retrofit despite significant wetting, elevated moisture content occurs within the wood substrate. Successful techniques were demonstrated to mitigate moisture retention, such as use of self-adhered waterproofing membrane or including an underside-deck air gap within the ccSPF retrofit layer that resulted in substantial reduction (90% and 80%, respectively) in moisture contents within the sheathing. The study has led to recommendations for the installation and maintenance of ccSPF-retrofitted residential roofs, and the use of similar wood-foam composite systems in wood-framed buildings.

BACKGROUND

Failure of roof sheathing during extreme wind events is a common failure mode in residential roofs. The majority of hurricane-related losses are sustained by residential homes and 95% of these are from failures within roof-systems (Baskaran and Dutt, 1997). Inadequate fastening of wood sheathing to roof framing members is the most common failure mode. Roof sheathing failure causes major losses for two primary reasons: (1) the loss of diaphragm action weakens the lateral stability of the roof, leading to roof failure and progressive collapse of the building; and (2) openings made in the roof can allow water to intrude which severely damages interior components and building contents. Despite enhanced building code provisions that have improved the construction of newer homes, over 80% of the existing residential housing stock in these hurricane-prone regions were built before any building code changes (Datin et al, 2011). Thus, a significant portion of the existing housing stock remains vulnerable to these damages. Therefore it is beneficial to identify viable retrofit options to improve the uplift capacity of these vulnerable roof systems.

Several studies have reported methods of using structural adhesives to retrofit wood (Jones, 1998; Turner, 2009; Datin et al, 2011) and the uplift capacities are increased by three to five times when compared to minimum code-required fastening schedules and sizes. In addition to its effect on sheathing uplift capacity, ccSPF is also an attractive retrofit option due to its insulating properties and presence as a secondary water barrier. Despite the benefits of ccSPF to roof sheathing, certain performance issues have not been fully addressed, including their structural performance when exposed to water. Datin et al (2011) postulated that water leakage into a ccSPF-retrofitted wood roof may become trapped between ccSPF and wood structural members and could cause diminished performance of the roof. This hypothesis led to the current study which consists of two phases.

The objective of Phase I was to determine if elevated moisture contents in a roof affected the bond strength of the ccSPF to the wood substrate, specifically with regards to the uplift capacities of the ccSPF-retrofitted panels. The objective of Phase II is to examine the mechanics of the moisture travel within a ccSPF-retrofitted roof system and evaluate possible techniques for mitigating the moisture intrusion and buildup. Phase I was completed in January 2011; Phase II is scheduled for completion in January 2013.

Datin et al (2011) conducted wind uplift capacity tests on ccSPF-retrofitted panels using the following three configurations as shown in Figure 1: Level I - 3 in. triangular fillet of ccSPF at the wood framing to sheathing panel joint; Level II - 3 in. fillet plus ½ in. layer between fillets; Level III - continuous 3 in. thick ccSPF layer. Uplift tests showed that the ccSPF-retrofitted panels yielded two to three times greater capacity than the control panels. .

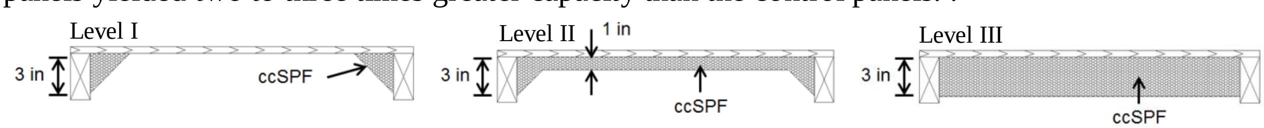


Figure 1. Retrofits Types

PHASE I SUMMARY

Full details of the Phase I study are available elsewhere (McBride, 2011) and will not be discussed at length here. The objective of the study was to identify if moisture buildup occurred and if so, quantify the effect it had on the uplift capacity of the roof sheathing. Both large-scale and small-scale testing was utilized to evaluate the effect of moisture on the ccSPF-to-wood bond. In the large-scale tests, five full-scale attic roofs were constructed out of wood trusses and OSB sheathing, and were retrofitted as shown in Table 1.

Table 1: Summary of Test Variables – Phase I

Roof 1	Roof 2	Roof 3	Roof 4	Roof 5
No Retrofit	Type II Retrofit	Type II Retrofit	Type III Retrofit	Type III Retrofit
Leak Gaps	Leak Gaps	No Leaks	Leak Gaps	No Leaks

A hundred and four ½" leak gaps were cut into three of the five roofs, all of which were then exposed to both natural and simulated rainfall for 150 days. Moisture contents of the truss top chords, temperatures and humidity were continuously monitored for the duration of the exposure period. After the completion of the exposure period, eight 4'x8' panels were harvested out of each roof and tested to failure using a Pressure Loading Actuator (PLA) and steel chamber. Significant moisture buildup did indeed occur in the retrofitted roofs with leaks (shown in Figure 2) and not in the non-retrofitted roof, which also had leaks, but the moisture had no observable effect on the uplift capacities.

(a) Moisture Buildup in Sheathing (b) Moisture Buildup in Framing Members

Figure 2. Observed Moisture Buildup in Retrofitted Roofs with Leaks

Increased moisture contents in wood did not produce statistically significant changes in panel failure pressures over the 150-day weathering period. However, the moisture content in leaking ccSPF-retrofitted roof panels increased at a faster rate than in leaking un-retrofitted roof panels. In fact, the un-retrofitted roof did not see any sustained water content values above 22%. The moisture contents in ccSPF-retrofitted roofs with leaks often exceeded thresholds for fungal decay and strength loss, with moisture contents above 70% observed in Roof 2 and 60% in Roof 4 truss members. Truss moisture contents above 20% were observed for over three months in both Roofs 2 and 4. Although wood degradation/rot was not measured during this experiment, the results of this Phase I study demonstrate that the presence of the impermeable ccSPF layer on the underside of the sheathing inhibits the removal of the moisture from the wood. This can increase the risk of degradation from long-term exposure to the elevated moisture contents.

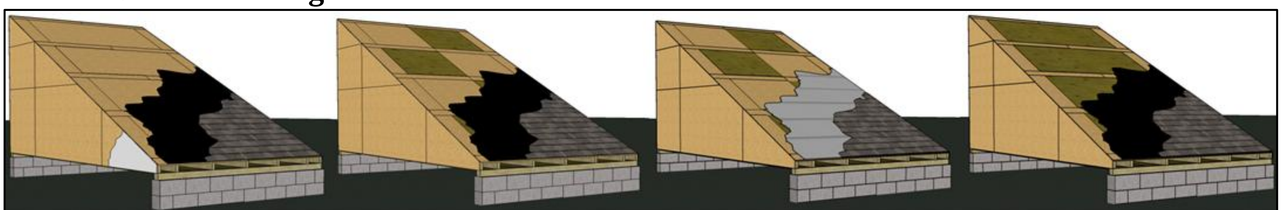
PHASE II RESEARCH: MECHANICS OF MOSITURE BUILD-UP

Due to the impermeability of ccSPF, it is difficult to detect leaks in retrofitted wood roofs, and it was shown in Phase I that if roof leaks are allowed to occur for long periods, the wood moisture content can remain at levels that lead to decay in wood. Hence an important goal should be to identify better means of preventing leaks or methods to increase the drying rate and reduce moisture buildup in the wood. The objective of the Phase II study was to investigate how the mechanics of the moisture travel through the ccSPF-retrofitted roof system differed from a standard roof and identify techniques to mitigate water buildup in the wood. Additionally, since OSB was used exclusively in Phase I, evaluation is made on whether the use of plywood has further implications either in regards to the uplift capacity or moisture travel mechanisms. Both large-scale and small-scale testing was utilized in Phase II and the test methods and results are discussed.

Large-Scale Test Methods

Four 10’x16’ monoslope attic roofs were constructed at a 6:12 slope facing south using wood trusses and wood roof sheathing. Table 2 provides a summary of the test matrix.

Table 2: Phase II Large-Scale Test Matrix



Roof 4	Roof 3	Roof 2	Roof 1
OSB	Plywood/OSB	Plywood/OSB	Plywood
Reduced Leakage	Reduced Leakage	Reduced Leakage	Full Leakage
	Air Gap	Self-Adhered Membrane	

Two techniques were evaluated for their effectiveness in minimizing moisture buildup and drying times in ccSPF-retrofitted roofs. Roof 2 used a self-adhered waterproofing membrane at the top surface of the wood sheathing in lieu of the felt used in standard roof systems. It was expected that the self-adhered membrane would limit the amount of moisture entering the roof system through the leaks, but there were also concerns that its use would prevent any moisture from leaving the roof sheathing due to the presence of vapor barriers on both sides of the sheathing. Roof 3 utilized a vented approach, whereby an air gap was provided at the underside of the sheathing through the use of a plastic vent system, installed prior to the installation of the ccSPF. The dimensions and installed view of the air gap is shown in Figure 3.

(a) Cross-section View (b) Air Gap Prior to ccSPF Installation

Figure 3: Details of the Air Gap in Roof 3

Moisture content, temperature and relative humidity in the roofs were monitored throughout the exposure period using resistance-based, temperature-corrected moisture content devices placed into the wood sheathing. Proprietary software developed by Structures Monitoring Technology collected and converted signals wirelessly from the sensors and stored the data in an internet-accessible database. Placement of the sensors is shown in Figure 4.
Leaks were also provided through the waterproofing membranes to the sheathing, the locations of which are provided in Figure 4. The number and spacing of leaks in Roof 1 reflected that of Phase I, except that leaks were not installed at the very edge on the eave flashing as they were in Phase I. The number and spacing of leaks in Roof 2, 3 and 4 were reduced to represent more isolated leak conditions for each panel as shown.

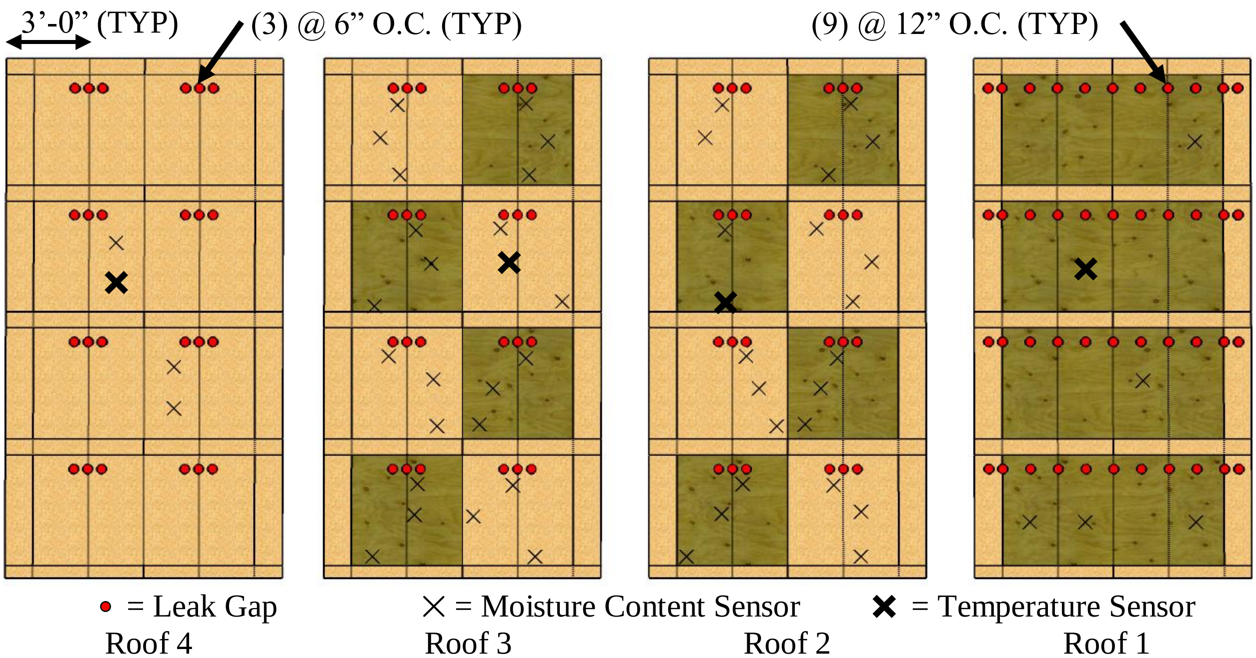


Figure 4: Location of Leaks and Moisture Sensors in Phase II Roofs

Bench-Top Test Methods

Bench-top testing was performed to examine in detail the effect of ccSPF on moisture buildup for several common roof scenarios, summarized in the test matrix in Table 3.

Table 3: Summary Small-Scale Test Matrix

Sample ID	ccSPF	Plywood	OSB	Horizontal Joint	Vertical Joint	Self-Adhering Membrane	Quantity
A	X	X					14
A-c		X					14
B	X		X				14
B-c			X				14
C	X	X				X	14
C-c		X				X	14
D	X		X			X	14

D-c			X			X	14
E	X		X		X		14
E-c			X		X		14
F	X		X	X			14
F-c			X	X			14

Samples consisted of 6”x6” sheathing specimens retrofitted with a 3” ccSPF layer as shown in Figure 5. Felt underlayment and shingle samples were fastened to the top of the samples to represent true roof conditions and the edges were sealed with a waterproofing sealant to restrict moisture absorption to the top surface only. Samples were oriented on a 6:12 slope and exposed to a continuous drip of water at a rate of 2mL/min for 24 hours in accordance with a modified ASTM D1037 procedure. Mass, dimensions and moisture contents of the samples were taken before and after the exposure period. Moisture contents were monitored for 96 hours after the exposure period ended using a Delmhorst BD-2100 Handheld Moisture Meter with 5/16” contact pins. Each sample was subdivided into nine subsections, 2”x2” as shown in Figure 6, when taking moisture contents in order to better quantify the distribution of moisture across the samples. Testing was performed in a conditioned environment with a temperature of 76°F and 45% RH.


Figure 5: Typical sample prior to testing

Figure 6: Nine subsections to each sample

RESULTS

Harvesting of the sheathing panels from the full-scale roofs was not due to be completed before the writing of this paper and thus only the results of the moisture content monitoring can be shown for the full-scale specimens. These results should be considered preliminary until the full condition of the roofs are observed at the conclusion of the exposure period.

Sheathing Moisture Contents in Full-Scale Specimens

Figure 7 presents a summary of the maximum observed moisture contents in the roof sheathing at each sensor location. The majority of the moisture was observed in the plywood rather than the OSB.

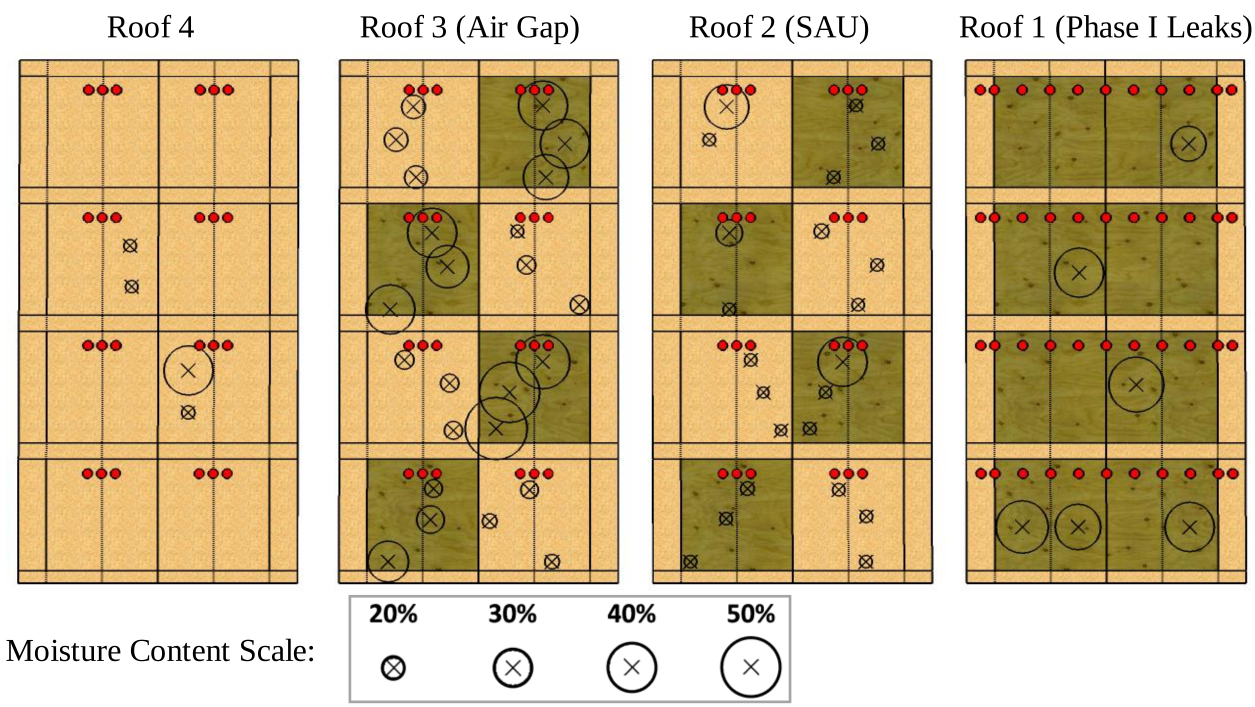


Figure 7: Maximum observed moisture contents in full-scale roofs

Table 4 presents a comparison of the number of days that each moisture sensor in a given roof recorded moisture content greater than 20%. This result illustrates more clearly the duration of the exposures to significant moisture contents rather than the maximum value recorded from possibly a single peak.

Table 4: Summary of Moisture Content Observations in Full-Scale Specimens

Roof ID / Description	Total Number of Sensors	Total Sensor-Days	Sensor-Days w/ MC ≥ 20%	% Sensor-Days of Significant Moisture
Roof 1 (Plywood, more leaks)	6	2388	417	17.5%
Roof 2 (Self-adhered memb.)	22	8757	26	0.30%
Roof 3 (Vented)	24	9553	367	3.80%
Roof 4 (OSB)	4	1592	170	10.7%

Sheathing Temperature in Full-Scale Specimens

Sheathing temperatures were continuously monitored over the duration of the exposure period at the mid-slope of the full-scale specimens. Locations of the temperature sensors were previously shown in Figure 4. Results are presented in Table 5 as the difference between maximum daily temperatures observed in Roofs 2 through 4 and those observed in Roof 1. Thus a negative value implies that the observed maximum daily temperature in the specified roof was lower than that observed in Roof 1. Distributions of the differences in maximum daily temperatures are illustrated in Figure 8.

Table 5: Observed Maximum Daily Temperatures Relative to Roof 1

Roof ID	Mean	Median	Std. Dev.
Roof 2	0.50°C (0.89°F)	0.46°C (0.83°F)	2.14°C (3.85°F)
Roof 3	-2.24°C (4.02°F)	-2.26°C (-4.07°F)	1.71°C (3.08°F)
Roof 4	0.52°C (0.94°F)	0.29°C (0.52°F)	2.20°C (3.96°F)

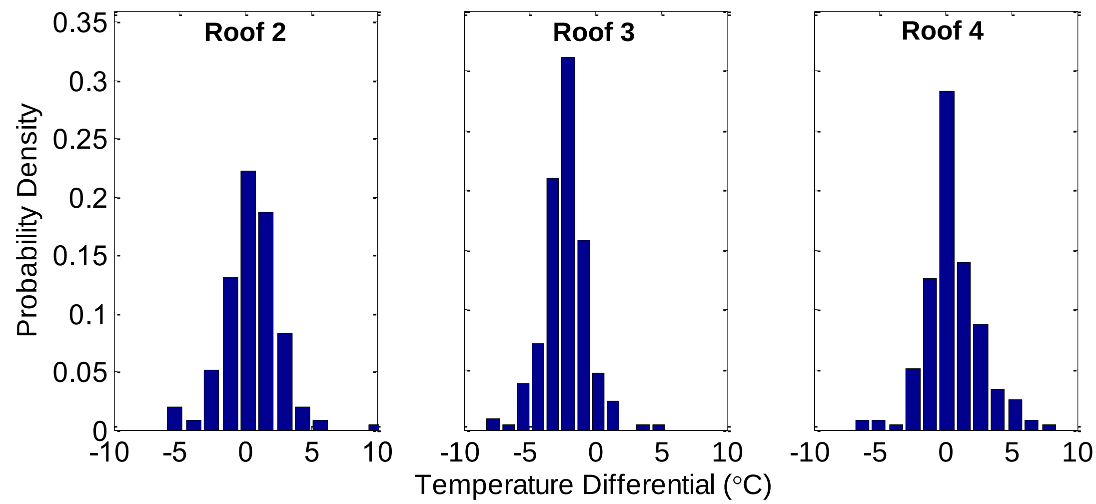


Figure 8: Distributions of Temperature Differentials as Compared to Roof 1

Bench-Top Test Results

Results from the bench-top testing consist of moisture contents, total absorption and drying times for the samples forming the test matrix shown in Table 6. As the drying rates were fitted exponentially, drying times are represented using the half-life measure.

Table 6: Summary of Bench-Top Testing Results (Samples without Joints)

Sample Description	Total Absorption (mL) [+Std Dev.]	Max. Moisture Content (%) [+Std. Dev]	Half-Life (hrs)
A (Ply w/ ccSPF)	28.0 [+15.8]	30.2 [+12.6]	32
Ac (Ply w/o ccSPF)	32.8 [+15.96]	35.2 [+7.0]	45
B (OSB w/ ccSPF)	9.93 [+2.8]	20.43 [+4.2]	62
Bc (OSB w/o ccSPF)	9.00 [+2.7]	19.25 [+4.1]	40
C (Ply, SAU w/ ccSPF)	14.79 [+4.6]	34.67 [+7.0]	110
Cc (Ply, SAU w/o ccSPF)	2.57 [+1.6]	16.58 [+3.7]	48
D (OSB, SAU w/ ccSPF)	4.21 [+1.3]	19.43 [+4.0]	70
Dc (OSB, SAU w/o ccSPF)	6.88 [+1.81]	15.33 [+4.2]	55

The effect of ccSPF on moisture accumulation at joints was also examined using samples with both horizontal and vertical joints, shown in Figures 9 and 10. In addition to the sheathing moisture contents monitored in all samples, moisture contents were also measured at ½" depths in eight locations along the exposed surface of the framing members present in samples with vertical joints. A summary of the results for samples with joints is given in Table 7.

Figure 9: Sample with Horizontal Joint (HJ)

Figure 10: Sample withVertical Joint (VJ)

Table 7: Summary of Bench-Top Testing Results (Samples with Joints)

Sample Description	Total Absorption (mL) [+Std Dev.]	Max. Sheathing M.C. (%) [+Std. Dev]	Avg. Framing M.C. (%) [+Std. Dev]
E (OSB, VJ, w/ ccSPF)	14.8 [+3.9]	30.2 [+12.6]	22.4 [+2.8]
Ec (OSB, VJ, w/o ccSPF)	47.6 [+20.7]	35.2 [+7.0]	38.5 [+1.9]
F (OSB, HJ, w/ ccSPF)	13.3 [+2.1]	20.43 [+4.2]	N/A
Fc (OSB, HJ, w/o ccSPF)	17.4 [+3.9]	19.25 [+4.1]	N/A

CONCLUSIONS

In Phase 1 of this study it was shown that when ccSPF-retrofitted roof sheathing panels were subjected to extensive, long-term roof leakage, the moisture contents in the framing members and sheathing panels are higher than those in conventional wood roof construction [6]. The study also confirmed that the wind uplift capacity of the retrofitted panels was not affected by the high moisture content, although it was observed that the durability of the wood itself could be adversely affected. As a result, Phase 2 evaluated techniques to mitigate water accumulation in the roof structure by installing a) under roof deck air gaps or b) self-adhered waterproofing membrane. In the self-adhering membrane roof specimen, moisture contents remained below 20% for all but a few instances, while in the roof with underside air gap the elevated moisture contents that did occur were quickly reduced in half the time it took for moisture level to fall in the roof without air gaps.

Bench-top studies demonstrated that the ccSPF did not have a significant effect on water absorption or drying over a 24-hr exposure period for standard roof configurations (i.e., wood sheathing, felt underlayment, asphalt shingles). However when used in combination with a self-adhered waterproofing underlayment, the samples with ccSPF had higher moisture contents and dried 130% and 30% slower, respectively for plywood and OSB sheathing. The effect of the ccSPF on moisture accumulation at sheathing joints was mixed, with the ccSPF actually being beneficial at reducing moisture contents in the framing members at vertical joints. The ccSPF layer functioned as secondary water barrier, preventing further downward travel of water into the joint and onto framing member. The moisture content in the sheathing near a horizontal joint increased slightly (by 4%) as compared to the sheathing samples with no joints.

The issues related to moisture travel and mitigation of moisture build-up in the wood roofs examined here has implications beyond that of ccSPF-retrofit of roof sheathing. New technological developments have produced structural adhesives and impermeable foams used in composite construction with structural wood framing and sheathing, and they are likely to experience (or exhibit) similar performance in presence of water leaks. Structural insulated panels (SIPs) are a case in point, and the authors have found no information in the literature addressing potential effects of water leakage on these systems. Any system that retards water from draining away from the wood can promote decay or insect infestation. The mitigation techniques described in this study can be applicable in minimizing potential damage to critical components of the building envelope.

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Housing Reconstruction and Community Recovery Following Disasters – No Easy Choices

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ABSTRACT

In the aftermath of a disaster, communities experience significant housing demands for the survivors. Although there will be many volunteer, local, state and federal organizations involved, a significant housing recovery challenge is the reality that everybody will be in charge. Property owners, investors, builders, community leaders, insurance providers, and various state and federal leaders all have a stake in the operation and success of the reconstruction effort, yet none have the absolute power necessary to direct the collective recovery. This reality is symptomatic both of the inherent chaos after disasters and of the current response system. Those involved in facilitating community recovery must understand the opportunities and constraints of the various courses of action available to leaders, residents and community advocates. This will enhance the ability to rapidly respond to the housing demands of the post disaster environment.

A community's long-term recovery is highly dependent on the availability and quality of physical housing units in the short- and mid-term, in particular. Housing supports the larger community recovery effort in numerous ways. However, housing responses are still among the most complex and disaggregated in disaster recovery. This paper first presents a comprehensive structure for conceptualizing the inputs and activities associated with housing responses through the "Seven Rs"; repair, rent, rebuild, remediate, replace, relocate and most importantly, resources. The authors argue that conscious consideration of these concepts will support more effective pre-disaster planning and efficient post-disaster assistance. Secondly, the paper argues that a glaring omission of past housing responses has been the involvement of the housing industry itself, including the expansive knowledge of technology, production efficiencies (or inefficiencies), and cost that can be brought to bear. The decisions that lead to programs for disaster response and recovery often are made quickly and frequently without analysis of or input from the residential design and construction industry and markets. Integrating these parties strategically will strengthen the process and speed the recovery.

INTRODUCTION

Although the images we often see on the evening news following a disaster typically suggest vast destruction, those images belie the fact that the number of homes that are destroyed may be limited. Following a disaster, great efforts are targeted at cleanup and repair, and these typically provide great latitude for homeowner's decisions about repair and reconstruction. The challenges facing communities stem from the decisions made early in the process that may place families at risk from future disasters and can impact broader community or regional plans to improve the resilience of the area.

While there may be an urge to quickly begin repairs and reconstruction (often demanded as a "show" of community resilience or strength), a more prudent and potentially cost-effective approach might be to simply plan in an effective manner beforehand. For example, changing the land use or construction requirements for a risky location (from residential to open space or requiring elevation of the home) could be rendered moot by the rebuilding actions of a few property owners, decisions by insurers, or basic lack of knowledge among local builders and remodelers. As a consequence, the costs of later implementing the open space conversion (both financial as well as political) increase dramatically.

DISASTER RECOVERY FRAMEWORK

As we are seeing with the aftermath of Superstorm Sandy in New York and New Jersey, many priorities are established by a host of parties, often advocating conflicting positions. Such conflicts can lead to wasted time, effort and community focus. In a perfect world, a comprehensive plan would be developed and that plan would be implemented throughout the community. Unfortunately, because of individual priorities and resources, that often does not happen. Property owners will, by virtue of their own priorities and resources, move at different rates. These owners may take actions much more quickly than the community and in others, much slower.

For effective housing recovery following a disaster, it is not enough to simply provide a temporary housing unit to a family and then declare community recovery complete. While expedient, those actions will just shift the costs and impacts of the disaster to a later time by not addressing the physical, economic, and social needs of the disaster's most needy victims. As the vast majority of the nation's housing stock is privately held by residents or investors, the burden of repair and replacement of housing will primarily fall on the private sector.

Those involved in the challenge of facilitating community recovery must understand the opportunities, constraints, and costs of the various courses of action available to leaders, residents and housing advocates. This will enhance the ability to rapidly respond to the housing demands of the post disaster environment. Absent the locations that present too great of an individual, community or societal risk for repair and reconstruction, it is likely that all damaged housing (or developable lots) will be ultimately returned to the community.

Because of the flexibility of action available to the disaster survivors and need for housing recovery, the choices and issues can be broadly characterized as falling into one of "Seven Rs"; repair, rent, rebuild, remediate, replace, relocate, and most importantly, resources. Virtually all housing programs will fall into one or more of these categories.

REPAIR

Typically most of the housing that has experienced a disaster has not been destroyed, with a significant portion experiencing repairable damage. Although the media typically shows homes and buildings with the greatest damage in reports and stories, much of a community's housing stock is often habitable or close to habitable.

With most disasters, the damage to housing, businesses and institutions follows a predictable continuum, where the vast majority of the structures are either undamaged or lightly damaged. In the recent analysis of preliminary damage on housing following Superstorm Sandy, FEMA inspectors noted 63.5% of the 468,643 units inspected in the 41 counties (in five states) declared for individual assistance had experienced no damage. Table 1 below shows a U.S. Department of Housing and Urban Development analysis of those homes that were received no flooding from an extract of FEMA property inspections (provided by FEMA on November 26, 2012). Examination of other disaster events suggests a similar distribution of damage.

Table 1. Non-Flood Damage Observed

Classification of Damage	Number of Homes	Percentage of Total
No damage	297,542	90.6%
Minor Damage Low	21,191	6.5%
Minor Damage High	6,041	1.8%
Major Damage Low	2,123	0.6%
Major Damage High	960	0.3%
Severe Damage	491	0.1%
Total Units	328,348	

For this analysis Minor-Low damage was estimated at under $3,000, Minor-High at between $3,000 and $7,999, Major-Low between $8,000 and $14,999, Major-High at between $15,000 and $28,800 and Severe at over $28,800 (or destroyed).

Among the units that experienced flooding, the depths observed are shown in Table 2. The depth classifications used by FEMA for flooding are not linear, with basement flooding up to a depth of 6-9 feet, the 1-4 foot depth representing a three foot range, and the flood depth over four feet has a wide depth range. This would account for the relatively small number of homes reported as receiving flooding to a depth of one foot.

Table 2. Flood Depth Observed

Depth of Flooding	Number of Homes	Percentage of Total
Flooding Limited to Basement	50,393	35.9%
Flooding to First Floor, Depth up to 1 Foot	21,984	15.7%
Flooding to First Floor, Depth 1 to 4 Feet	52,307	37.3%
Flooding to First Floor, Depth Over 4 Feet	15,611	11.1%
Total Units with Flooding	140,295	

The more quickly residents can return to their homes, the faster the community will recover. That said, it mustn't occur too quickly as the ability of the community to such a return is dependent on the availability of essential services which would include utilities and open transportation routes (which would support residents as well as emergency services). Reoccupancy before those services are operational stress the available emergency systems charged with delivering supplies such as food, fuel, water and services for responders and survivors.

After the essential services are available, families may be discouraged from returning to a disaster affected community because of the lack of businesses providing services (such as groceries, fuel, medical care, restaurants) and those businesses are discouraged from reopening without a client base, a classic chicken-egg conundrum. Including the availability of schools and other public services adds an additional facet to the issue. Without attempting to resolve the conundrum, it is critical to get families back home. In addition to supporting the remainder of the community, returning to one's home can improve the emotional stability of the family while decreasing demand on temporary lodging which may be needed to support those who lost their homes.

As discussed above, if minor repairs can be rapidly accomplished, a significant number (possibly as many as two thirds) of the residences in the affected area might be quickly reoccupied. This presents opportunities for builders, remodelers, non-profit organizations and others with community links to help families in the least damaged homes return. While involving such organizations virtually assures a fairly relaxed organizational structure, homes with modest damage generally do not require much technical capacity. If temporary repairs are provided, follow up will be essential.

RENT

In the event a property or neighborhood has received substantial damage or immediate repair is not possible, the residents of the affected homes will need temporary housing. In rare instances, property owners might immediately purchase a new residence with the intent of living in the new unit until the repairs are made to their damaged home. In most cases, the property owners will need temporary housing in the form of rental properties, a trailer or some other temporary unit. Although the general desire of disaster survivors is to remain on or near their property, temporary housing sited on their property or rental housing in the immediate proximity is often not available.

For many families who must remain in the area affected by a disaster because of employment, reconstruction of their homes or other reasons; renting a home or apartment is often an effective alternative. Disaster-induced demand typically tightens the rental market and the increased rental costs may result in market decisions to bring units online or to develop new multi-family housing. Bringing units online may often be done for a relatively small investment for minor repairs, paint, carpeting and appliances. In some cases, the new market dynamic might result in investment decisions to construct new rental housing as a permanent addition to the local housing market.

In all but the tightest rental markets, there is likely a significant amount of rental housing. In most communities or metropolitan areas, the housing market often has enough vacancies to absorb a significant number of renters. In a normal housing market, housing which is both vacant and available is generally less than the actual vacancy rate by 3-5%, an estimate of the amount of housing in transition or out of service. The rental market that approaches that level of vacancy is largely saturated and bringing the vacancy rate below that level would require aggressive efforts and coordination. In the period since 2005 the rental vacancy rate has ranged from 8.6% to 11.1% nationally. In an analysis of the Washington, DC area (based on 2011 Census estimates) there are 1.64 million housing units with 495,000 rental units. The rental vacancy rate of 6.1% results in a total of 32,000 vacant rental units, with up to 16,000 available for rental.

As the housing markets tighten, the distance many renters are willing to travel typically increases, expanding the local housing supply to a regional housing supply. Property owners in New Orleans following Hurricane Katrina had moved to the outer suburbs across Lake Pontchartrain (about a one hour commute) and to Baton Rouge (about a two hour commute) where they lived and commuted into New Orleans for work and to manage their home repairs. While the commute distance one will accept is an individual decision, anything in excess of 100 miles would be logistically difficult (the 2011 American Community Survey reports a mean commuting time of 25.5 minutes with only 8.1% of commuters having commutes in excess of 60 minutes).

REBUILD

For the small fraction of homes that are damaged and uninhabitable, the property owner is faced with decisions that must balance the personal needs for reconstruction with the available resources. Because homes which may be rebuilt occupy a narrow band between those lightly damaged and catastrophically destroyed, the property owner may be faced with the challenges of repairing the disaster damage, complying with the new building code, and performing selective upgrades to satisfy both functional and atheistic needs. This effort will be conducted during a time where the construction industry in the community is likely to be stressed with too much work. The strong competition for contractors are likely to increase labor and materials cost and will probably extend the construction period as well. Because of the demand, less experienced construction firms may enter the market and construction quality issues may increase.

Homes which are being significantly repaired or reconstructed generally will have to comply with current building codes. Homeowners may attempt to take actions that will allow them to avoid such code compliance, often by challenging assessments that estimate the severity of the damage. While such actions may result in reduced construction standards for the rebuilding effort, they may also prove to be a false economy (leading to an increased long-term liability) in the long run.

REMEDIATE

Allowing the reconstruction of the home may be delayed because it might be appropriate for the community to consider land use changes to heavily damaged areas before reconstruction. The community might elect to change construction requirements (building codes), flood maps might be changed (FEMA often reexamines flood maps following disasters) or the community might elect to change the land use. After Hurricane Katrina, Louisiana adopted a more modern building code. It is reasonable to expect that a community might identify construction requirements to reduce the threat of future disasters. In a flood zone, the community might change the requirements for construction in flood zones to increase the amount of freeboard required above the base flood elevation. This is a protective strategy that can be adopted by the community without the development of new flood maps. In some areas, it might be appropriate to change the land use, possibly changing zoning from single family housing to multifamily. Elevating multifamily housing will probably be more cost effective, as requirements such as elevators can be amortized across a number of units. Because of the public processes communities use to implement laws and policies often results in lengthy discussions, there may be some value in slowing the reconstruction process to allow for the implementation of revised planning, zoning or construction policies.

REPLACE

In the event a home is completely destroyed, the only option is replacement. This provides the greatest opportunities for upgrading the homes or using products or processes that provide significant safety, performance and energy improvements. Although the personal and financial impacts to the families should not be minimized, replacement of housing is an opportunity to improve the future performance and disaster resistance of the homes that shouldn’t be overlooked. To implement this, a number of government and community organizations may be in a position to assist with planning, technical or financial assistance.

If significant amounts of housing require replacement, the local construction industry will likely be stressed and may have difficulty satisfying the demand. The sudden influx of construction workers places additional stresses on the rest of the community in that those workers require lodging, food, fuel and occasionally emergency services. In the immediate post-disaster period, the impact is greatest as many of those services are already operating at capacity. As a result, we should consider construction options that reduce the stress to that local market. Increasing the use of factory built components provides some relief by moving much of the construction off-site, where labor and support services are more available. Not only does this reduce the logistical demands on the impacted community but it can speed the construction process. In a coastal environment where the building codes may require significant elevation, factory built components can help eliminate significant labor associated with that elevation (coastal residential construction projects often have workers dedicated to passing materials from ground level to the work site).

RELOCATE

In some locations, the specific risks of damage from repetitive disasters may present far too great a community and societal threat to allow reconstruction. In those cases, the prudent action would be to prevent the survivor's return to those locations. This would be most typically appropriate when the risk of flooding presents risks that cannot be tolerated. Relocation might be an option where risks are known and their location predictable, such from riverine or coastal flooding. Other disaster events, such as tornadoes, are more random in nature and relocation wouldn't change the risks significantly. Relocation is likely to involve great costs (financial as well as political) as in many situations; the homes that are undamaged or undergoing reconstruction when the relocation decision is made will suffer significant impacts to property value.

Although relocation often is seen as a complete movement of a community (such as the movement of Valmeyer, Illinois following the 1993 floods), in many cases it would look more like community land use planning where local decisions are made to select land uses that serve to minimize the risk to the residents and community. Following Hurricane Katrina, the town of Bayou La Batre, Alabama developed an area that was away from the coastal areas that were prone to flooding but still part of the town. Even in small communities, the risk often varies with location.

While some might argue whether it is relocation, vertical relocation might be worthy of consideration in coastal or riverine areas. Many features of homes that make elevation expensive can often be shared (structural design and construction, elevators, etc.) and locations where elevation is needed might lend themselves to multifamily housing. As project planners consider designs, mitigating disaster risk should be addressed just like any other environmental or site condition. While there are some locations that shouldn't be developed (for environmental or public safety reasons), many other locations may be developed with appropriate safeguards and designs.

RESOURCES

Resources include funding, time, capacity and a regulatory environment. This is similar to the meaning of the word in the corporate, institutional or government context.

FEMA and other federal agencies often provide support for property owners in a number of ways. They may provide temporary housing to the disaster survivor while the property owner must pay the cost of the repairs. Financing the permanent repair of the residence is typically the responsibility of the property owner, although there may be assistance in the form of loans or grants from a number of federal agencies. As is experienced in virtually every disaster, many homes are likely to be uninsured or underinsured (in a rental home that would include renters insurance for the contents of the home). This appears to be most evident with respect to homes owned without mortgages and homes without flood insurance. Without the financial resources to reconstruct or relocate, recovery becomes a drawn out process where the property owner attempts to muster the resources to reestablish their home and lives.

The challenge we face is that the funding streams for disaster reconstruction are often quite diverse. These might include individual savings, insurance proceeds, loans, private or government disaster assistance, local funds, assistance from philanthropic organizations, and federal assistance. Because each of these funding sources is likely to have a unique set of priorities and program requirements, "threading the needle" of these multiple programs is likely quite individualized. Some funding sources might be mutually exclusive, but many can be blended with others.

Some funding sources are designed to assist disaster survivors and other are adapted from ongoing programs. Because some non-disaster programs are regularly adapted to support the needs of communities after disasters, the planning efforts that are typically expected in advance must be performed on a compressed timeline. In some cases, reconstruction programs may be tailored to accommodate the funding program requirements. While this may increase the speed and flexibility of the program, it might also create opportunities for others with differing priorities to advance those agendas.

The virtual certainty in the process of identifying and providing resources for reconstruction is that those resources will be limited. As a result, it is imperative that the program decisions made allow property owners the flexibility necessary to complete reconstruction in an effective and affordable manner.

Because of the myriad sources funding that will be available to the survivors and the communities; there will be no dominant funding strategy. While it might be convenient to look at the funding as a single source that will be applied consistently, that isn't the case. Property owners will favor funding sources that satisfy their individual goals and objectives, an approach that may result in conflicts with community or other priorities. As the funding becomes available, those receiving funding will make decisions that may restrict the ability to plan effectively. For example, in some neighborhoods along the Gulf Coast following Hurricane Katrina, survivors who began reconstruction early in the process of determining the most effective reconstruction strategy tied the hands of the community as a "critical mass" of housing had been reconstructed, virtually eliminating the possibility of not rebuilding the most risky areas.

Time is a resource which must be considered. The capacity of the community to rapidly develop and execute a recovery plan is likely to be viewed by most survivors as too slow. Based on studies of communities recovering from natural disasters, Kates et al (2005) identified four phases of disaster recovery: emergency, restoration, reconstruction, and commemorative or betterment reconstruction. Although there are overlaps in each phase (for example some restoration may be occurring while roads are being cleared or flood waters removed), the duration of the restoration and reconstruction phases have been shown to be 10 times longer than the earlier phase. In a disaster situation where the emergency phase lasts six weeks, the restoration phase would last about 60 weeks and the reconstruction phase about 600 weeks (11 years). Individuals displaced want to repair and return to their homes as soon as possible, as that is a critical step towards recovery. This desire is heightened by the fact many displaced residents may be living in temporary housing units or rental properties and they often see those arrangements as inadequate. At the community level, the public demand to return to normalcy will likely not reflect that long reconstruction timeline.

While some might view the regulatory environment as something other than a resource for reconstruction, regulations in place before the disaster (and those enacted in the immediate aftermath) serve to shape the decisions and housing in the post disaster environment. Regulations might prevent redevelopment of particularly risky locations or provide the necessary updates to the building codes for new (or reconstructed) buildings. Planners should consider such actions well in advance of a disaster, if only to understand the implementation requirements.

Perhaps the least studied resource in disaster recovery studies, however, is the cumulative knowledge, capacity, and efficiency of the local building and remodeling industry. In each of the respective stages (or "Rs") described in this paper, the industry may be a resource or a critical bottleneck. To date, no sufficient consideration is made in pre-disaster planning and mitigation to having constant monitoring of the industry's capacity—particularly with assessments immediately after a disaster—in a fashion similar to the inspections and needs assessments of the housing stock itself.

RECOMMENDATIONS

It is essential that design and construction professionals join in the planning for and response to disasters in our communities. Absent such involvement, the communities will respond to disasters in a reactive mode that may not take advantage of the capabilities and expertise of the members of the design and construction industry.

Mitigation is clearly the best strategy to minimize losses. By working to implement building and land use requirements that reflect the threats, we can increase the number of homes that remain habitable following a disaster.

Because resources for reconstruction are often limited, it is critical communities encourage all property owners to carry appropriate levels of insurance on their properties. This will provide the necessary resources to help those residents repair or rebuild their homes and initiate the larger community recovery.

CONCLUSIONS

The challenges facing our disaster affected communities demand we identify ways to effectively and inclusively develop strategies for post-disaster recovery. As we have seen in the Gulf Coast following Hurricane Katrina and more recently in New York and New Jersey, this is too important to be left to the federal government, local governments or our elected leaders. The skill sets of the housing design and construction industry are critical to the recovery process and we must get and stay involved.

DISCLAIMER

This paper is the opinion of the authors and does not reflect the position or policy of the Federal Government or Abt Associates.

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1st Residential Building Design and Construction Conference

The Pennsylvania State University
February 20-21, 2013

Residential Reconstruction in Haiti

By Assistant Prof. Mark Taylor
School of Architecture, University of Illinois at Urbana Champaign

Residential Reconstruction in Haiti

Abstract:
The Haitian earthquake of January 2010 revealed inadequacies in the design and construction quality of the island nation's housing stock. The result of these deficiencies turned a natural hazard into a human disaster. This presentation will outline the systemic problems that led to the establishment of such vulnerable construction. Drawing on research gathered from six field trips to Léogâne, Haiti, the town at the epicenter of the January 2010 earthquake, I will also highlight two distinctly different approaches to rectifying historic failings in construction standards:

(1) Working with local partners in the construction industry to strengthen local capacity for sustainable resilience.

(2) Inviting new investors, with new products, into the Haitian market to improve building performance and provide new economic opportunities.

The government of Haiti is pursuing both approaches in order to replace over 200,000 homes that were destroyed or damaged as a result of the 7.0 magnitude earthquake. An examination of this recent tragedy will inform stakeholders of appropriate measures that can and should be taken in the wake of a natural disaster of similar magnitude.

For presentation in the following topic sessions:
Performance of Residential Buildings under Natural Disasters
Temporary Housing for Disaster Situations

Residential Reconstruction in Haiti

1. The context at the epicenter
2. "Temporary" Housing
3. Methods, Material and Craft
4. Methods - Heavy Masonry
    a. Confined Masonry
    b. Column and Beam + Masonry Infill
    c. Reinforced Masonry
5. Education, Training / Re-Training
6. Materials - Testing / Accountability
7. Lighter More Ductile Systems
    a. Wood and Stucco (by All Hands)
    b. Stucco on Steel
8. Conclusions
9. Questions and Answers

Light, Flexible & Tolerant

Heavy, Ridged and Precise


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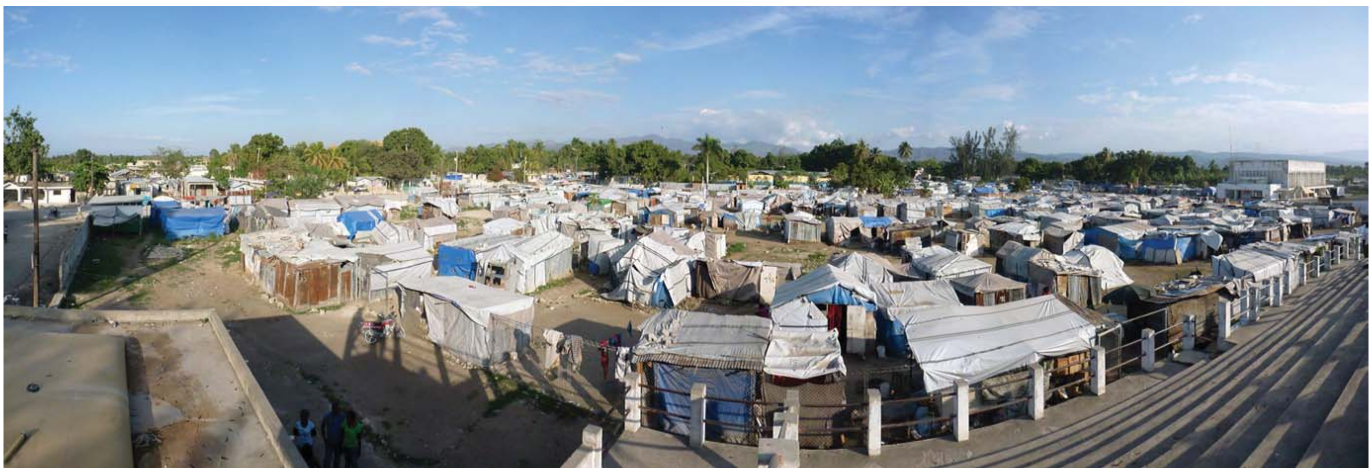
RUE D'ENFER

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CHF
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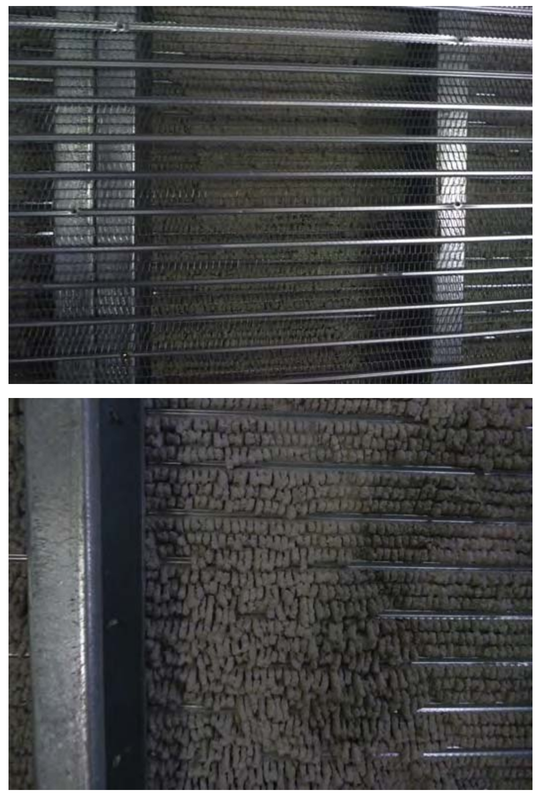
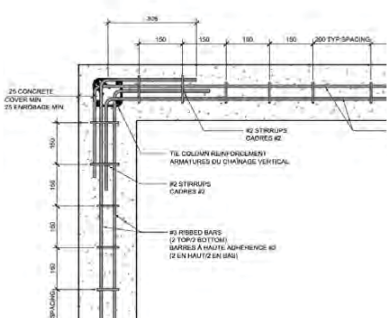
Date: March 23rd 2011

Date January 14th 2012

What Happened



What Could Have Happened
(system by Shelter2Home)



Methods

Materials

Craft / Skill / Education

RÈGLES DE DIMENSIONNEMENT ET DE CONSTRUCTION POUR LES LOGEMENTS EN MAÇONNERIE CHAÎNEE

Build Change, Programme d'Assistance Technique à la Reconstruction de Logements suite au Séisme à Haïti

Préparé pour

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31 Janvier 2011

Par

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1.0 RÈGLES DE DIMENSIONNEMENT ET DE CONSTRUCTION

Les règles suivantes devraient être suivies pour dimensionner et construire une maison en maçonnerie chaînée de plain-pied ou à un étage.

1.1 Matériaux et Qualité de la Construction

1.1.1 Blocs de Béton

La résistance au séisme d'une maison en maçonnerie chaînée dépend de la résistance à la compression et de la qualité des blocs de béton utilisés. Par conséquent, le tableau suivant devrait permettre d'identifier la résistance minimale des blocs de béton permettant d'atteindre le niveau de résistance au séisme souhaité. Une campagne d'essais (avec une taille d'échantillon suffisante) devrait être mise en place afin de s'assurer que les blocs atteignent la résistance à la compression souhaitée.

Maison de Plain-Pied avec Toiture Légère

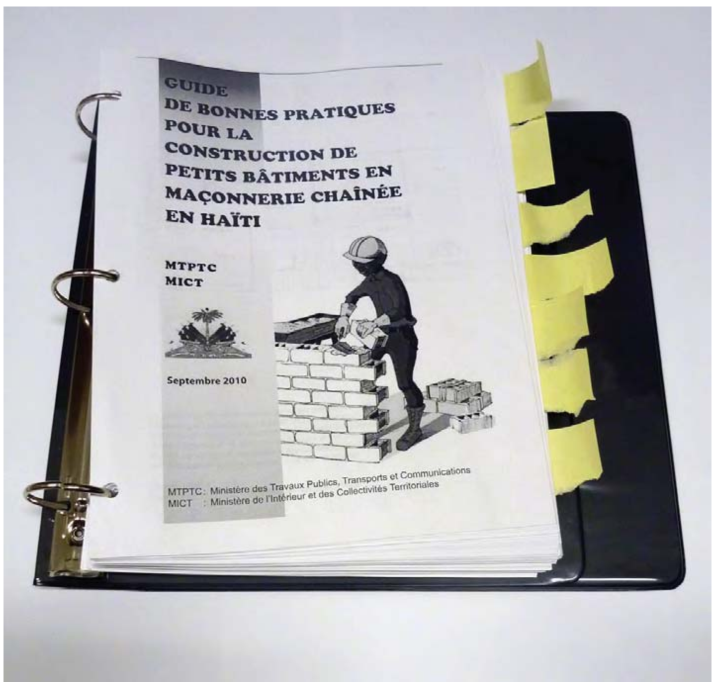
RÉSISTANCE DES BLOCS DE BÉTON	CRITÈRE DE DIMENSIONNEMENT AU SÉISME
4.8 MPa (700 psi) min	Autorisé dans toutes les zones (Sds = 1.05g à 1.67g)

Maison de Plain-Pied avec Toiture en Béton

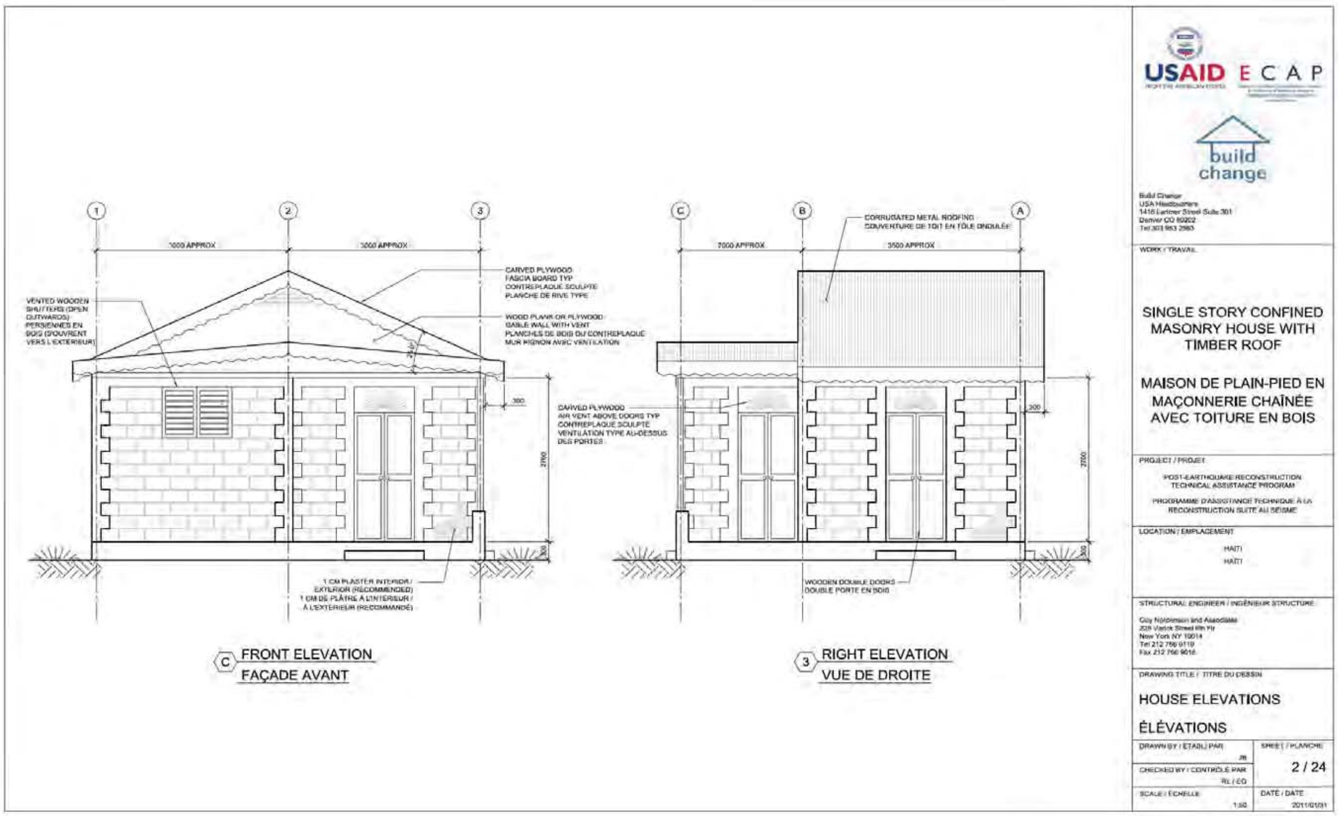
RÉSISTANCE DES BLOCS DE BÉTON	CRITÈRE DE DIMENSIONNEMENT AU SÉISME
4.8 MPa (700 psi)	Non Autorisé
6.9 MPa (1000 psi)	Autorisé dans les zones jaune et orange seulement (Sds = 1.05g)
11.7 MPa (1700 psi)	Autorisé partout (Sds = 1.67g)

Maison à un étage avec Toiture Légère ou en Béton

RÉSISTANCE DES BLOCS DE BÉTON	CRITÈRE DE DIMENSIONNEMENT AU SÉISME
4.8 MPa (700 psi)	Non Autorisé
6.9 MPa (1000 psi)	Autorisé dans les zones jaune et orange seulement (Sds = 1.05g)
11.7 MPa (1700 psi)	Autorisé partout (Sds = 1.67g)



Ministry of Public Works, Transportation and Communication: Publications


VENTED WOODEN SHUTTERS (OPEN OUTWARDS) PERSIENNES EN BOIS (S'OUVRENT VERS L'EXTERIEUR)
CARVED PLYWOOD FASCIA BOARD TYP CONTREPLAQUE SCULPTE PLANCHE DE RIVE TYPE
WOOD PLANK OR PLYWOOD GABLE WALL WITH VENT PLANCHES DE BOIS OU CONTREPLAQUE MUR PIGNON AVEC VENTILATION
CARVED PLYWOOD AIR VENT ABOVE DOORS TYP CONTREPLAQUE SCULPTÉ VENTILATION TYPE AU-DESSUS DES PORTES
1 CM PLASTER INTERIOR / EXTERIOR (RECOMMENDED) 1 CM DE PLÂTRE À L'INTÉRIEUR / À L'EXTÉRIEUR (RECOMMANDÉ)
FRONT ELEVATION
FAÇADE AVANT
CORRUGATED METAL ROOFING COUVERTURE DE TOIT EN TÔLE ONDULÉE
3500 APPROX
WOODEN DOUBLE DOORS DOUBLE PORTE EN BOIS
RIGHT ELEVATION
VUE DE DROITE
SINGLE STORY CONFINED MASONRY HOUSE WITH TIMBER ROOF
MAISON DE PLAIN-PIED EN MAÇONNERIE CHAÎNÉE AVEC TOITURE EN BOIS
PROJECT / PROJET
POST-EARTHQUAKE RECONSTRUCTION TECHNICAL ASSISTANCE PROGRAM
PROGRAMME D'ASSISTANCE TECHNIQUE À LA RECONSTRUCTION SUITE AU SÉISME
LOCATION / EMPLACEMENT
HAITI
HAITI
DRAWING TITLE / TITRE DU DESSIN
HOUSE ELEVATIONS
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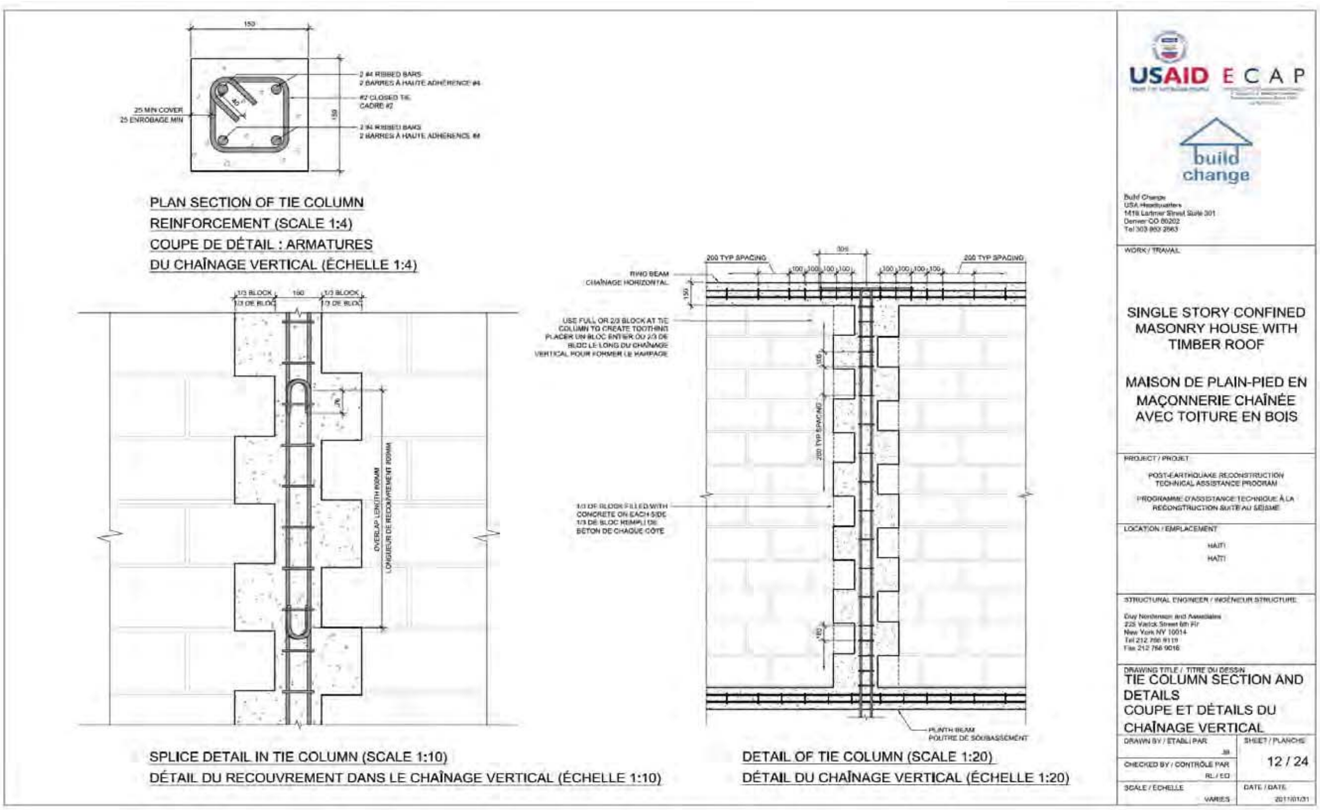
PLAN SECTION OF TIE COLUMN
REINFORCEMENT (SCALE 1:4)
COUPE DE DÉTAIL : ARMATURES
DU CHAÎNAGE VERTICAL (ÉCHELLE 1:4)
SPLICE DETAIL IN TIE COLUMN (SCALE 1:10)
DÉTAIL DU RECOUVREMENT DANS LE CHAÎNAGE VERTICAL (ÉCHELLE 1:10)
DETAIL OF TIE COLUMN (SCALE 1:20)
DÉTAIL DU CHAÎNAGE VERTICAL (ÉCHELLE 1:20)
USAID
E C A P
build
change
SINGLE STORY CONFINED
MASONRY HOUSE WITH
TIMBER ROOF
MAISON DE PLAIN-PIED EN
MAÇONNERIE CHAÎNÉE
AVEC TOITURE EN BOIS
TIE COLUMN SECTION AND
DETAILS
COUPE ET DÉTAILS DU
CHAÎNAGE VERTICAL
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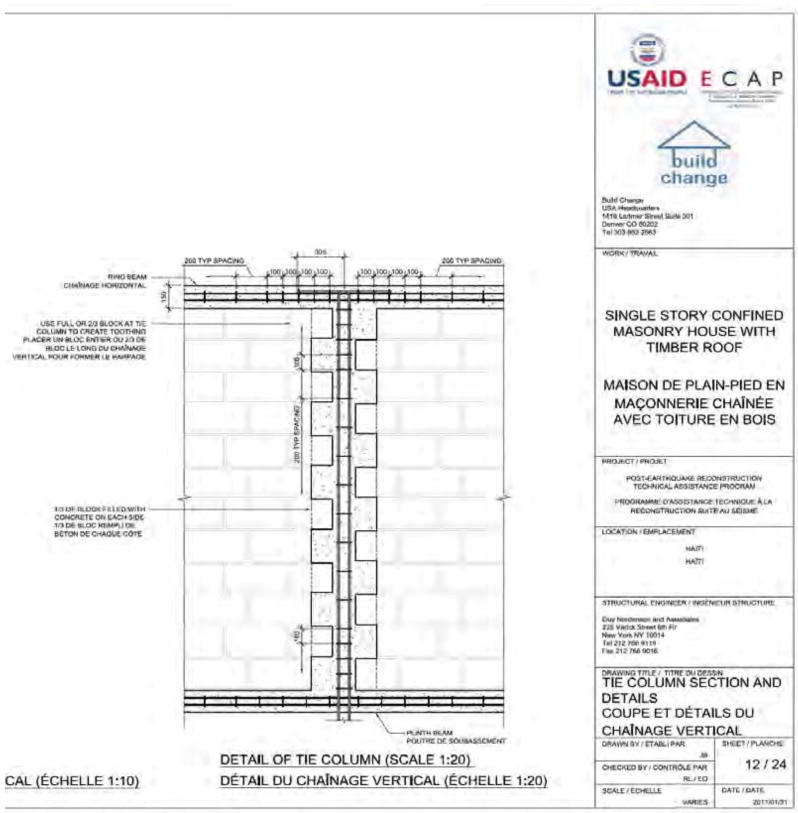

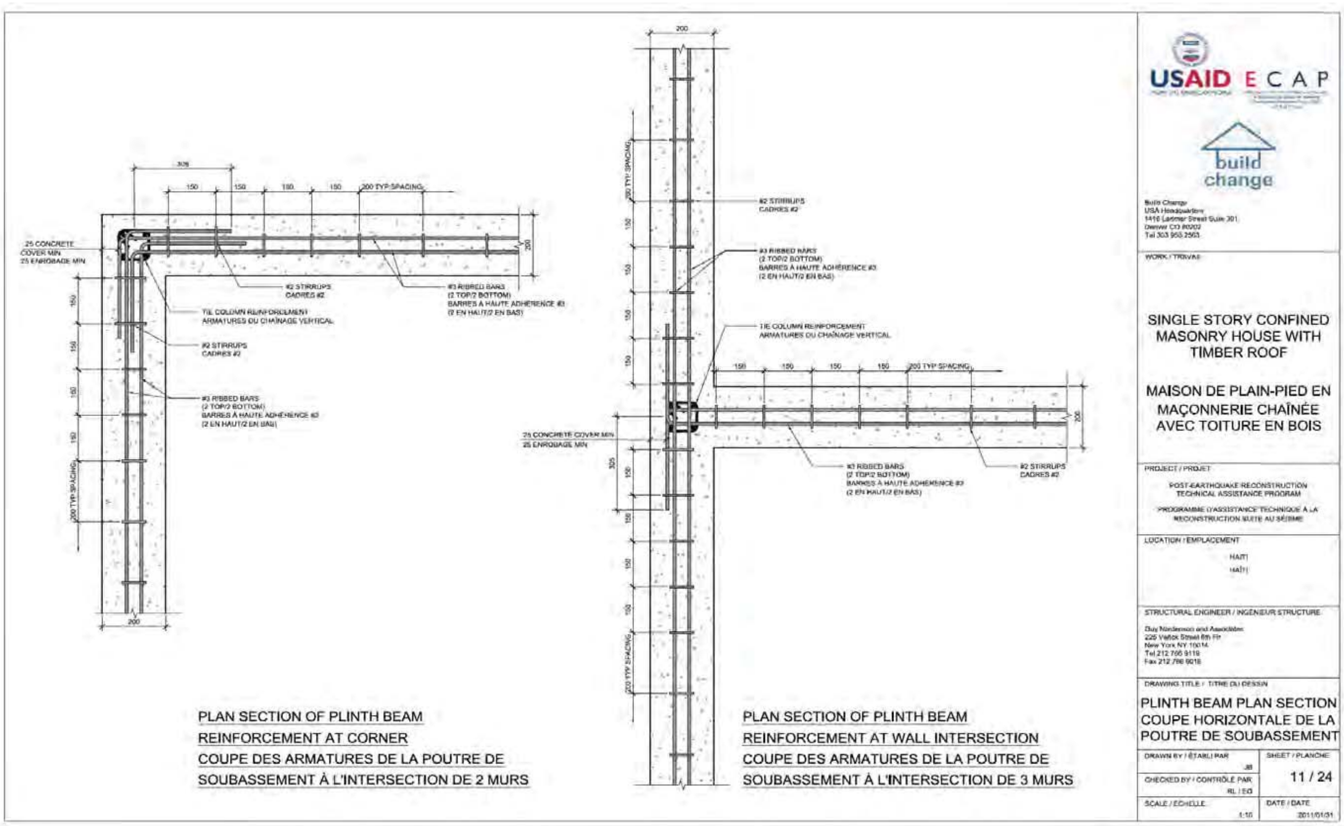
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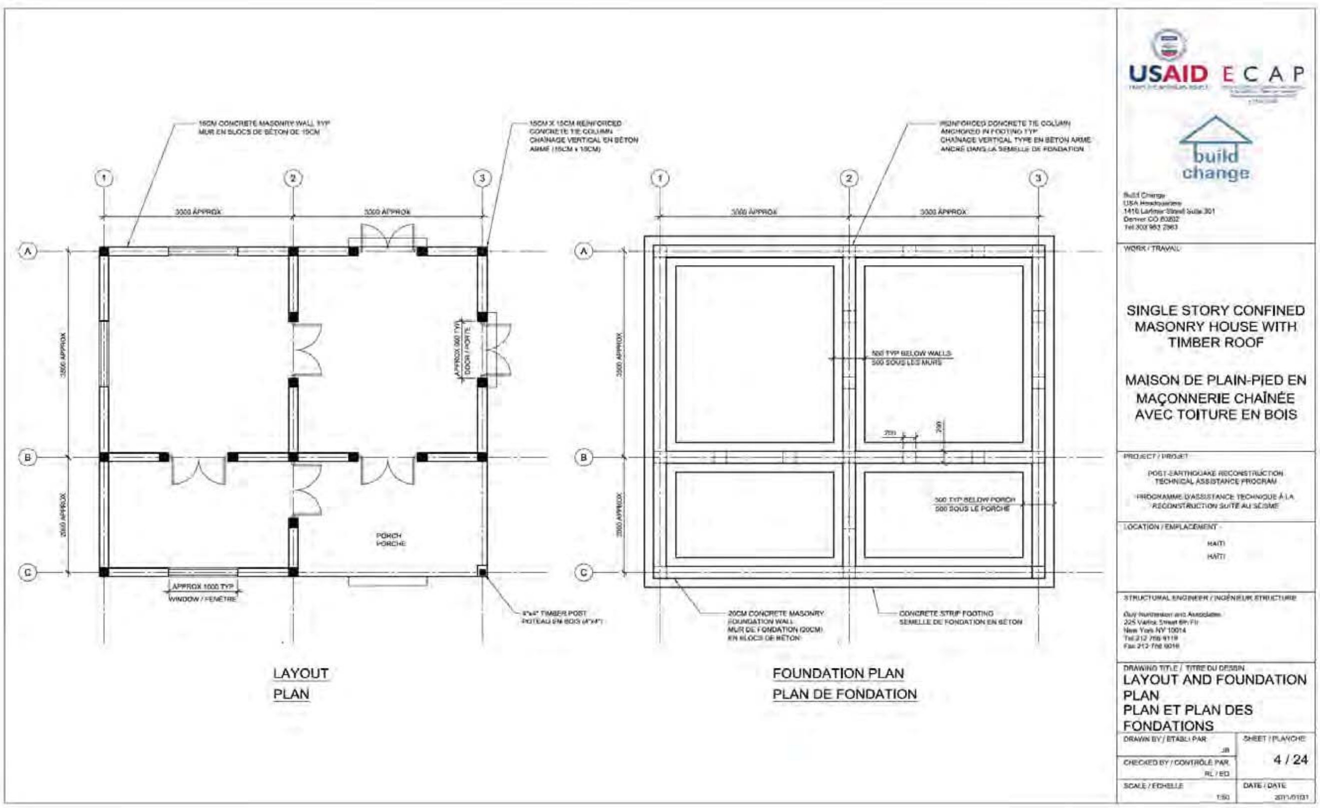
SINGLE STORY CONFINED MASONRY HOUSE WITH TIMBER ROOF
MAISON DE PLAIN-PIED EN MAÇONNERIE CHAÎNÉE AVEC TOITURE EN BOIS
PLINTH BEAM PLAN SECTION
COUPE HORIZONTALE DE LA POUTRE DE SOUBASSEMENT
11 / 24
PLAN SECTION OF PLINTH BEAM REINFORCEMENT AT CORNER
COUPE DES ARMATURES DE LA POUTRE DE SOUBASSEMENT À L'INTERSECTION DE 2 MURS
PLAN SECTION OF PLINTH BEAM REINFORCEMENT AT WALL INTERSECTION
COUPE DES ARMATURES DE LA POUTRE DE SOUBASSEMENT À L'INTERSECTION DE 3 MURS


LAYOUT
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FOUNDATION PLAN
PLAN DE FONDATION
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PORCHE
3000 APPROX
SINGLE STORY CONFINED MASONRY HOUSE WITH TIMBER ROOF
MAISON DE PLAIN-PIED EN MAÇONNERIE CHAÎNÉE AVEC TOITURE EN BOIS
WORK / TRAVAIL
PROJECT / PROJET
LOCATION / EMPLACEMENT
HAITI
STRUCTURAL ENGINEER / INGÉNIEUR STRUCTURE
DRAWING TITLE / TITRE DU DESSIN
LAYOUT AND FOUNDATION PLAN
PLAN ET PLAN DES FONDATIONS
DRAWN BY / ETABLI PAR
SHEET / PLANCHE
4 / 24
CHECKED BY / CONTRÔLE PAR
SCALE / ECHELLE
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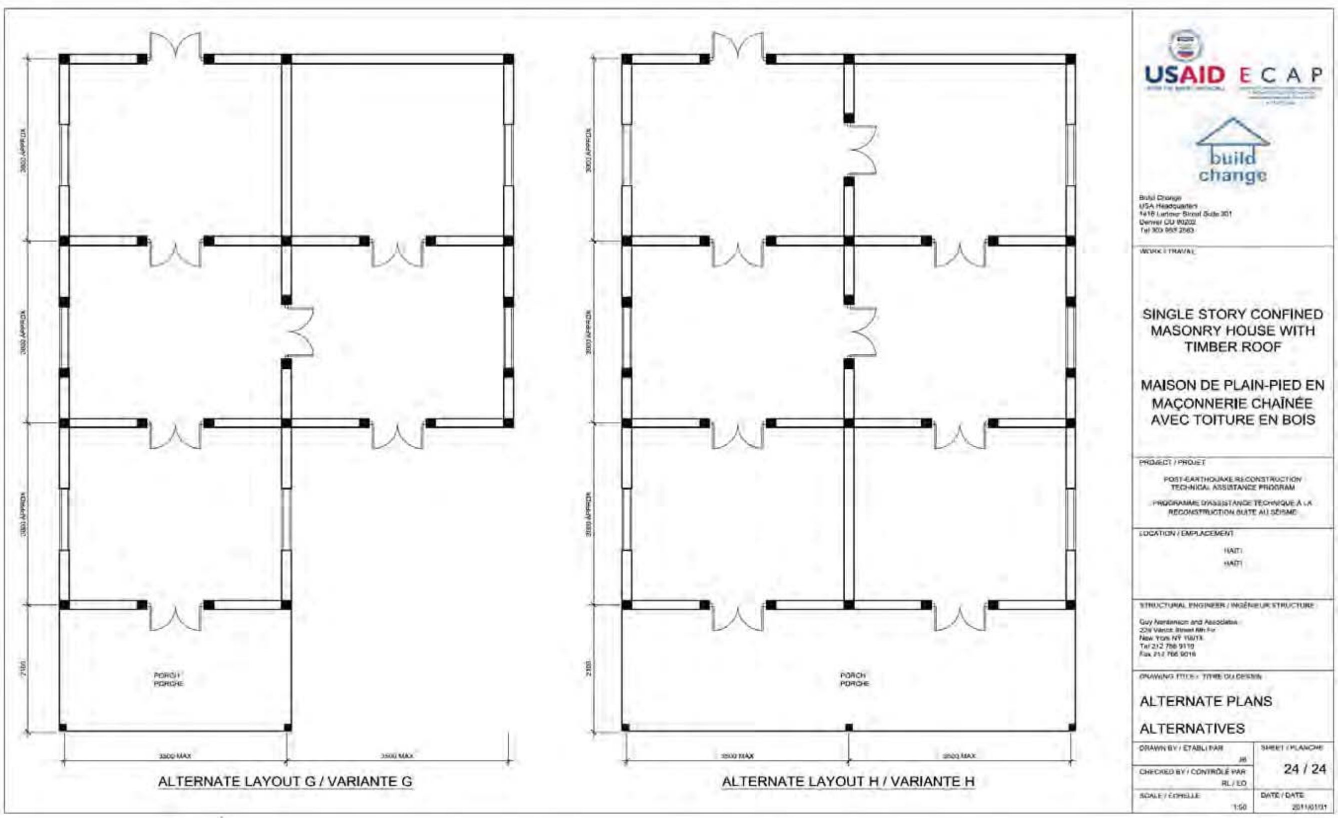
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SINGLE STORY CONFINED MASONRY HOUSE WITH TIMBER ROOF
MAISON DE PLAIN-PIED EN MAÇONNERIE CHAÎNÉE AVEC TOITURE EN BOIS
PROJECT / PROJET
POST-EARTHQUAKE RECONSTRUCTION TECHNICAL ASSISTANCE PROGRAM
PROGRAMME D'ASSISTANCE TECHNIQUE À LA RECONSTRUCTION SUITE AU SÉISME
LOCATION / EMPLACEMENT
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STRUCTURAL ENGINEER / INGÉNIEUR STRUCTURE
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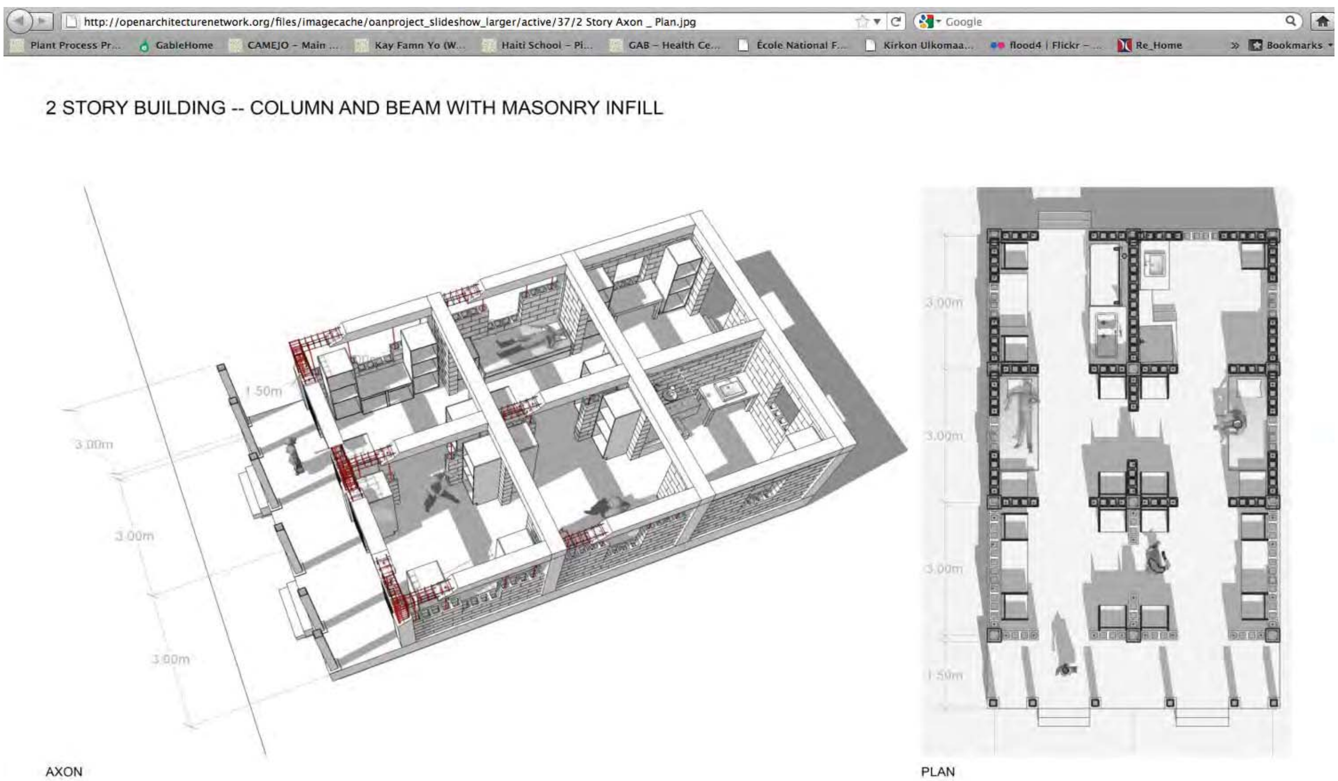

http://openarchitecturenetwork.org/files/imagecache/oanproject_slideshow_larger/active/37/2 Story Axon _ Plan.jpg
2 STORY BUILDING -- COLUMN AND BEAM WITH MASONRY INFILL
1.50m
3.00m
3.00m
3.00m
AXON
3.00m
3.00m
3.00m
1.50m
PLAN

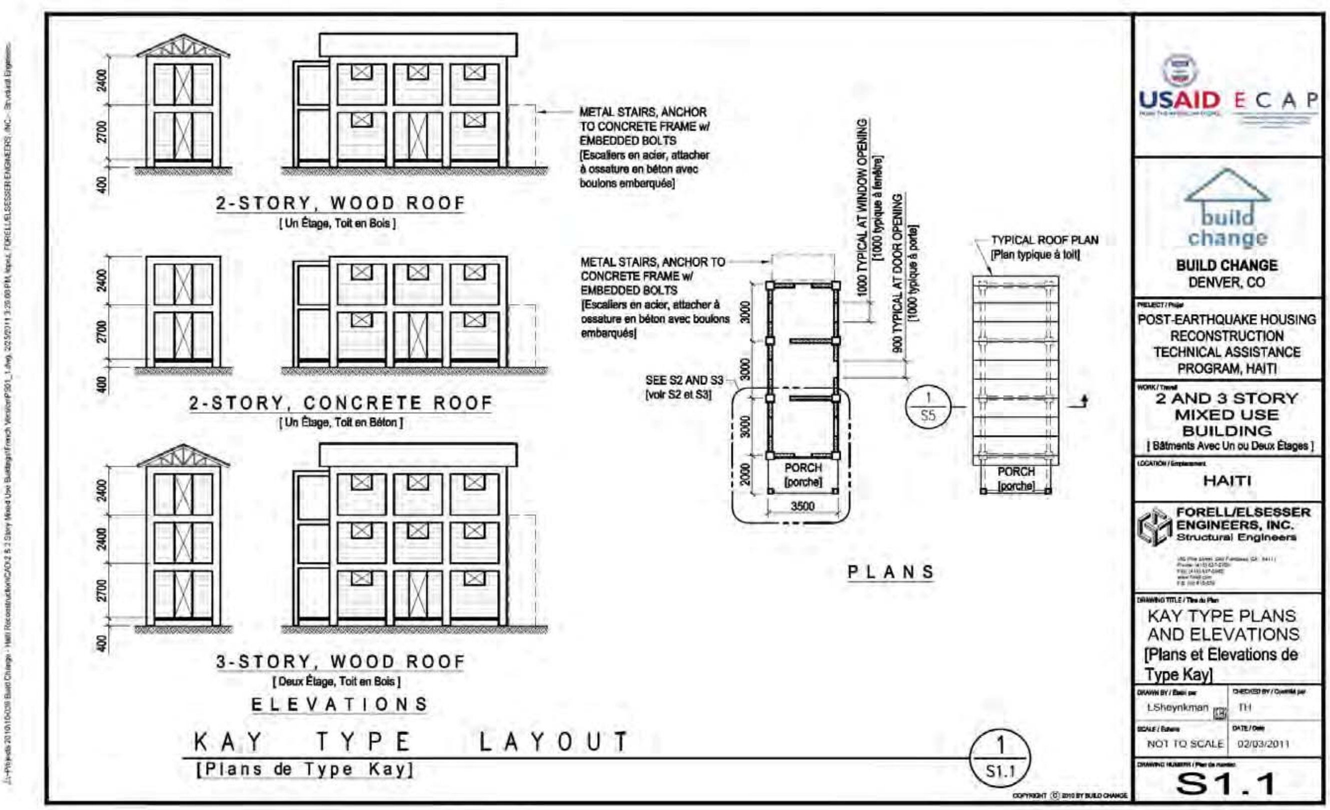
BUILD CHANGE
DENVER, CO

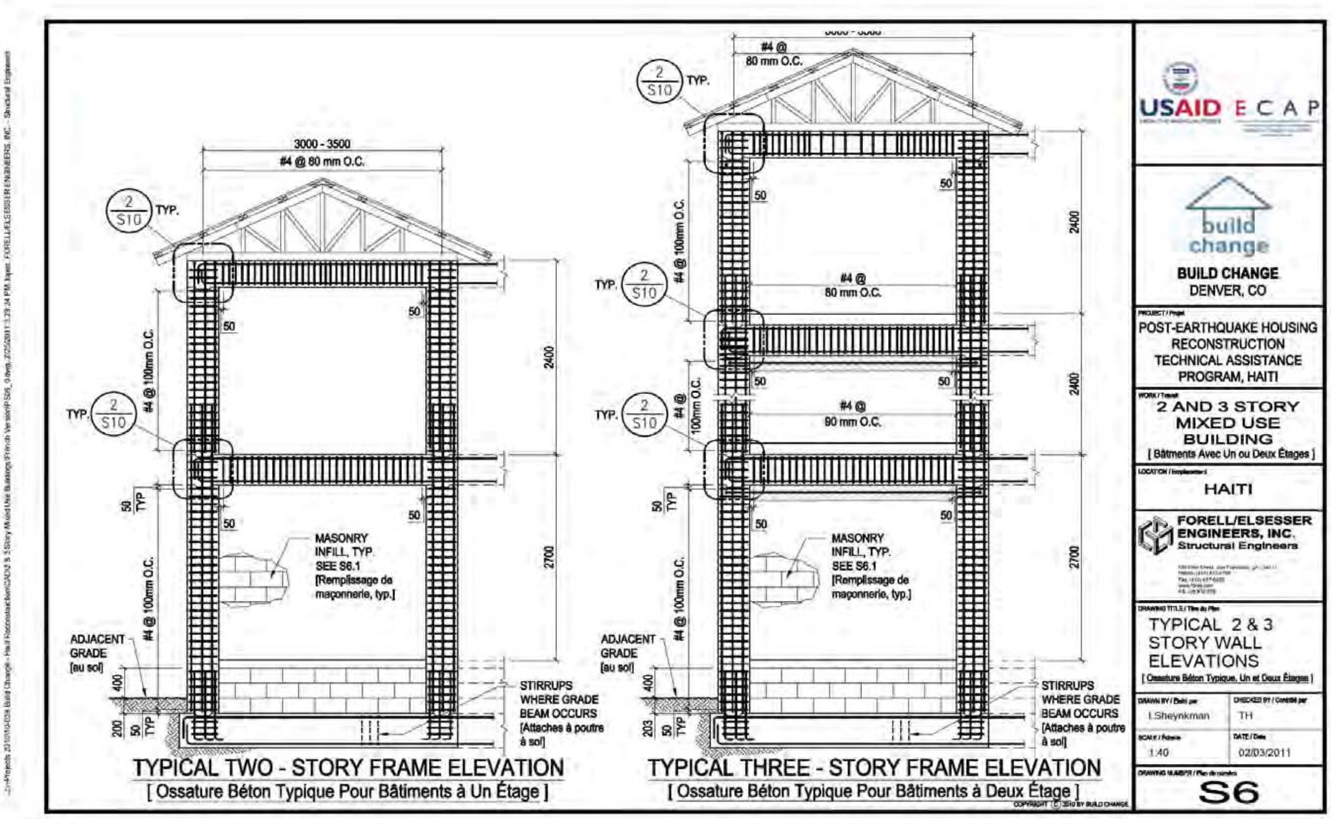
CONSTRUCTION DRAWINGS
[Plans de Construction]

2 AND 3 STORY MIXED USE BUILDINGS
[Bâtiments Avec Un Ou Deux Étages]

HAITI POST EARTHQUAKE HOUSING RECONSTRUCTION
TECHNICAL ASSISTANCE PROGRAM

[Program d'Assistance Technique à
la Reconstuction de Logements suite an Séisme à Haiti]


2-STORY, WOOD ROOF
[Un Étage, Toit en Bois]
2-STORY, CONCRETE ROOF
[Un Étage, Toit en Béton]
3-STORY, WOOD ROOF
[Deux Étage, Toit en Bois]
ELEVATIONS
METAL STAIRS, ANCHOR TO CONCRETE FRAME w/ EMBEDDED BOLTS
[Escaliers en acier, attacher à ossature en béton avec boulons emberqués]
SEE S2 AND S3
[voir S2 et S3]
1000 TYPICAL AT WINDOW OPENING
[1000 typique à fenêtre]
900 TYPICAL AT DOOR OPENING
[1000 typique à porte]
TYPICAL ROOF PLAN
[Plan typique à toit]
PORCH
[porche]
3500
PLANS
KAY TYPE LAYOUT
[Plans de Type Kay]
USAID ECAP
build change
BUILD CHANGE
DENVER, CO
POST-EARTHQUAKE HOUSING RECONSTRUCTION TECHNICAL ASSISTANCE PROGRAM, HAITI
2 AND 3 STORY MIXED USE BUILDING
[Bâtments Avec Un ou Deux Étages]
HAITI
FORELL/ELSESSER ENGINEERS, INC.
Structural Engineers
KAY TYPE PLANS AND ELEVATIONS
[Plans et Elevations de Type Kay]
LSheynkman
TH
NOT TO SCALE
02/03/2011
S1.1


TYPICAL TWO - STORY FRAME ELEVATION
[Ossature Béton Typique Pour Bâtiments à Un Étage]
TYPICAL THREE - STORY FRAME ELEVATION
[Ossature Béton Typique Pour Bâtiments à Deux Étage]
MASONRY INFILL, TYP. SEE S6.1 [Remplissage de maçonnerie, typ.]
STIRRUPS WHERE GRADE BEAM OCCURS [Attaches à poutre à sol]
ADJACENT GRADE [au sol]
3000 - 3500
#4 @ 80 mm O.C.
#4 @ 100mm O.C.
USAID ECAP
build change
BUILD CHANGE
DENVER, CO
POST-EARTHQUAKE HOUSING RECONSTRUCTION TECHNICAL ASSISTANCE PROGRAM, HAITI
2 AND 3 STORY MIXED USE BUILDING
[Bâtiments Avec Un ou Deux Étages]
HAITI
FORELL/ELSESSER ENGINEERS, INC.
Structural Engineers
TYPICAL 2 & 3 STORY WALL ELEVATIONS
I.Sheynkman
TH
1:40
02/03/2011
S6

CONCRETE BEAM SCHEDULES

[Tableau de Poutre Beton]

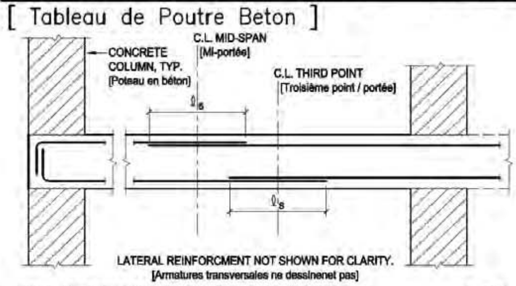
CONCRETE BEAM SCHEDULE ZONE B
[Tableau de Poutre Beton – Zone B]

BEAM MARK [numéro de poutre]	LEVEL [niveau]	B = D	LONG. REINFORCING [armatures longitudinales] TOP [haut]	BOTT. [bas]	LATERAL REINF. [armatures transversales]	REMARKS [notes]
B1	GRADE [sol]	300	2 – #5	2 – #5	#3 @ 250mm O.C.	[voir] SEE 2/– & 4/–
	2	250	2 – #5	2 – #5	#3 @ 150mm O.C.	[voir] SEE 4/–
	3	250	2 – #5	2 – #5	#3 @ 150mm O.C.	[voir] SEE 4/–
	ROOF [toit]	250	2 – #5	2 – #5	#3 @ 150mm O.C.	[voir] SEE 4/–
B2	GRADE [sol]	400	2 – #6	2 – #6	#3 @ 250mm O.C.	[voir] SEE 2/– & 4/–
	2	350	2 – #6	2 – #6	SEE S6 [voir S6]	[voir] SEE 4/–
	3	300	2 – #6	2 – #6	SEE S6 [voir S6]	[voir] SEE 4/–
	ROOF [toit]	300	2 – #6	2 – #6	SEE S6 [voir S6]	[voir] SEE 4/–

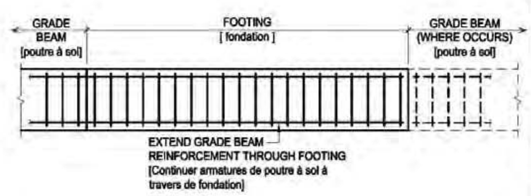
CONCRETE BEAM SCHEDULE ZONE C
[Tableau de Poutre Beton – Zone C]

BEAM MARK [numéro de poutre]	LEVEL [niveau]	B = D	LONG. REINFORCING [armatures longitudinales] TOP [haut]	BOTT. [bas]	LATERAL REINF. [armatures transversales]	REMARKS [notes]
B1	GRADE [sol]	300	2 – #5	2 – #5	#3 @ 250mm O.C.	[voir] SEE 2/– & 4/–
	2	250	2 – #5	2 – #5	#3 @ 150mm O.C.	[voir] SEE 4/–
	3	250	2 – #5	2 – #5	#3 @ 150mm O.C.	[voir] SEE 4/–
	ROOF [toit]	250	2 – #5	2 – #5	#3 @ 150mm O.C.	[voir] SEE 4/–
B2	GRADE [sol]	450	3 – #5	3 – #5	#3 @ 250mm O.C.	[voir] SEE 2/– & 4/–
	2	400	2 – #6	2 – #6	SEE S6 [voir S6]	[voir] SEE 4/–
	3	350	2 – #6	2 – #6	SEE S6 [voir S6]	[voir] SEE 4/–
	ROOF [toit]	300	2 – #6	2 – #6	SEE S6 [voir S6]	[voir] SEE 4/–

1/S8



BEAM REINFORCING DIAGRAM 4/S8
1:20 [Armatures à Poutre]



TYP. GRADE BEAM/FOOTING INTERSECTION 2/S8
1:20 [Détail à Carrefour de Poutre à Sol et Fondation]

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PROJECT / Projet
POST-EARTHQUAKE HOUSING RECONSTRUCTION TECHNICAL ASSISTANCE PROGRAM, HAITI

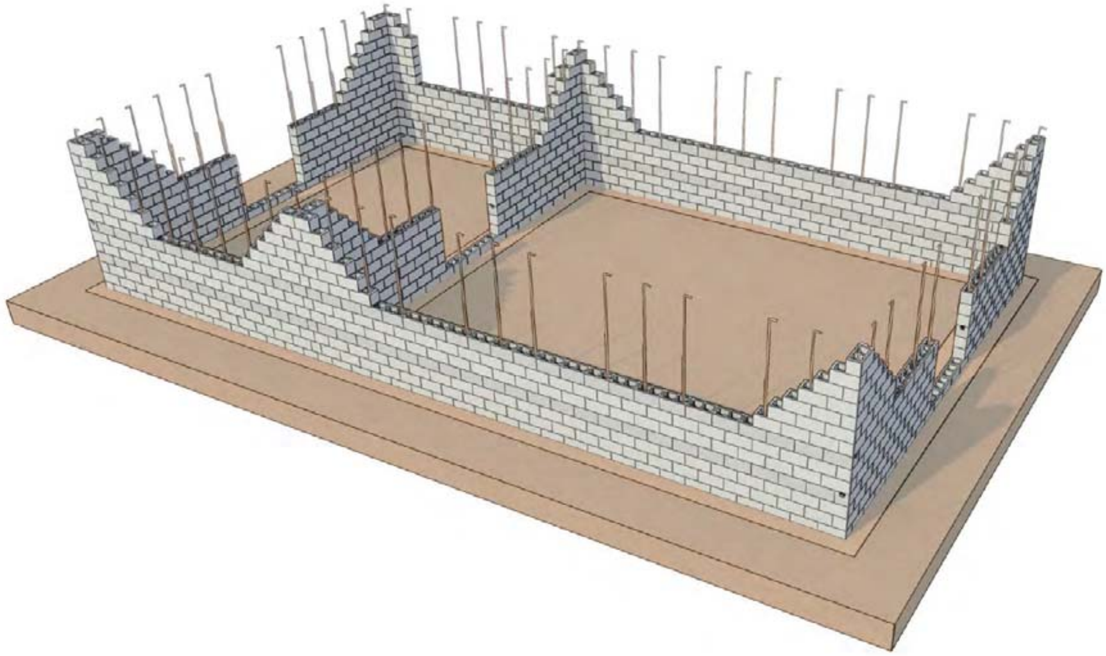
WORK / Travail
2 AND 3 STORY MIXED USE BUILDING
[Bâtments Avec Un ou Deux Étages]

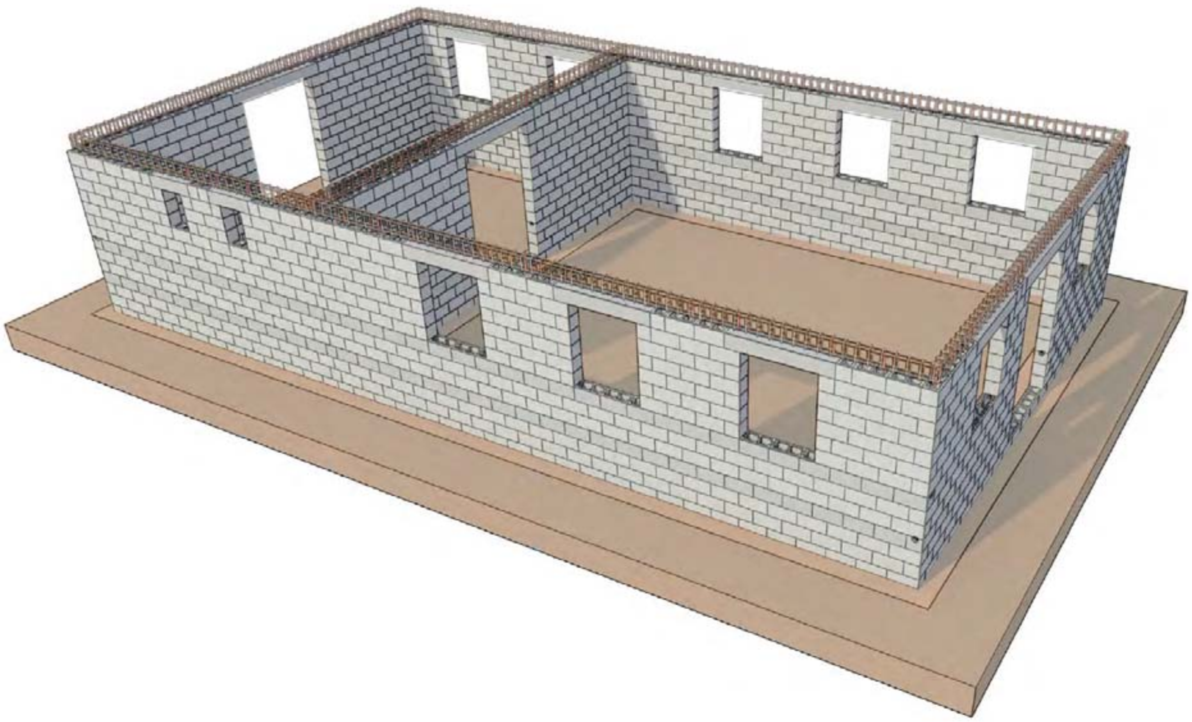
LOCATION / Emplacement
HAITI

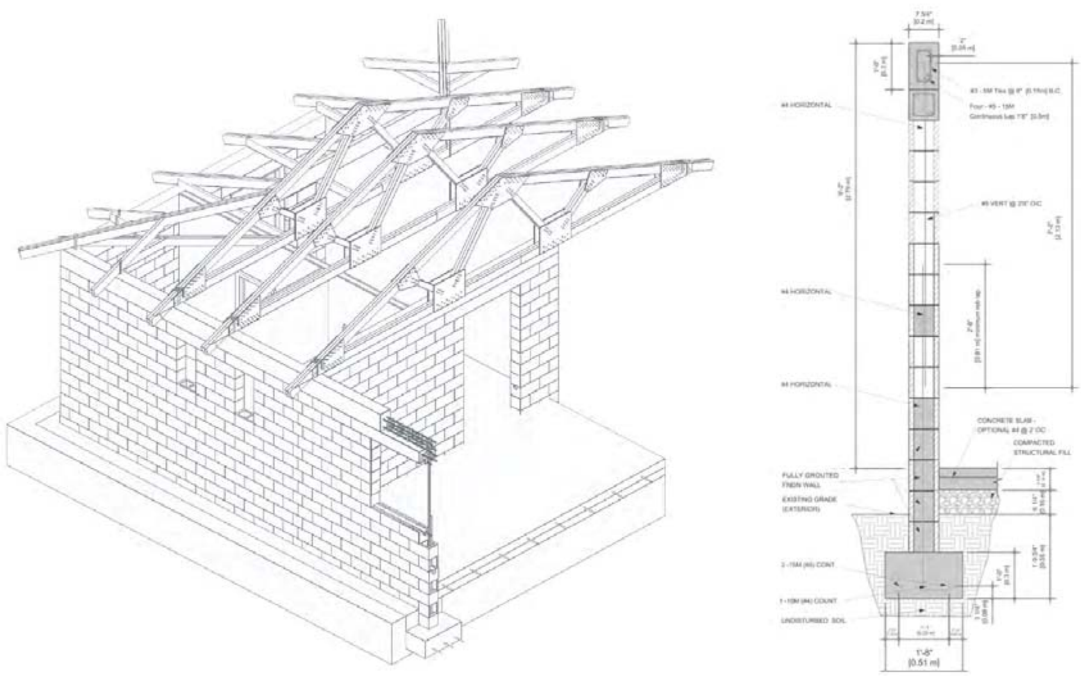
FORELL/ELSESSER ENGINEERS, INC.
Structural Engineers

DRAWING TITLE / Titre de Plan
SCHEDULES
[Tableaux]

DRAWN BY / Établi par: I.Sheynkman
CHECKED BY / Contrôlé par: TH
SCALE / Échelle
DATE / Date: 02/03/2011
DRAWING NUMBER / Plan de numéro
S8





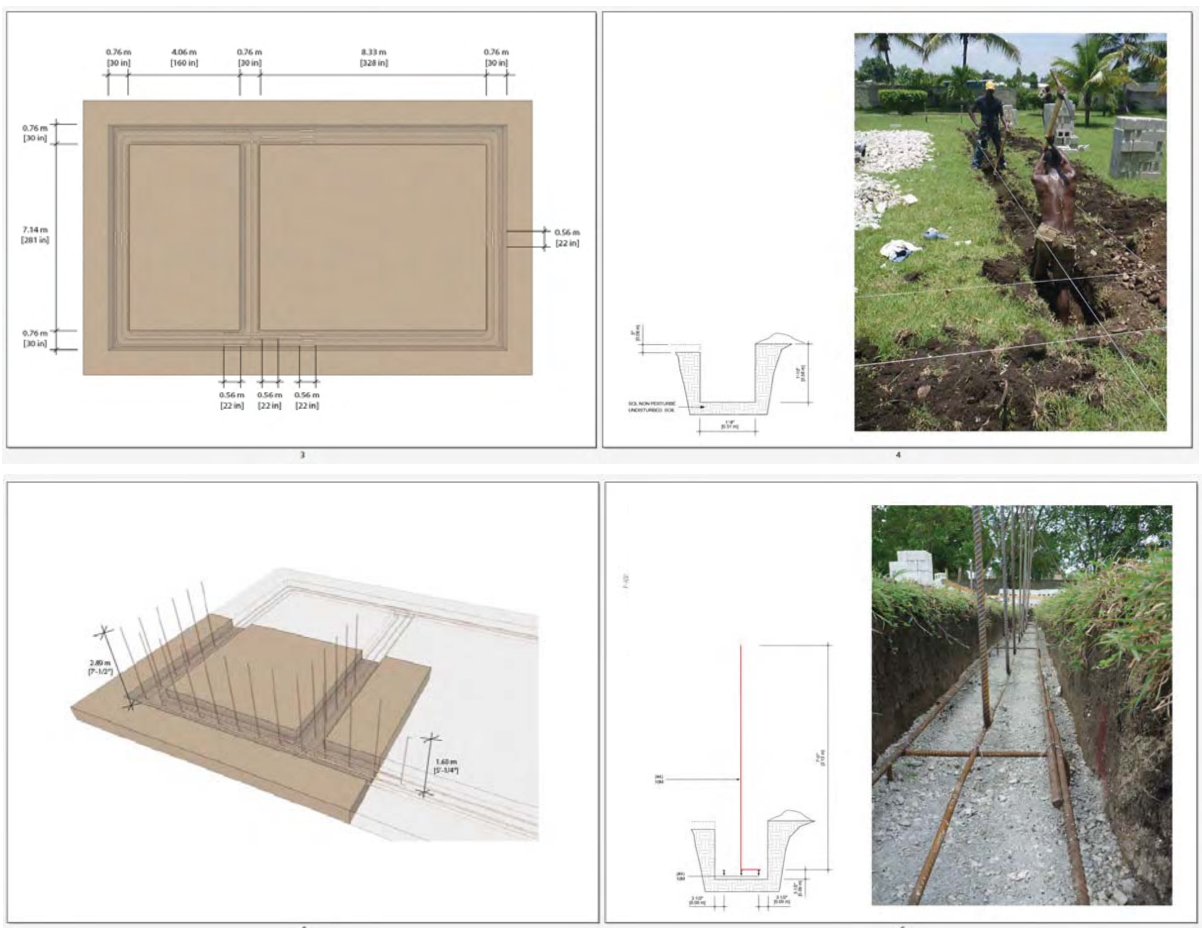


Principles of Reinforced Masonry Construction

"Kay Fanm Yo" - Women's House: Construction Manual

Léogâne, Haiti

by Mark Taylor and Shengxi Wu


0.76 m
[30 in]
4.06 m
[160 in]
0.76 m
[30 in]
8.33 m
[328 in]
0.76 m
[30 in]
0.76 m
[30 in]
7.14 m
[281 in]
0.76 m
[30 in]
0.56 m
[22 in]
0.56 m
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0.56 m
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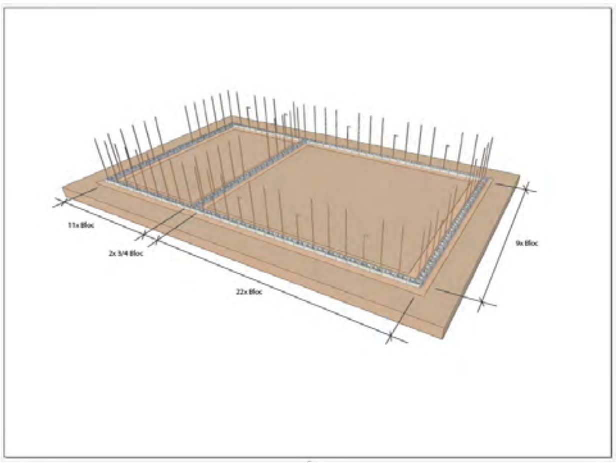
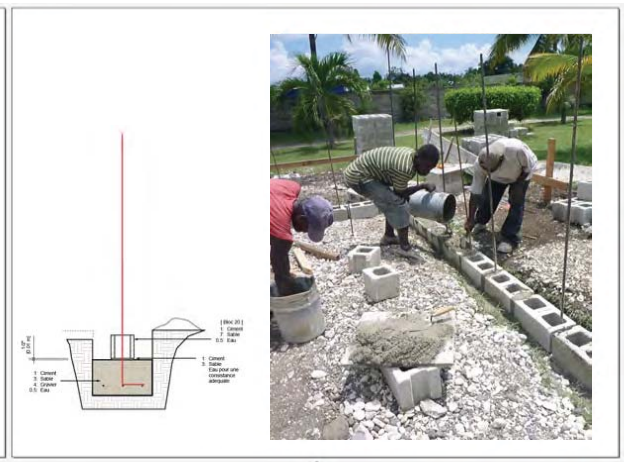
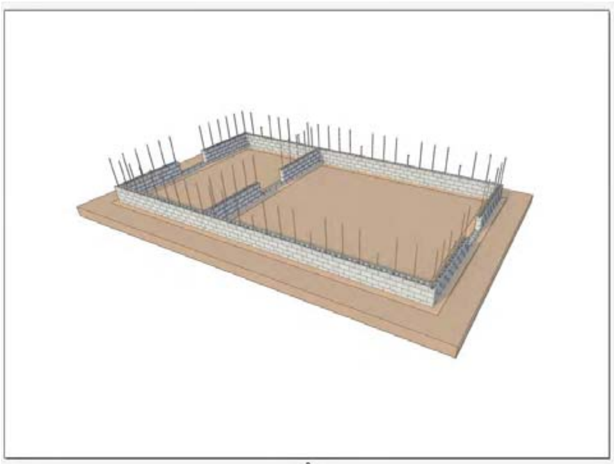
3
4
5
6







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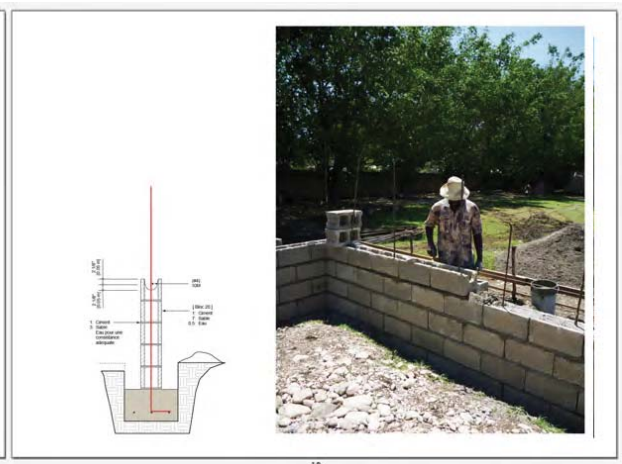

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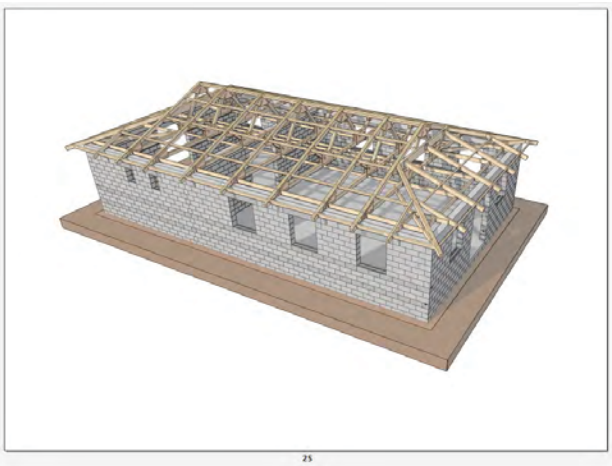
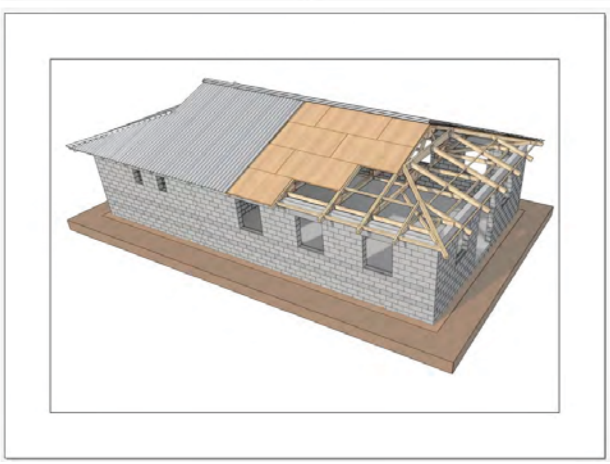





LEOMAT CONSTRUCTION S.A
2E COMPAGNIE
FABRICATION : 2 A 3 JOURS
ACHAT : 10/05/12
A & J
ACHAT
10/05/2012
1 Semaine
LEOGANE

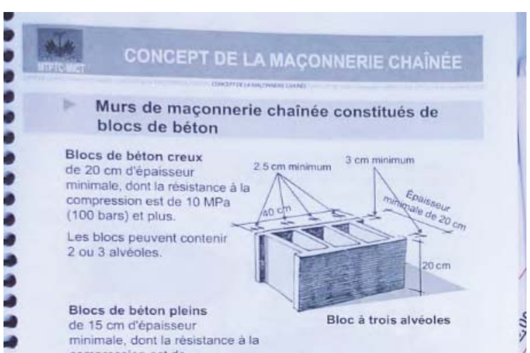
Producer 1
700 blocks a day

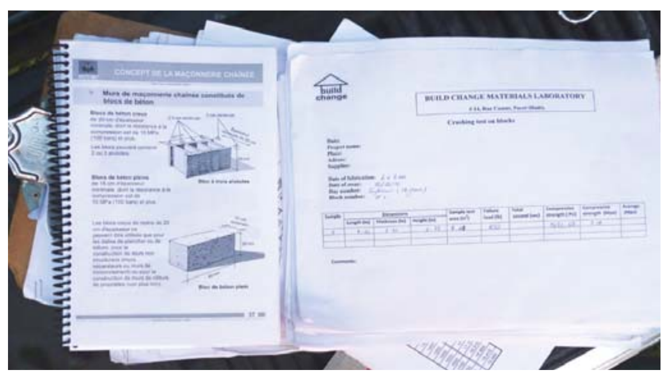
Producer 2
3,000 blocks a day

Producer 3
4,000 blocks a day

Data Collected
May - June 2012

Block Manufacturer	Block Type/s	Blocks Qty. Per 1 Bag of Cement	Price for block 15m	Days Cured Before Sale	Blocks Vibrated	Claimed Mpa	Cured in Shade	Watered During Curing	Additional Notes	Test Result (MPA)	Average Strength (Mpa)	Average Strength (psi)
Producer 1	All Types 30,20,15,12,10cm	45-48	N/A	2	Yes	10.5	No - but would like to	Yes	Invested in 2 new machines from Dominion Republic after the earthquake	7.80 7.04 5.53	6.79	984.81
Producer 2	2-hole 15cm block tested. Availability of other types tbc.	38	24.5 HTG (0.58 USD)	22	Yes	10.5	Yes - under tarps.	Yes	Mechanized production. Owner trained in production tech. in Germany	6.29 6.29 7.04	6.54	948.55
Producer 3	3-hole 15cm block only	50	19 HTG (0.45 USD)	2	Yes	N/A	No	No	Most common type of medium sized production machine and techniques	6.40 5.71 5.81	5.97	865.88
Producer 4	All Types 30,20,15,12,10cm	45	19 HTG (0.45 USD)	3	Yes	10.5	Some Batches - Not All	Yes	3 of the most common type of medium sized production machine on large site	4.61 5.24 5.24	5.03	729.53





Génie Structures d'Ayiti

12, rue Rebecca, Pétion-ville, Haïti
+509 31 14 55 36

Photos:

Fig. 1 Couleur du sable

Fig. 2 Type de ciment

Fig. 3 Couleur Verdâtre de l'eau

Fig. 4 Couche de graisse à la surface

Fig. 5 Versement du sable dans la machine

Fig. 6. Versement du ciment

Fig. 7 Versement de l'eau

Fig. 8 Sortie de la machine à mélanger

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Fig. 9 La machine à bloc

Fig. 10 Mis en place de la plaquette

Fig. 11 Table roulante

Fig. 12 L'ouvrier qui place les blocs

Fig. 13 Arrosage des blocs après 30 minutes

Fig. 14 Enlevage des plaquettes


10 28 2010
SHELTER 2 HOME
SHELTER 2 HOME
SHELTER 2 HOME
SHELTER 2 HOME


SHELTER 2 HOME
SHELTER 2 HOME
HAITI


SHELTER 2 HOME
SHELTER 2 HOME
HAITI


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3
4
2
A

Haiti Wood-Framed Housing Initiative

G. R. Boone, PE[1] and J. D. Kiehl, AIA, NCARB[2]

[1]Weyerhaeuser, 444 Myer Terrace, Leola, PA 17540;
PH (717) 413-1832; email: glyn.boone@weyerhaeuser.com
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PH (610) 373-6667; email: jkiehl@entecheng.com

ABSTRACT

The January 2010 earthquake near Port-au-Prince, Haiti was devastating to the nation. The scale of the disaster led many individuals and companies in the housing industry to lend aid in the recovery and rebuilding effort as well as to seek ways to improve the integrity of structures long-term. Forest products company Weyerhaeuser provided an immediate donation of building materials for temporary housing, and committed to introduce safer products for the long-term rebuilding of Haiti. This paper describes these efforts, the results accomplished, and the lessons learned.

THE TRAGEDY AND A COMMITMENT TO HELP

A 7.0 magnitude earthquake occurred about 15 miles west of Port-au-Prince, Haiti the afternoon of January 12, 2010. While estimates vary, most believe the disaster resulted in over 200,000 deaths, 300,000 homes destroyed, and over 1 million people living in tent cities. Poor construction quality and the lack of a building code resulted in widespread structural failures in and around Port-au-Prince. Inadequately reinforced masonry and concrete construction resulted in catastrophic structural collapse of a wide range of buildings.

On January 28, 2010, Weyerhaeuser made a $250,000 commitment to aid in the rebuilding of Haiti in the form of both donated building materials and technical expertise to help rebuild safer structures, properly designed for both wind and seismic loads appropriate for Haiti. While long-term rebuilding needed to take place, the more urgent need was to provide emergency and transitional shelters. Weyerhaeuser dedicated approximately half of the funds to providing building materials to be used by two organizations active in these phases of the recovery in the months after the earthquake.

TRANSITIONAL SHELTERS

Habitat for Humanity International used 161,000 board foot (BF) of framing lumber in the construction of 300 shelters in the Léogâne and Cabaret areas outside of Port-au-Prince. While not designed to resist the full wind and seismic forces that the area may experience, these structures (Figure 1) were intended to provide basic shelter as the 2010 hurricane season was approaching.


Figure 1. Habitat for Humanity transitional shelters.

The second organization with which Weyerhaeuser partnered was a Chilean-based Non-Government Organization (NGO) called Un Techno Para mi Pais (UTPMP). Weyerhaeuser provided plywood to support their construction of 150 transitional shelters (Figure 2) for over 600 people in the Canaán tent city about 5 miles north of Port-au-Prince in July 2010.

Figure 2. UTPMP transitional shelter.

PERMANENT HOUSING PHASE

Once the transitional shelter phase was complete, Weyerhaeuser began the second phase of its commitment. It is at this point that the authors took an active role in the project. It was also important to select an in-country partner to provide logistics support, a local connection and "owner" input into the design of the homes.

After exploring numerous options, we partnered with Nehemiah Vision Ministries (NVM) (www.nehemiahvisionministries.org). NVM works in the communities surrounding Chambrun, about 15 miles northeast of Port-au-Prince. They began in 1995, serving about 30,000 residents in small rural villages. After the earthquake, the population in this same geographic area grew to over 500,000 people as a result of the mass movement of people out of Port-au-Prince.

Our initial desire was to select a few Haitian families to receive the homes that we designed and supplied. In working with NVM, we soon realized that asking them to select the few families out of the thousands that they have contact with to receive these homes would be like asking them to select a lottery winner. This process would do more harm than good for NVM and the community. Instead, we chose to design and build five homes to be used by Haitian and international staff and volunteers to support NVM's work in the community. This approach ensured the homes met a real need, helped those who were helping others, and would still provide valuable experience and feedback to Weyerhaeuser and the wood industry.

ARCHITECTURAL DESIGN

Two home designs were prepared. The *Medical Staff House* (Figure 3 and 4) was intended to be used by expatriate staff or volunteers serving for extended duration in the hospital on the NVM campus. These 1,100 square foot (SF) homes would feature three bedrooms, 1½ baths, a kitchen, laundry room, living area and a small porch. Having plumbing, a full kitchen and bath, and air conditioning, these homes would be somewhat consistent with a low-end US style housing. Two of these homes are planned.

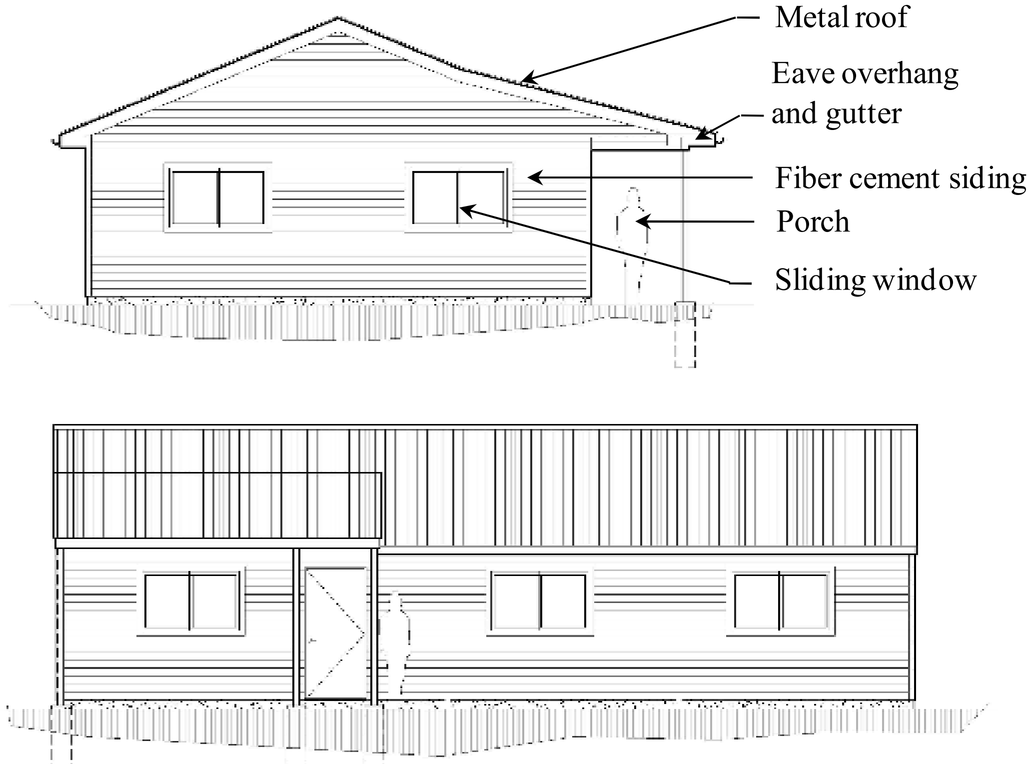

Figure 3. Medical Staff House elevations.

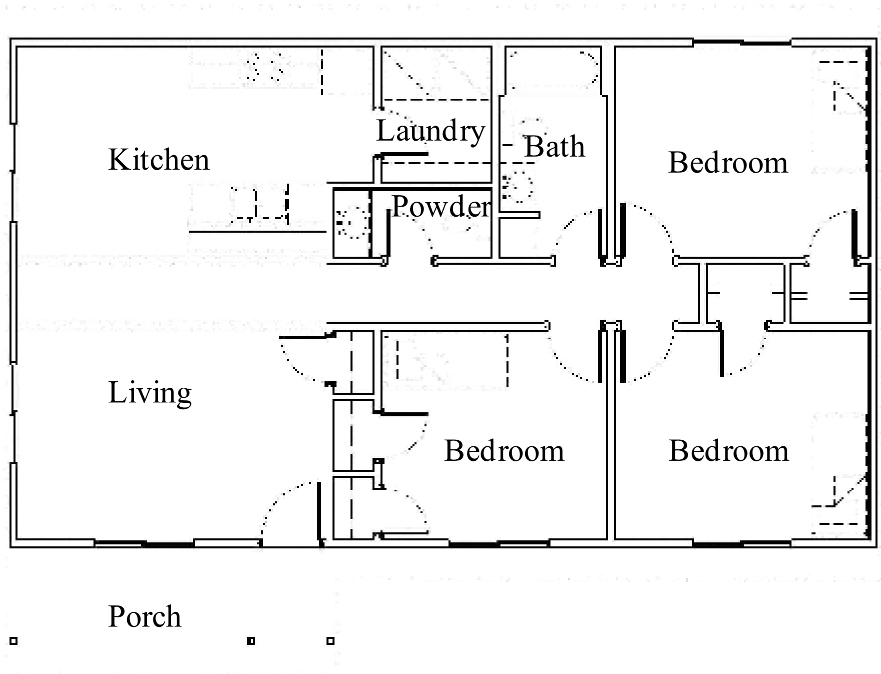

Figure 4. Medical Staff House floor plan.

The *Intern House* (Figures 5 and 6), of which there are 3 planned, was designed more in line with the needs of a typical Haitian family. At less than 500 SF in size, these homes would have two small bedrooms and a central living area. There would be no kitchen or plumbing. Instead, a full length porch (180 SF) would provide a shaded outdoor living area where cooking would also take place. Community lavatory facilities would be used rather than individual bathrooms. These homes were also designed with large windows centered across from each other on either side of the building to allow natural cross ventilation. While most homes would not have electricity or air conditioning, these particular homes were upgraded to include electricity, insulation, moisture control, and air conditioning.

Another consideration of the design was the depth of the roof overhangs. In climates subject to both heavy rainfall and sun, overhangs can perform the dual purpose of providing shade to the building and shielding the walls from wind driven water. Large overhangs, however, can complicate structural considerations in designing for uplift forces. Therefore, moderate eave overhangs were provided to direct water away from the walls while shading the majority of the windows. Overhangs were minimized on the gables which had fewer openings and less exposure to roof run-off.

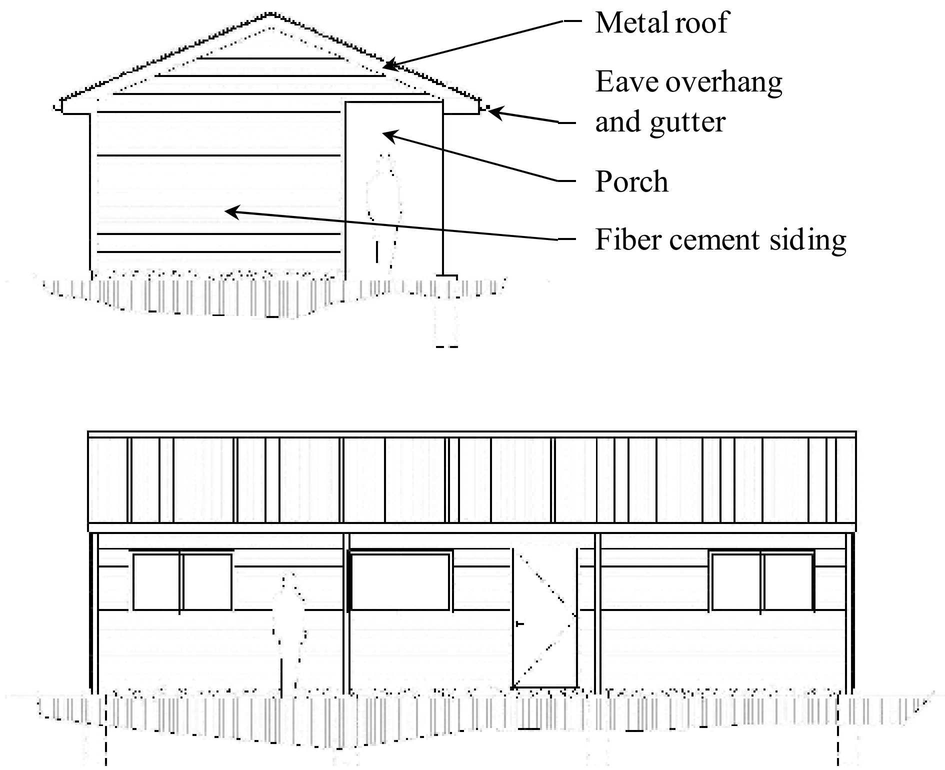

Figure 5. Intern House elevations.

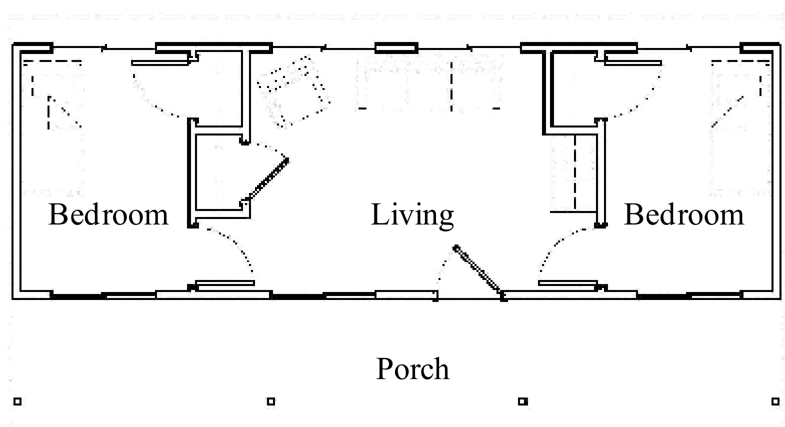

Figure 6. Intern House floor plan.

ENVIRONMENTAL PROTECTION

In addition to structural forces, the design of a permanent wood-framed structure in Haiti must provide for protection from termites. It is inappropriate to assume active protection via inspection and pest control measures, so passive protection of wood products to at least 6 feet above grade was implemented. Sill plates and wall studs were pressure-treated with 0.14 pcf of dispersed Copper Azole, Type C. The TJ®-Shear Brace was made with zinc borate additive in the TimberStrand® LSL. FrameGuard® treatment was applied to the plywood & T1-11 paneling.

Because the structures would be insulated and air conditioned, there existed the chance that a dew point would be present in the wall between the conditioned interior space and the warm moist exterior air. To prevent condensation in the wall envelope, an exterior vapor barrier was achieved by the use of taped Styrofoam SIS™ Brand Structural Insulated Sheathing (SIS) panels on walls and ceiling. For non-insulated and non-conditioned buildings where the potential for a dew point is minimized, this vapor barrier will be less critical. Emphasis on protection from liquid water will remain important. HardiePlank® cement board siding and trim was used to provide increased UV resistance, and higher strength and durability. It also will provide inherent moisture and insect resistance.

STRUCTURAL DESIGN

Space does not allow a presentation of the full design steps associated with these structures. However, some portions of this analysis are presented here to highlight the key structural approaches and construction details. The primary design consideration was wind design based on a 150 mph wind speed (3 second gust). The zone D2 seismic loading did not control the design given the lightweight wood framing of these single-story structures. With an importance factor of 1.00, exposure C, 8′ eave height, and 5/12 roof pitch, the resulting design pressures are summarized in Tables 1 and 2.

Table 1. Main Wind Force Resisting System (MWFRS) Wind Pressures. (psf)

Location		Zone	
		Interior	**End/Edge**
1	Windward wall	14.9	24.6
2	Windward roof	-26.4	-37.4
3	Leeward roof	-26.9	-34.5
4	Leeward wall	-24.7	-32.4
5 & 6	Endwalls	-26.2	N.A.

Table 2. Components and Cladding (C&C) Wind Pressures. (psf)

Component	Zone/Direction		
	Interior/Pressure	**Interior/Suction**	**End & Corner/Suction**
Studs	47	51	62
Rafters	24	43	82
Overhangs	N.A.	92	141
Wall fasteners	N.A.	66	66
Roof fasteners	N.A.	45	95

Lateral Resisting System. The MWFRS forces shown in Table 1 produce lateral and overturning loads that must be resisted. These forces on the Intern House are shown in Figure 7, with the resulting horizontal diaphragm and shearwall forces shown in Figure 8.

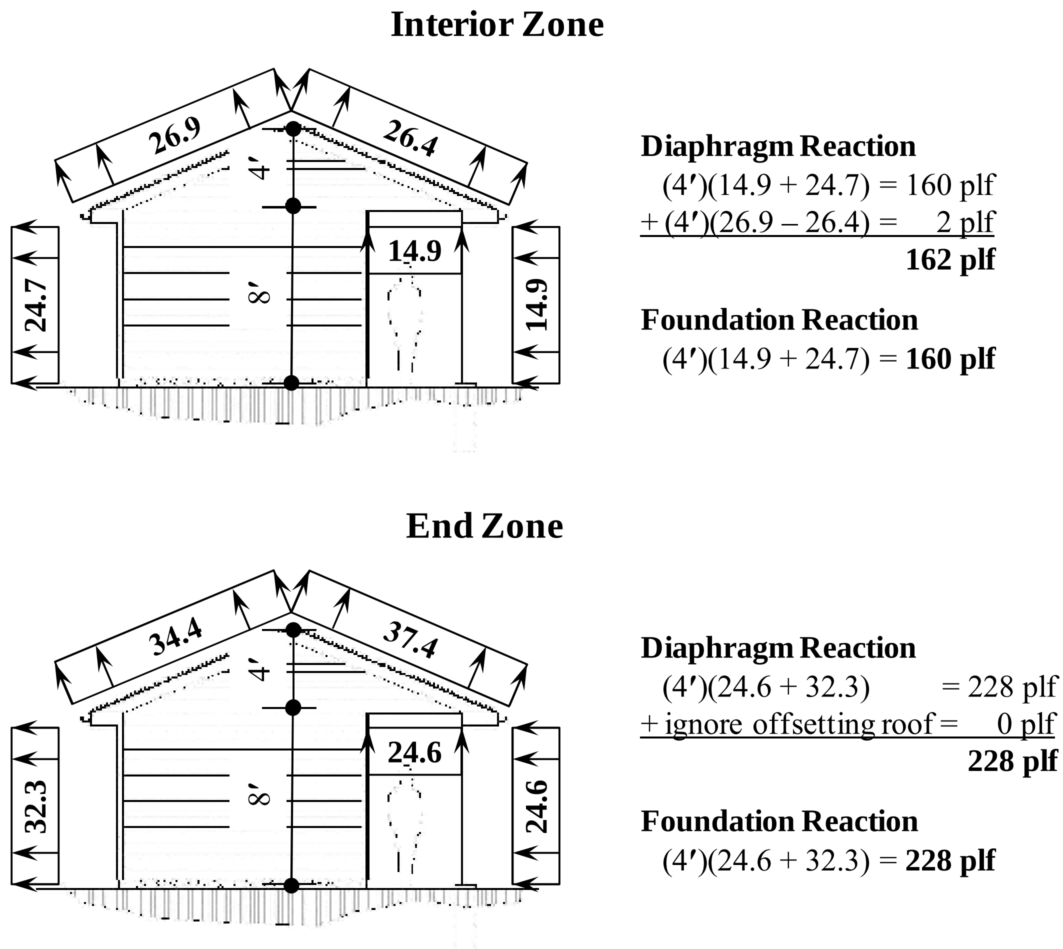

Figure 7. Intern House MWFRS loads.

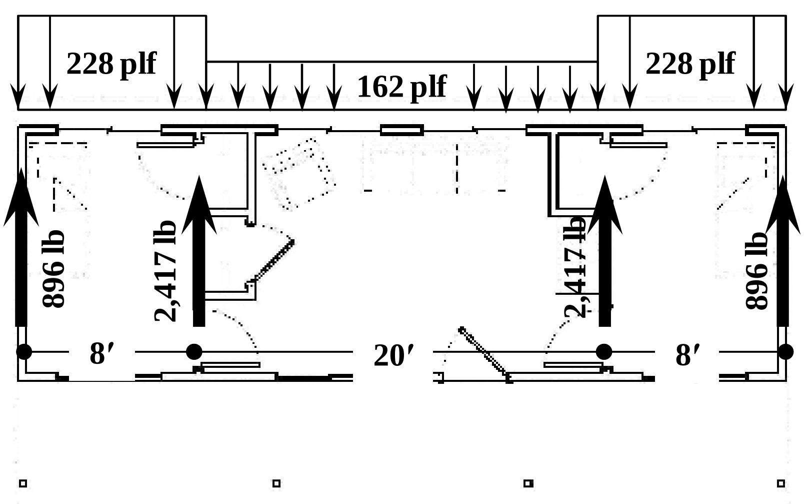

Figure 8. Intern House diaphragm and shearwall forces.

Horizontal diaphragm resistance was provided by a combination of the metal roofing, SIS ceiling sheathing (top of the ceiling joists) and wood panel ceiling (bottom of the ceiling joists). Blocking and fastening of the horizontal diaphragms was specified to ensure adequate transfer of the horizontal shear forces from the diaphragms to the resisting shear walls. The TJ®-Shear Brace was used at the interior shear walls (Figure 9) while the SIS and wood sheathing provided lateral resistance at the outside shear walls.

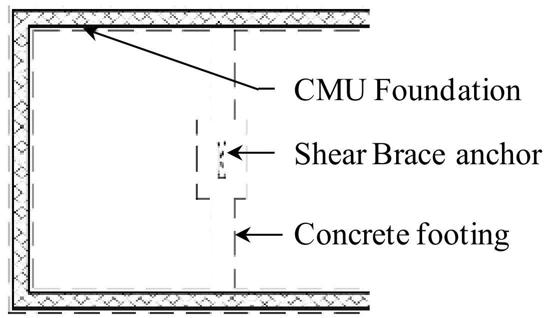

Figure 9. TJ-Shear Brace at interior braced wall location.

Uplift and Overturning. Various Simpson® connectors were used to transfer uplift forces from the roof and wall down through the wall framing to the foundation (Figure 10). Uplift anchors were specified at corners and openings to resist overturning forces, and wind uplift forces on the roof were resisted by screw fastening of the purlins to the rafter framing. Furthermore, decreased purlin spacing at the ends and corner zones (Figure 11) allowed for a concentration of framing and sheathing fasteners to resist the higher loads in these zones.

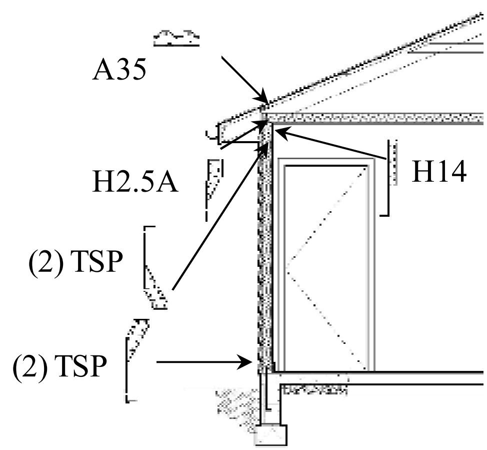

Figure 10. Typical uplift connections.

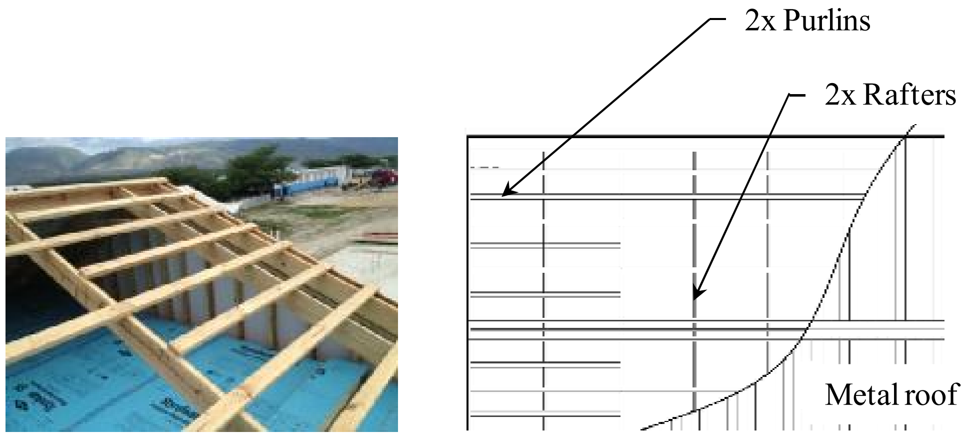

Figure 11. Increased end/corner zone framing.

CONSTRUCTION LESSONS

In October 2012, thirty volunteers spent from one to two weeks in Chambrun, Haiti, to begin construction of these five homes. The project was extremely humbling and rewarding. It was a chance to experience and better understand the Haitian culture, and to help those involved in recovery and development efforts.

The team experienced several construction challenges including a delay in the release of our materials from customs, the heat and intensity of the Caribbean sun, and the wind, rain and resulting mud brought by the nearby passing of Hurricane Sandy. Despite these challenges, we were able to get two homes (one Intern House and one Medical Staff House) weathered in and partially sided. The remaining siding, electrical, plumbing and interior finish work was completed by Haitian workers and other NVM volunteers. Construction of the final three homes is scheduled for February, 2013.

The availability of construction lumber remains very limited in Haiti—especially higher grades, wider dimensions and treated material. Other structural components required for wood-frame construction, including shear brace systems or components, rated structural sheathing, connection hardware and fasteners, are also not available. Furthermore, supplementary materials to support wood-frame construction are also not readily available. This includes concrete hardware such as threaded anchor bolts and electrical components like junction boxes and nail plates designed to fasten to wood studs. Products to provide for conditioned spaces and weatherproofing such as building wraps, insulation, sealants, tapes and flexible flashings are also difficult to obtain.

A lack of knowledge and experience with wood-framed building techniques among Haitian construction workers is significant. However, during our work on these homes we were able to train several Haitians in wood framing and installation of metal roofing, lap siding, and windows. They had a curiosity and enthusiasm about learning these new methods and began to refer to these homes as “bèl kay” – meaning “beautiful house” in Creole.

Based on our design and construction experience, we recommend several changes if similar homes were to be built. These include:

- Utilize oriented strand board (OSB) for the exterior sheathing rather than SIS panels. This approach would be less costly, would be easier to install without pneumatic nailers, and provide more reliable lateral resistance. Other methods of providing a vapor barrier could be used for a conditioned home.
- While the Copper Azole-treated studs provided termite protection, this treatment was more costly than required, and necessitated increased corrosion resistance of the fasteners and hardware. FrameGuard® brand, or similar treatment of the framing, would provide adequate protection.
- Treated wood column embedment (for uplift resistance) directly into the column footing rather setting column anchors would be less expensive and easier to accomplish in this construction environment.
- Consider options to reduce the amount of connection hardware in the structure. Multiple connectors were required at many locations to properly transfer the loads. This created a construction challenge of getting all of this hardware installed when there is limited space to work with.
- Consider the application of a stucco exterior finish over the wood structural panel wall sheathing. The application of stucco is a skill readily available in Haiti and would provide a finished appearance similar to the masonry & concrete walls more typical of the region. However, this approach would require additional investigation and detailing to ensure adequate moisture control given the heavy driving rains during certain times of the year.
- Metal wall sheathing would provide another exterior finish option, but may not be as readily accepted.

While these homes were designed and constructed as entirely wood-framed structures, it is realized that a more incremental approach to improving wood construction in Haiti may be appropriate. Properly reinforced masonry, “confined masonry”, or reinforced concrete walls with wood framed floors and/or roofs may increase the use of wood while also improving the structural integrity of the homes.

NEXT STEPS

This Weyerhaeuser-led initiative is scheduled for completion in early February and there are no specific plans for further work beyond the five homes. We have been able to provide support for immediate relief efforts in the aftermath of the 2010 earthquake as well as make a long-term impact on the redevelopment efforts in Haiti by providing permanent structures that will help those who are helping others. We have been able to provide limited training of a few Haitians associated with this effort. We have demonstrated, within Haiti as well as to the US wood industry, the feasibility and challenges of the design and construction of wood-framed homes in Haiti.

This effort will not change the way homes are built in Haiti nor will it lead to the sale of vast amounts of lumber from US mills. We know the task of implementing new construction practices and/or products even in the US is a costly and time-consuming challenge. In sharing the details of this project, the authors hope to encourage other individuals and the wood industry to learn from this experience and to continue efforts to address supply-chain issues and provide design and construction training to improve the reliability of construction practices in Haiti as well as other Caribbean and developing nations.

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Effects of Installation Method on Nail Withdrawal Capacities

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ABSTRACT

Nail withdrawal capacities are tested in accordance with ASTM D1761 and are typically estimated using the empirical equation $W=6900G^{2.5}D$ given in the National Design Standard for Wood Construction. A previous study by Shreyans et al found that in-situ nail withdrawal capacities were over-estimated by the NDS equation and suggested that loss of capacity may be due to the installation of the nail through the sheathing, which is not done in ASTM D1761. This paper presents an experimental study that explores the effects of installation method on the nail withdrawal capacity by testing nails installed through both Oriented Strand Board (OSB) and Plywood. Type of nail used for testing was 6d common nails with diameter of 2.87 mm (0.113 in) and length of 50.8 mm (2 in).

The effect of installation method on nail withdrawal capacity was evaluated by comparing capacities using ASTM D1761 Standard Test Methods for Mechanical Fasteners in Wood to those obtained with the nail installed through the sheathing. The effect of the nail withdrawal method was also quantified for three methods: 1) Withdrawal with the sheathing left in place, 2) Withdrawal by means of a steel plate notched to fit around the installed nail, 3) Withdrawal by direct pull using a steel jaw.

Results demonstrated that installation through the sheathing consistently reduced the withdrawal capacity; however the test setup and withdrawal methods also significantly affected the withdrawal capacities. The National Design Standard empirical formula may be non-conservative in representing the withdrawal capacities of nails in a roof setting.

INTRODUCTION

Sheathing attachment is extremely important in residential structures. The roof is usually the first thing to fail in a windstorm and once this happens the remaining structure is more unstable. Wood residential buildings account for 60% of all damages in wind storms (Sparks, 1991) and 95% of residential economic losses are from failures associated with the roof (Baskaran, 1997). These failures are due in part to inadequate strength in fasteners (primarily nails) attaching wood sheathing to the wood rafter (Shreyans, 2012).

Nail withdrawal capacities are tested in accordance with ASTM D1761. This requires that the fastener to be withdrawn from the wood with a testing machine capable of keeping a constant withdrawal rate of 2.54 mm/min (0.1 in/min) with a gripping device that fits the base of the fastener head. In this study the Direct Pull Method described below would be the equivalent of the ASTM D1761 Test Protocol and thus all other test results will be compared to this.

Shreyans et al. performed in-situ tests on 1,458 nails from 17 Florida homes using a modified Portable Nail Extractor (m-PNE), which required the removal of the sheathing around the nail in order to test the withdrawal capacity. Results of the study demonstrated that not only was the withdrawal capacity affected by the method of sheathing removal, but also that mean in-situ nail withdrawal capacities were lower than nail withdrawal capacities implied using the NDS empirical equation. It was concluded that installation through sheathing may have been responsible for the loss in strength. The objective of this current study is to evaluate the effect of the nail installation method on the nail withdrawal capacity.

TEST METHODS

Materials

Nails were chosen to match those observed in the in-situ tests, and consisted of galvanized common nails with dimensions of 2.87 mm x 50.8 mm (0.113 in x 2 in). Sheathing consisted of 11.11 mm (7/16 in) oriented strand board (OSB) and 11.91 mm (15/32 in) 4-ply plywood. Framing members used were No. 2 Southern Yellow Pine 38 mm x 89 mm x 244 mm (nominal 2 in x 4 in, 8 ft long). Moisture contents and specific gravities were determined at five locations in each framing member in accordance with ASTM D2395 "Test Methods for Specific Gravity of Wood and Wood-Based Materials" and ASTM D4442 "Test Methods for Direct Moisture Content Measurement of Wood and Wood Based Materials." The average values for each framing member are shown in Table 1.

Table 1: Specific Gravity and Moisture Content per Board

	Specific Gravity		Moisture Content	
Board	Mean	COV	Mean (%)	COV
A	0.47	4.8%	14.0	5.8%
B	0.48	1.9%	14.4	3.3%
C	0.44	8.0%	14.7	4.3%
D	0.57	6.1%	13.6	2.5%
E	0.43	2.0%	13.3	4.7%
F	0.50	7.3%	14.5	3.4%

Equipment

Nails were either installed through the sheathing or by means of a nail guide that ensured a nominally consistent embedment depth of 38.1 mm (1.5 in). Nails were installed using an air compression nail gun at an air pressure chosen to ensure the top of the nail head was not embedded beyond the specified lengths. Any nails that were embedded too far were not tested, and those that were not embedded far enough were corrected by using a hammer to impact the nails to the correct depth.

Withdrawal Methods

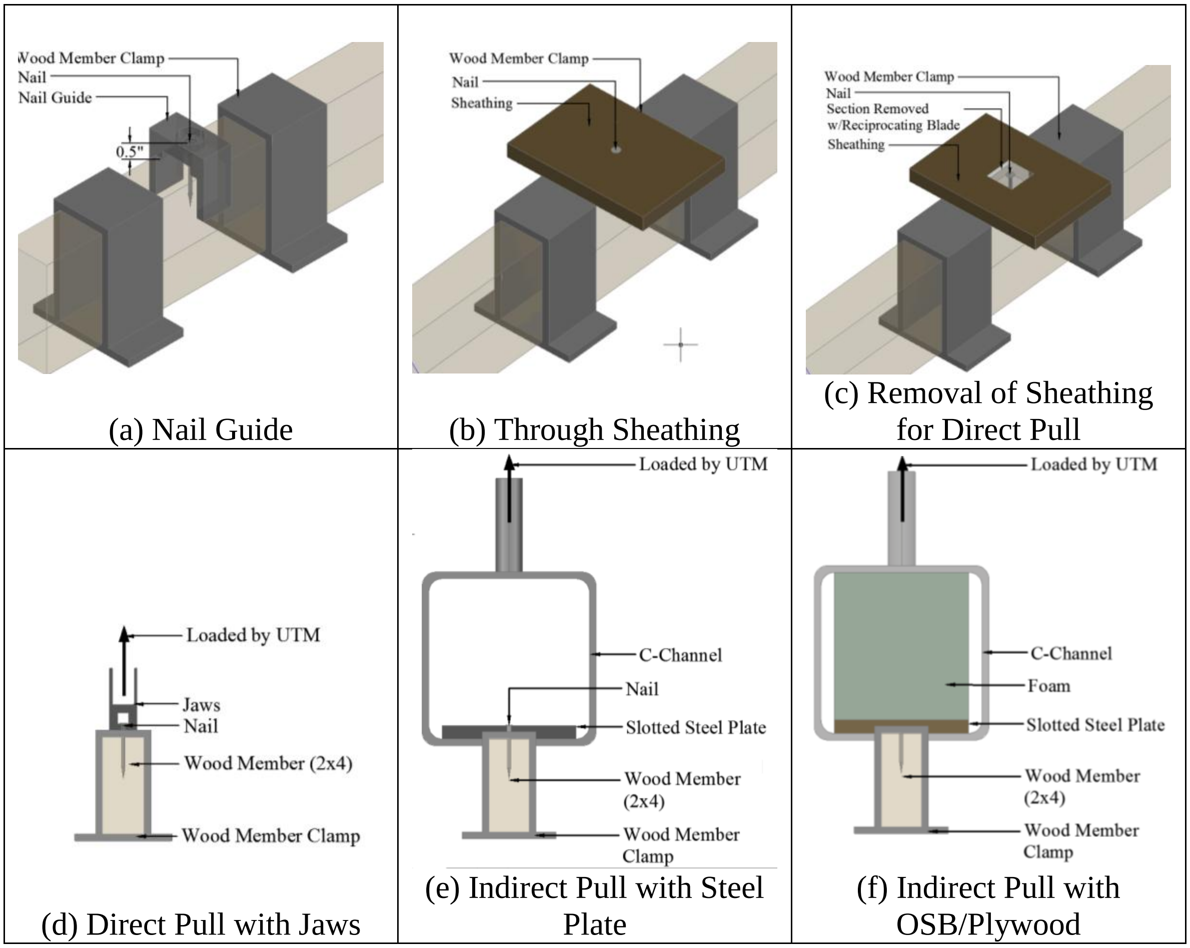
All withdrawal tests were performed using an Instron Universal Testing Machine (UTM) Model 3384 with 150 kN (33,721 lbf) capacity. The withdrawal rate for all tests was kept constant at 2.54 mm/min (0.1 in/min).

Test Matrix

Six different test methods were performed to quantify the effect of installation method on the nail withdrawal capacity. These six methods were chosen to best isolate the effects of the installation method and the withdrawal method. Two installation methods were considered, installation through sheathing and installation using the nail guide. Three withdrawal methods were considered which included direct pull using a steel jaw, indirect pull using a steel plate notched to fit around the nail shaft, and indirect pull using the sheathing itself. The test matrix is displayed in Table 2. Illustrations of the installation and withdrawal methods are shown in Figure 1.

Table 2: Test Matrix

Test ID	**Installation Method**	**Withdrawal Method**	**Number of Nails**
NGDP-S	Nail Guide	Direct Pull	134
NGSP-S	Nail Guide	Indirect – Steel Plate	59
OSB-S	OSB	Indirect – Sheathing	97
ODP-S	OSB	Direct Pull	60
PLY-S	Plywood	Indirect – Sheathing	76
PDP-S	Plywood	Direct Pull	40



(a) Nail Guide (b) Through Sheathing (c) Removal of Sheathing for Direct Pull
(d) Direct Pull with Jaws (e) Indirect Pull with Steel Plate (f) Indirect Pull with OSB/Plywood

Figure 1: Nail Installation and Withdrawal Methods

When nails were installed through the sheathing but withdrawn using the direct pull method, it was necessary to cut away the sheathing from the nail. This was done using a Rockwell SoniCrafter Model RK5100K reciprocating saw, as Shreyans et al. demonstrated that this removal method had the least effect on the withdrawal capacity of the nails. When nails were withdrawn using the indirect method with sheathing, it was necessary to prevent the sheathing from failing prematurely during the test. This was accomplished by filling the C-channel shown in Figure 1f with dense closed-cell foam.

Nails were installed at the center of the narrow face of the SYP wood member 50.8 mm (2 in) on center with an initial offset of 101.6 mm (4 in) from the edge. Both sides of the wood member were used in these tests with no offset between the nails on opposite sides. Each specimen was labeled based on the board, the side, and the location. For example a nail tested on Board A, on side 2 and is the 16th nail tested on that board it would be given the name A2-16.

RESULTS

The maximum withdrawal load was recorded for each nail. The results were then reported in units of force per unit length which was calculated by dividing the recorded maximum load by the length of the nail embedded in the SYP wood member.

Table 3 reports the smooth shank nails average withdrawal and COV and Table 4 compares all the test methods to the Direct Nail Pull Method.

Table 3: Mean Withdrawal Capacity for Nails in kN/m* (COV %)

	Board	A		B		C		D		E		F	
	Specific Gravity	0.47		0.48		0.44		0.57		0.43		0.50	
	Side	1	2	1	2	1	2	1	2	1	2	1	2
Test Method	NGDP	27.7 (15)	23.7 (12)	24.5 (17)	28.3 (18)	25.1 (16)	23.6 (18)	19.0 (23)					
	NGSP	29.4 (13)		24.2 (23)				21.2 (23)					
	OSB		23.4 (17)			22.5 (9)			25.9 (10)	18.0 (13)			19.4 (19)
	ODP								22.0 (12)	13.4 (19)			13.7 (27)
	PLY				25.7 (11)		22.7 (11)				16.5 (18)	20.2 (20)	
	PDP										12.8 (19)	15.0 (27)	

**Coversion 1kn/m = 5.7 lb/in*

Table 4: Comparison of Smooth Shank

Method	Mean Nail Capacity kN/m (lb/in)	Ratio to Direct Nail Pull
NGDP	24.6 (140.2)	-
NGSP	25.0 (142.9)	1.02
OSB	21.7 (123.8)	0.88
ODP	16.4 (93.6)	0.67
PLY	21.3 (121.5)	0.87
PDP	14.0 (79.7)	0.57

An observation from these tests was that the specific gravity seemed to have no discernible effect on the withdrawal rate as shown in Figure 2.

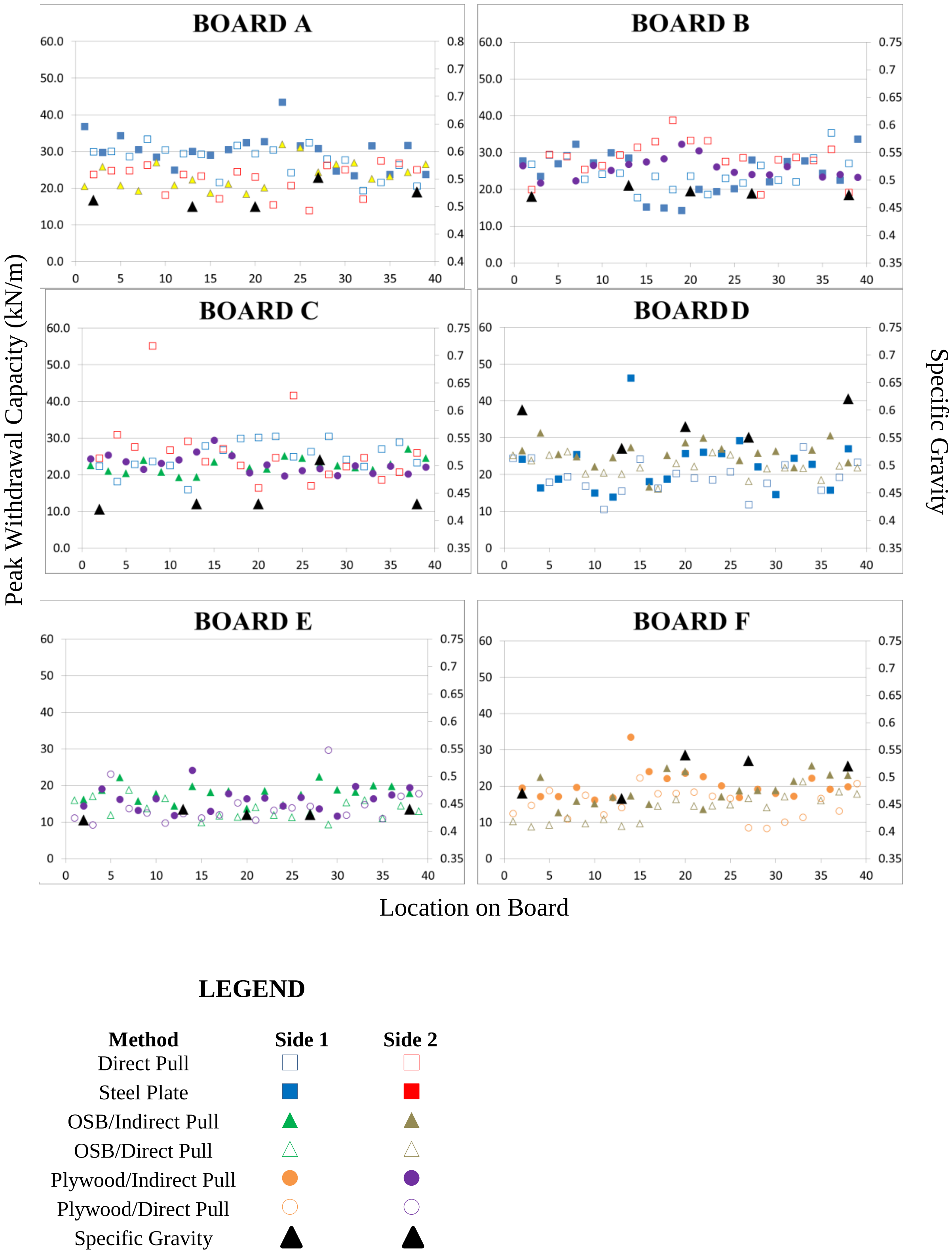


Figure 2: Withdrawal Capacity and Specific Gravity vs. Location on Board

Discussion

A Two Sample Student's *t*-test was performed using Matlab version R2009b in which the calculation were adjusted to assume unequal variance. The data was grouped together per method and tested to determine if there was a statistical similarity or difference between them. Table 5 shows a summary of the p values comparing each of the methods.

Table 5: T-test p-values comparing each test method

Test Method	NGDP	NGSP	OSB	ODP	PLY	PDP
NGDP	1	.3342	1.50E-5	3.57E-18	3.11E-6	1.95E-19
NGSP		1	1.27E-4	1.22E-13	2.79E-5	2.47E-16
OSB			1	3.12E-10	.3884	7.01E-13
ODP				1	7.91E-8	.0590
PLY					1	5.92E-11
PDP						1

A confidence level of 5% was used to determine that the sets of data were from the same sample. As indicated in Table 5, the Direct Nail Pull and Steel Plate Test can be treated as one sample population, the OSB and Plywood Indirect Pull as another sample population and the OSB and Plywood Direct Pull as a third. This demonstrates that the steel plate indirect pull method has no effect on the withdrawal rate in comparison to the ASTM D1761. An indirect pull with sheathing does affect the withdrawal capacity however the type of sheathing seems to have no effect. And finally, installation through sheathing, whether through plywood or OSB, also reduced the nail withdrawal capacities. Table 6 gives p values again from a Two Sample Student's t-test but now grouping the methods that the previous test determined to be from the same sample. Figure 3 gives the boxplots showing the median withdrawal for each test method group, with the box representing the 25^{th} to 75^{th} percentile.

Table 6: T-test pvalues comparing grouped test methods

Test Method Group	NGDP/NGSP	OSB/PLY	ODP/PDP
NGDP/NGSP	1	8.88E-10	6.39E-34
OSB/PLY		1	5.55E-19
ODP/PDP			1

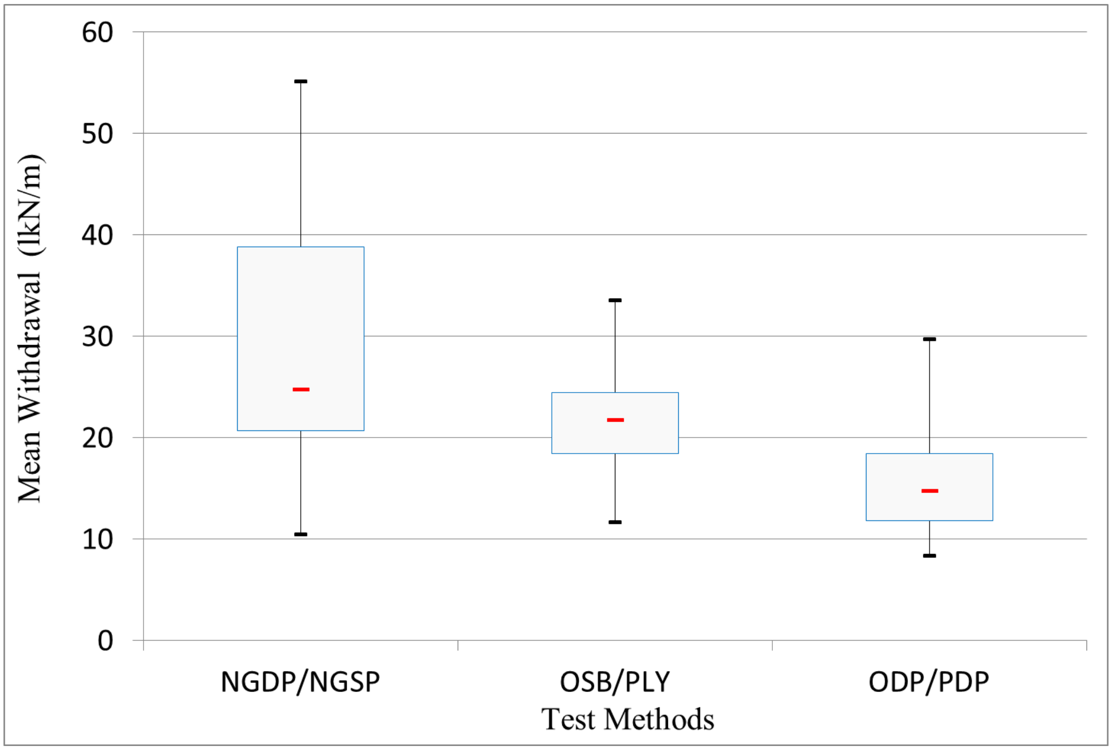


Figure 3: Withdrawal vs. Test Method Group

The statistics indicate that the three test samples are from different sample sets. This demonstrates that installing through sheathing does affects withdrawal capacity.

Conclusion

In the ASTM D1761 Standard Test Methods for Mechanical Fasteners in Wood the setup and method is similar to the Direct Pull method. The direct pull method does not give withdrawal strengths parallel to real world applications. In the National Design Standard, the empirical equation $W=6900G^{2.5}D$ does not take into account how the nail is installed. Though it is generally accepted that nail withdrawal values are dependent primarily on embedment length and specific gravity of the framing member, this study suggests that other factors, such as installation through sheathing, may also be of importance. Further testing will be performed to establish this trend with a larger dataset and further isolate the effect of installation through sheathing.

ACKNOWLEDGEMENT

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Modular Green Roof Systems in Mid-rise Multifamily Residential Units

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ABSTRACT

This paper presents the results of a full-scale research project undertaken to assess scour losses/gains for modular tray green roof specimens placed on a mock-up building, and identify important factors to consider for wind design criteria. Visual assessment of the experimental results showed that usage of vegetation, parapet height, wind direction, and test duration were the predominant factors affecting scour resistance of the growth media in tested specimens. Statistical analysis results indicated that the differences in soil losses measured among Phase 2's test trials were more significant than those in Phase 1. This was attributed to the lack of parapet, cornering wind conditions, and longer test duration found in Phase 2. Findings presented in this paper constitute a benchmark for future research to improve the knowledge gap that exists in green roof wind design.

BACKGROUND

The housing sector accounts for a large and growing portion of the built infrastructure within cities worldwide, and in the global context, urban populations surpassed rural populations for the first time in 2008. It is projected that by 2050, there will be a 70 percent increase in global urban populations (UN Populations Division 2008). From the U.S. perspective, most of its population currently live in single-family residential structures (in over 100 million homes) (U.S. Census Bureau and American Community Survey 2012), but current trends suggest that an increasing number of people will live in urban multi-family complexes. This change will provide opportunities to construct structures that are more sustainable, resilient to natural hazards (wind, seismic, floods), and responsive to growing urban population needs.

On the other hand, higher density (multi-family) housing can present some drawbacks, two of which are increased *urban heat island* effects and increased stormwater runoff, both triggered by the alteration of the natural landscape. Green (or vegetative) roofs offer a solution to several urban issues as they can be installed on new or existing, impervious low-slope roofs for commercial and residential buildings to increase the vegetation footprint in urban environments with otherwise limited open areas. Further, large-scale implementation of green roof systems help to effectively alleviate urban heat island effects, as opposed to single-roof installations (Bass 2012). Green roofs can potentially reduce stormwater runoff, increase biodiversity, and prolong the service life of the underlying roofing system (Saiz et al. 2006).

Green roof systems are multi-layer assemblies typically consisting (from top to bottom) of live vegetation, growth media, filter fabric, optional root barrier, drainage layer, and a waterproofing membrane. The growth media is classified by its depth, as either intensive (greater than 150 mm [6 in.]), or extensive (less than 150 mm [6 in.]). This classification dictates the types of plants that are suitable for the green roof system, as well as the structural details of the supporting roof structure. Green roofs can be installed either as built-in-place (continuous) roofing or modular tray systems assembled in a grid using rectangular metal or plastic-polymer containers. The installation of a modular tray green roof is similar to that of roof pavers in that discrete units are placed on the roof and provide protection and the gravity load (ballast) that holds the roofing membrane in place. Modular green roofs are subject to similar failure mechanisms that roof pavers are in extreme winds. And while modular tray roofs may have the advantage of more efficient installation and maintenance over built-in-place green roof systems, their installation in discrete modules may also increase the risk of wind uplift failures, a risk that until recently has not yet been evaluated.

Green roof history. The contemporary green roof movement began in the U.S. around the mid-1990s, through adaptation from Europe's (mostly Germany's) green roof industry. The green roof industry gained popularity in the U.S. after a green roof was installed on Chicago's City Hall Building in 2001 and on the roof of Ford Motor Company's River Rouge Plant in Dearborn, MI in 2003. Since then, the growth has concentrated in metropolitan areas like Chicago, IL, Washington, DC, and New York, NY. Currently, approximately 6,500 m^2 (70,000 ft^2) of green roofs have been installed in Florida (a hurricane-prone state) since 2001, compared with the 126,000 m^2 (1.3 million ft^2) of green roofs that were installed in Chicago and Washington, DC in 2011 alone (Green Roofs for Healthy Cities 2012; Greenroofs.com 2012). The limited number of Florida green roofs may be traced to the high design wind speeds in Florida and the lack of a wind design guide for these systems. Further, the Florida Building Code has strict requirements mandating submission of wind resistance evaluation reports for any building envelope element to be installed on a building. Currently there are no accepted test protocols for evaluating the wind resistance of green roof systems.

The first wind-performance tests reported for green roof systems were conducted on modular and built-in-place green roof systems by Retzlaff et al. (2010) and Wanielista et al. (2011), respectively. Their results established that the presence of fully established plants effectively mitigates growth media scour at high-wind speeds. Although, they are not adopted by any building code, there are two wind design guides for green roof systems in use for the United States; the ANSI/SPRI RP-14 (ANSI/SPRI 2010) and Factory Mutual's FM 1-35 (FM Global 2011). Although the wind tunnel study of Retzlaff et al. (2010) was referenced by the RP-14, its design specifications are based on earlier wind design provisions – RP-4 (ANSI/SPRI 2008). No full-scale tests were used in development of the RP-14 provisions. Thus, validation of the RP-14 design guideline has yet to be carried out.

Wind loading on flat roofs. Wind flow around a building produces spatially and temporally varying wind pressures on the walls and roof of a building. It is well-known that roofing systems can be damaged by the high suctions occurring at the corner regions and edges of a roof. Bienkiewicz and Sun (1992) showed that cornering winds on buildings (i.e. wind direction not parallel to a building edge) resulted in the production of conical vortices above the roof and commensurate extremely high suction forces. Such effects are known to cause failures of roof pavers via uplifting and sliding on roofs. It is therefore likely that similar failures would occur with green roof systems, particularly those that rely solely upon gravity loads to keep the roofing system in place. Another failure mechanism with green roofs is the scour loss of plants (vegetated materials) and growth media. These failures are analogous to the losses occurring in gravel ballasted roof systems that were the subject of several roof studies from the 1970s to late 1980s (Wardlaw and Kind 1985). Those studies clearly demonstrated the destructive power of conical vortices. More recently, Karimpour and Kaye (2012) described a potential problem whereby extreme winds may move roof gravels and other granular material around a roof, which could result in overloading sections of the structural system.

To further understand how green roofs perform under realistic wind loads, the authors conducted a two-year study evaluating wind effects on modular tray and built-in-place green roof systems. The goal of this study was to define pertinent features of a wind uplift design guide for the green roofs installed in Florida (Vo et al. 2012). Supported by the Florida Building Commission's Hurricane Research Advisory Committee, the analyses in this study compasses multiple design criteria such as local plant selection, and the performance of green roofs under extreme simulated wind speeds. Complementary statistical analysis of the wind-induced scour losses of modular tray green roof specimens are provided in addition to visual assessment of the wind experiments.

METHODS AND MATERIALS

Tests were conducted using a model building (measuring 2.4 m x 2.4 m x 2.4 m tall [8 ft. x 8 ft. x 8 ft.]) placed approximately 3.7 m (12 ft.) downstream of a hurricane simulator (Figure 1). The hurricane simulator generated test wind speeds using eight-1.5 m (5 ft.) diameter vane-axial fans to produce a 3 m x 3 m (10 ft. x 10 ft.) air jet at wind speeds up to 54 m/s (120 mph). The simulator also includes vertical fins that rotate side-to-side to simulate lateral turbulence. However these fins were not used in this experiment, resulting in unnaturally low turbulence intensity (Masters et al. 2008).

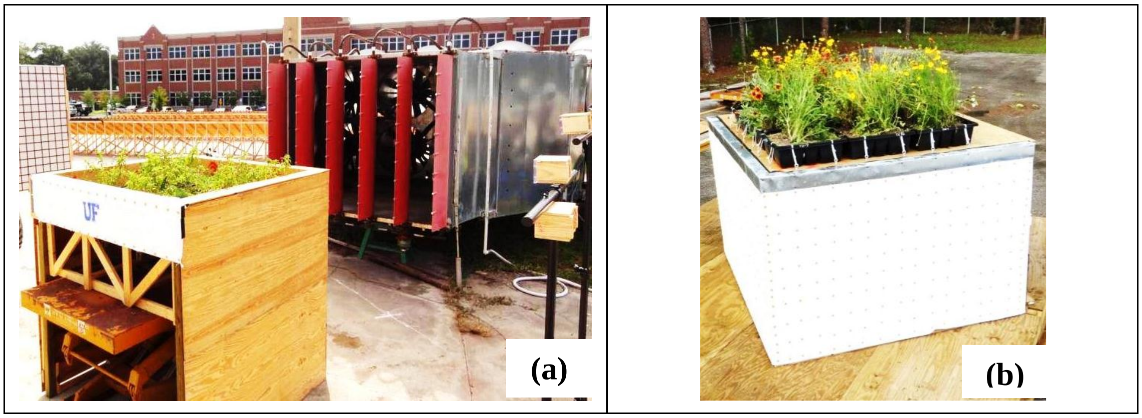

Figure 1. (a) Building at 90° wind azimuth (b) Building at 45° wind azimuth

Wind testing of the modular tray green roof specimens was divided into two phases (Table 1), with each test having nine 0.6 m by 0.6 m (24 in. by 24 in.) modular trays. Phase 1 tested eight planted and one unprotected (bare growth media tray) modules, and the wind flow was perpendicular (at 90°) to the front wall. The location of the unprotected module was varied between the six test trials to compare the specimen performances and identify the roof areas prone to high scour. Also, the building mock-up included a 300 mm (12 in.) high parapet. In Phase 2, the parapet was removed and the building was oriented to produce a 45° cornering wind direction, and some specimens from Phase 1 were re-tested in this configuration.

Modular tray specimens were weighed just before being placed on the deck of the mockup building for testing, and their positions were noted (Figures 2 and 3). Each nine-tray array of modules was then tested, and the plant and growth media behaviors were observed and recorded using three video- and still-cameras. The module tray specimens were weighed again following each wind test trial to determine the losses incurred.

Table 1. Comparison of Phase 1 and Phase 2 test parameters

	Phase 1	Phase 2
Successful test trials	6	6
Modular tray specimens*	54 (6 unprotected)	72 (0 unprotected)
Wind direction	0°	45°
Parapet	300 mm	0 mm
Plant heights	Mixed	Mixed (retested), tall, short
Establishment	3, 5, & 9 months	6 & 13 months
Wind speed	9 – 54 m/s	45 m/s
Test duration	5 minutes	10 or 20 minutes

*Unprotected: No vegetation, liquid binder, or erosion control mat.

GRAPHICAL RESULTS

A graphical representation of specimen weight differences in growth media and its relation to the roof locations and weight averages (denoted by the horizontal red line), are presented in Figures 4 and 5. Weight differences were taken as the final specimen weight minus the initial specimen weight. Tests were denoted as Stat IDs, and will be referenced as the latter term in the later sections. Visual assessment indicated four factors affecting the scour resistance of the green roof specimens: parapet height, growth media protection (i.e. planted vs. unplanted conditions), wind direction, and test duration.

Parapet height. The presence of the parapet in Phase 1 reduced growth media blowoff but resulted in substantial redistribution of growth media, depending on the location of the unprotected specimen. Growth media redistribution is most clearly represented in Tests 1.1 and 1.4 in Figure 4, where weight gains of 2.26 kg (4.98 lbs; 12 % increase) and 2.70 kg (5.95 lbs; 7% increase), were measured in roof locations 6 and 4, respectively. This contrasts with the results in Tests 2.1 – 2.6 (Figure 5), as observed instances of weight gains were rare and insignificant. Usage of a parapet in Phase 1 protected the windward row of specimens from direct wind exposure, but introduced a flow reversal along the inboard face of the leeward parapet (except in Test 1.6 where the leeward parapet was removed). This reversal can be observed by comparing plots for Tests 1.1 and 1.4 from Figure 4 with the plots for Tests 2.2 and 2.5 from Figure 5.

For Phase 2 tests, growth media losses were more pronounced in the leading corner specimen (Tests 2.2 and 2.5 of Figure 5), due to the increased wind flow at roof level with no parapet in place. Further details on the testing and results can be found in Vo et al. (2012).

Protected (planted) modules. Scour resistance of green roof specimens is directly related to their vegetation coverage. Vegetation coverage is provided by both the vegetation foliage/stems (captured by overhead photography) and planting density (i.e. number of plants per area and captured by frontal photography normal to the plant height). Retzlaff et al. (2010) showed that specimens with 100% vegetation coverage (overhead) were able to resist media scour for wind speeds up to 63 m/s (140 mph). This applicability of their result is limited since Retzlaff et al. did not simulate realistic turbulent wind flows and they only tested a single module tray installed within an aerospace wind tunnel. The present study calculated coverage ratios obtained from overhead photographs taken before and after wind testing in Phase 2.

Tests 2.1, 2.2, and 2.5 (Figure 4) resulted in the most observable weight losses in Phase 2. Thus, to identify any relationship between coverage and scour losses, their coverage ratios were summarized in Figure 6. It can be seen that Tests 2.2 and 2.5 (Figure 6), which shared identical types of vegetation and a comparable establishment period (but with different media depths), produced plots which differed from one another in Figure 4. This could be explained from the difference in vegetation coverage and height between the two tests. The greater vegetation height and coverage in Test 2.5 resulted in more effective sheltering of loose media, and reduced growth media losses further downwind of the array when compared to Test 2.2.

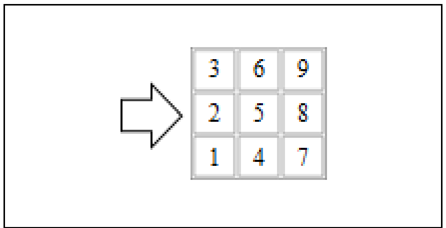

Figure 2. Phase 1 location IDs

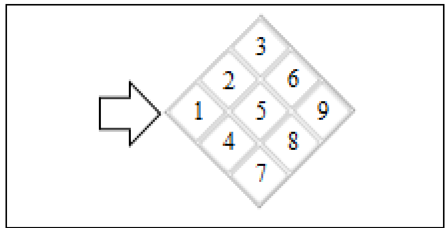

Figure 3. Phase 2 location IDs

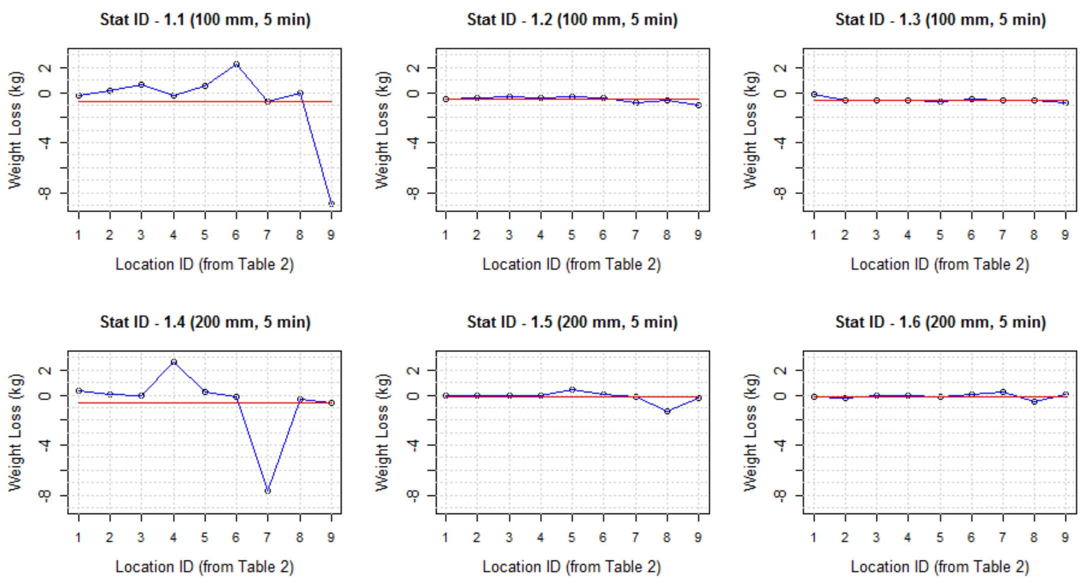

Figure 4. Phase 1 weight differences plotted against corresponding averages

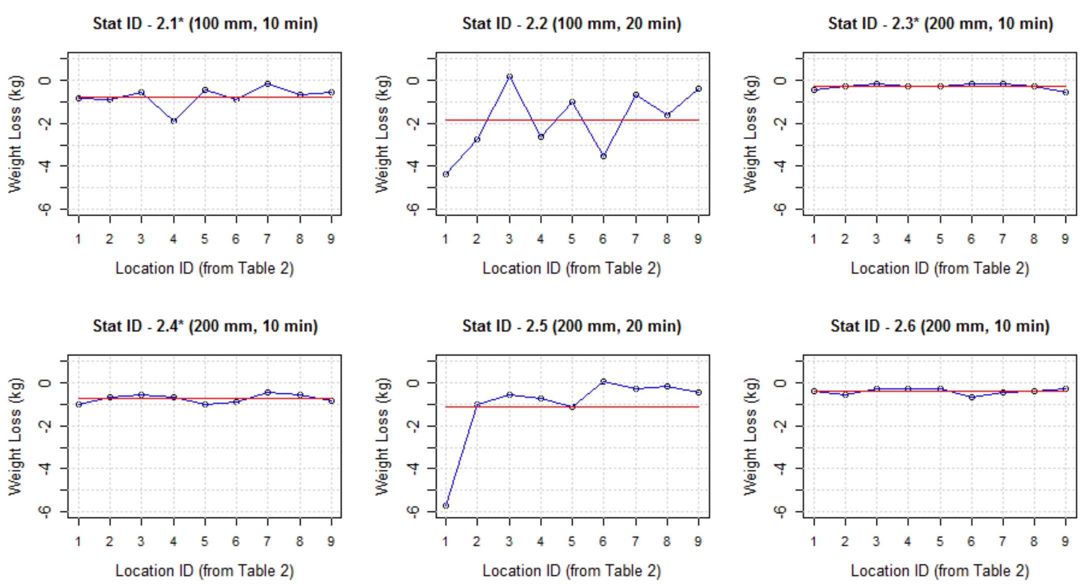

**Figure 5. Phase 2 weight differences plotted against corresponding averages.
*Modular specimens re-tested from Phase 1 were in identical locations.**

Wind direction and test duration. Determination of the effects due to varying the wind azimuth between Phase 1 and Phase 2 was not possible due to the inclusion of a parapet in Phase 1, while none was used in Phase 2. However, Test 2.2 (Figure 5) displays measurable losses in array locations, which suggest the presence of conical vortices. This is further reinforced by the plant bending patterns addressed in an earlier article by the authors (Vo et al. 2012). Present results suggest that longer test durations produced higher losses (as shown in Tests 2.2 and 2.5 from Figure 5), but because vegetation type and age varied throughout, this observation cannot be generalized without further analysis of statistical significance.

Stat ID	2.1	2.2	2.5
Before Wind Tests			
	64.5%	59.2%	77.9%
After Wind Tests			
	61.2%	52.6%	62.7%

Figure 6. Coverage ratios in Phase 2 for Tests 2.1, 2.2 and 2.5.

STATISTICAL RESULTS

To assess the impact of different environmental settings and green roof properties, comparative statistical analyses through different strata of project settings were completed on successful test trials. The uncontrolled factors between test trials (i.e. wind test duration, plant type, usage of unprotected module, etc.) in combination with the small number of experimental tests presented a limited sample pool for conducting a statistical analysis. Therefore, non-parametric comparative analyses were conducted for two cases: specimen weight differences' relation to corresponding experimental means and overall weight differences between test trials of similar variables. Test scores for different exercises will indicate different significance thresholds, thus standardized with the p-values shown in Tables 2 and 3. For both sets of comparative assessments, the null hypothesis (i.e. no difference between test samples) is rejected if the probability is less than 5%.

Table 2 presents the first set of comparative assessments used to determine the significance of the differences between the pre- and post-test weights of individual modules in each test trial. Because the overall weights were not independent of each other (i.e. gains from one specimen as a result of the losses from another), a paired analysis of the pre- and post- weights is more suitable for the data set under consideration. Non-parametric Wilcoxon signed rank-sum tests were used to test the specimen weights. Non-parametric analyses, unlike more common parametric statistics, do not rely on assumptions such as normality and are therefore more flexible (Hoskin), and considering the smaller sample size of the data points, they were adopted over more traditional parametric statistics.

The results from Table 2 state that significant differences *were* present between pre- and post- test weights for Tests 1.2, 1.3, and 2.1 – 2.6. When these results are compared against results in Figures 4 and 5, it is apparent that test trials which experienced net losses (i.e. test trials where more growth media blow-off occurred than redistribution) might have resulted in statistically significant differences between their specimens' pre- and post- test weights. Thus, the usage of a parapet during testing resulted in less significant differences in specimens' weights.

Table 2. Comparison of data between specimens within each experiment

Stat ID	Statistical Test	Test Score	p-value
1.1	Wilcox	24	.91
1.2	Wilcox	45	.004*
1.3	Wilcox	45	.004*
1.4	Wilcox	26	.73
1.5	Wilcox	26	.29
1.6	Wilcox	34	.20

Stat ID	Statistical Test	Test Score	p-value
2.1	Wilcox	45	.009*
2.2	Wilcox	44	.008*
2.3	Wilcox	45	.009*
2.4	Wilcox	45	.004*
2.5	Wilcox	44	.008*
2.6	Wilcox	45	.009*

*Null hypothesis rejected

Table 3 presents results from the second set of comparative tests conducted to assess the differences in observed soil losses for similarly-constructed test trials (i.e. same wind speeds and test durations, etc.). Provided the test setups had consistent treatments, it was assumed that there should be no statistically significant difference in the soil loss observed between the experiments for specimens placed in the same roof locations. The Kruskal-Wallis Method, which can be considered a non-parametric one-way ANOVA, was used to conduct statistical analyses among tests with more than two subgroups. Analyses with only two subgroups utilized the non-parametric Wilcox rank test. Table 3 presents eight cases tested in order to isolate treatment (i.e. factors changed between test trials) effects on weight changes. Pairwise (i.e. ad-hoc) comparisons were done to complement the Kruskal-Wallis test results.

The test results presented in Table 3 varied greatly in terms of rejection or acceptance of the null hypothesis. While cases 2 – 5 resulted in statistical confirmation of the initial hypothesis that similar test conditions produced no significant differences in weight changes within a 5% confidence, other cases appear to contradict that hypothesis. For example, in case 8 where the treatments were identical, the resulting p-value states that the weight changes between Tests 2.3 and

2.4 were statistically different. However, due to high variability between test trials (i.e. multiple treatments in an experiment), reliable conclusions from the second set of comparative tests cannot be made in this study.

Table 3. Comparison of data between experiments with similar treatments

Case	Stat ID	Treatment Varied	Statistical Test	Test Score	p-value
1	1.1, 1.2, 1.3	Unprotected module location	Kruskal-Wallis	6.03	.05*
2	1.1, 1.4	Module depth, unprotected module location	Wilcox	42	.93
3	1.4, 1.5, 1.6	Unprotected module location	Kruskal-Wallis	0.27	.88
4	2.1, 2.2	Plant types, test duration (2.2)	Wilcox	57.5	.14
5	2.2, 2.5	Module depth	Wilcox	26.5	.23
6	2.3, 2.4, 2.5, 2.6	Plant types, test duration (2.5)	Kruskal-Wallis	13.3	.004*
7	2.3, 2.4, 2.6	Plant types	Kruskal-Wallis	15.7	.0004*
8	2.3, 2.4	None	Wilcox	78.5	.001*

*Null hypothesis rejected

CONCLUSION

This paper presented an analysis of wind resistance of modular tray green roof systems tested on a model building. The methods were presented, and related trends and statistical comparisons were given which explored the effects that different factors have on the growth media scour performance. It was shown that the usage of vegetation and its resulting coverage ratio promotes more erosion control, and minimizes excessive weight changes in modular tray specimens. Further, the usage of a 300 mm tall parapet reduced growth media scour in specimens located along the windward wall, but also produced adverse wind flow conditions that were detrimental to the scour performance of modules located along the leeward wall. Overall, vegetation type and coverage, test duration, and wind direction significantly affect growth media scour. However, the statistical significance of scour-induced specimen weight losses and gains appears more dependent upon the containment of the total growth media on the roof and its limited net weight change during testing, than the successful scour resistance of individual specimen. The high variability between test trials prevented reliable results to be made from the statistical tests conducted between test trials. To better understand the growth media scour resistance of modular tray green roof systems, further studies are needed that utilize larger roofs and more modular tray specimens, limit the treatments varied, and test wind flows that exhibit natural wind characteristics.

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The Unsealing of Naturally Aged Asphalt Shingles: An In-situ Survey

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ABSTRACT

As part of a two-year research project investigating causes of premature roofing failures in windstorms, twenty-seven naturally aged asphalt shingle roof systems on residential houses in Florida were surveyed to investigate the condition of the sealant adhesive strips on the shingles. The thermally activated sealant strip located along the leading edge of an asphalt shingle is the primary load path that resists failure of the shingle due to the wind. The non-destructive survey consisted of applying finger pressure to each shingle edge to determine whether or not the sealant strip was adhered to shingle below. The investigation identified two distinct, nonrandom, patterns of partially unsealed shingles corresponding to the method of shingle installation; vertical patterns with racked installations and diagonal patterns for diagonal installation of shingles. The total percentage of roofs with partially unsealed shingles exhibiting these patterns ranged from less than 1% for a six year old roof to over 79% for a twenty year old roof. Whereas, roofs without the distinct unsealing patterns had less than 1% of the total number of shingle strips unsealed. A statistically significant increase in the total percentage of partially unsealed shingles was observed for older roofs (7-13 and 14-20 years) when compared to newer roofs (0-6 years). Partial and full unsealing also occurred on hip and ridge cap shingles, likely attributed to poor adhesion at the onset of service life. A similar pattern of wind damage was observed in shingles reported in post-hurricane damage assessment reports. This similarity suggests that pre-storm partial unsealing condition is a strong influence in the actual wind resistance of asphalt shingle roofs.

INTRODUCTION

Asphalt shingles are the predominant roof covering material for single-family residential structures throughout the United States. In hurricane prone Florida, asphalt shingles cover the roofs of over 80% of the existing residential building stock (Engineering Team Report, 2009). The study described in this paper was one of seven experiments undertaken under a two year research program at the University of Florida that focused on the wind resistance asphalt shingles. This holistic program quantified the performance of asphalt shingles at the component and system-level in order to define the roles of aging, product design, and wind load mechanics. The ultimate goal of this program is to provide a roadmap for mitigation strategies to improve wind resistance of asphalt shingles.

The asphalt shingle roof system consists of individual strips – up to 4000 for a common residential roof – of asphalt impregnated fiberglass or organic mats nailed to the roof substrate (Figure 1). The rectangular planform of a typical three-tab shingle strip is 305 mm (12 in) high by 914 mm (36 in) wide, while a laminate shingle strip is a slightly larger 330 mm (13 in) high by 965 mm (38 in) wide. Each shingle course (row) is lapped over the preceding course to produce an exposed (visible) surface that is approximately 127 mm (5 in) wide (Figure 1). The shingles are also horizontally offset between courses – three-tab shingles are offset 6 in (i.e., one-half tab width) and laminate shingle offsets range from 102 mm (4 in) up to 178 mm (7 in). Hip and ridge lines are covered with additional cap shingles consisting of either field cut three-tab shingles or pre-manufactured products.

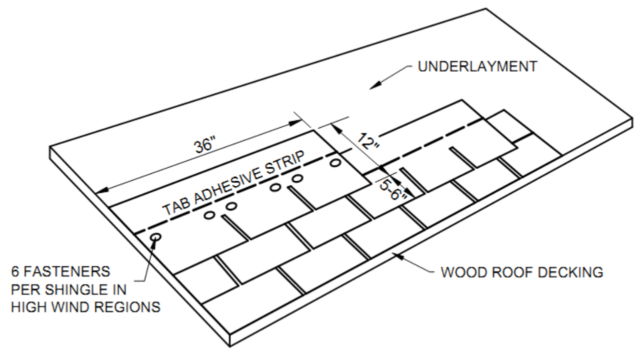

Figure 1. Three-tab field shingle installation (note: laminate shingle follows similar pattern).

The sealant strip located along the leading edge of each shingle is the primary vertical load path that transfers wind uplift forces from the shingle's surface down to the course below (Peterka et al., 1997). The sealant is a thermally-activated bitumen based product that bonds the shingle's leading edge once sealant temperatures exceed the softening point of the material – typically less than 60°C (140°F).

The wind resistance of modern shingle products is classified by test standards ASTM D7158/UL 2390, which evaluate the ability of the sealant strip to resist design level wind uplift loads. These standards are only valid for shingle products that are fully-sealed and the adhesion performance is defined for new products with no regard for changes in the sealant strength that may occur over the life of a roof. Wind uplift forces can increase with the loss of sealant strip adhesion due to wind being forced through gaps in the unsealed sealant strip that increases the underside pressure on the shingle (Peterka et al., 1997). This action increases the vulnerability of the shingle to blow off. Further details on the standard wind test methods for asphalt shingles and evolution of the sealant strip design to resist wind can be found in Dixon et al. (2012).

Post-storm damage assessments have repeatedly reported sealant strip failures of shingles in the field of the roof and along hip and ridge lines, however, their failure mode remains unknown (FEMA, 2005a; FEMA, 2005b; FEMA, 2006; FEMA, 2009). The limited data that exists regarding the long term in-situ sealant strip adhesive performance indicates that partial unsealing can occur on naturally aged shingle roof systems (Marshall et al., 2010). Yet, the extent and specific cause of this partial unsealing issue also remains unknown.

A potential link exists between the observed partial unsealing of field shingles and field shingle cracking issues reported in the early 1990s (Koontz, 1990). This report noted the formation of cracks on the face of three-tab shingles emanating from the end joint of the shingle course below (Koontz, 1990). The cause of the failure was attributed to an internal tensile failure of the reinforcement mat due to long-term thermal cycling of the asphalt shingle strip (Koontz, 1990). As with all other materials, shingles expand when heated and contract when cooled (Cullen, 1963); however, the precise expansion/contraction rate for asphalt shingles remains unpublished. Due to the horizontal offsets placed between shingle courses, each shingle strip is bonded along the sealant strip line to two separate shingle strips on the course below. Heating and cooling of the shingle will impart a differential movement relative to the two adjacent shingle strips, and, as a result, in-plane shear stress is applied through the sealant strip to the upper shingle's surface. For shingle cracking, the tensile strength of the reinforcement was less than the shear capacity of the sealant strip. In response, manufacturers increased the tensile strength of the fiberglass reinforcement mat. However, thermal cycling still exists, however.

The objective of this study was to evaluate the adhesive performance of naturally aged asphalt shingle sealant strips on residential structures throughout Florida. Twenty-seven asphalt shingles roof systems were surveyed in-situ to detect the presence of adhesion along the sealant strip line for shingles in the field of the roof and along the hip and ridge lines. The surveyed residential structures were occupied single-family residential structures that were acquired either through a Florida Department of Emergency Grant or through personal contact with the authors. The roof slopes ranged from 4:12 to 7:12. Roof ages were distributed as follows: one month to six years (six roofs), seven years to thirteen years (nine roofs), fourteen years to twenty years (seven roofs), and unknown age (five roofs). Ten roofs were three-tab style, while seventeen were laminate style. The following sections detail the survey method, results, discussion, and conclusions regarding the long-term adhesion performance of asphalt shingles sealant strips.

SURVEY METHOD

The purpose of the survey was to develop a boolean sealed or unsealed result, as opposed to a direct measurement of uplift resistance. The non-destructive survey method consisted of personnel using their fingertips to gently apply upward finger pressure along the leading edge of each field, hip, and ridge shingle installed on the roof (Figure 2). Due to the flexibility of asphalt shingles, an unsealed shingle, even partially so, provided nearly zero resistance to uplift and therefore only a small application of uplift force was required. Shingle temperature was recorded throughout each survey; however, no correlation was established between shingle temperature and patterns of unsealed shingles. A partially unsealed shingle was defined as any loss of adhesion on the shingles strip (for laminate) or tab (for three-tab) that was greater than or equal to a continuous 51 mm (2 in) length of sealant. A fully unsealed shingle was defined as the loss adhesion along the entire length of the sealant strip. For each unsealed shingle, the location of the shingle strip on the roof, total length of unsealing, location of unsealing on the strip (i.e., left corner, middle, etc.), and failure mode of the unsealed strip was noted on a roof plan. Each unsealed shingle was also marked on the shingles top surface, where unsealed, using a small strip of colored tape to assist with unsealed pattern recognition and photograph records.

Figure 2. Partially unsealed field shingle discovered during a survey.

RESULTS

Unsealing of Field Shingles

Two distinct, nonrandom, patterns of partially unsealed shingles were observed on 70% of the roofs surveyed and were found on both three-tab and laminate shingle systems. As shown in Figure 3, the patterns (marked with blue painter's tape) corresponded to the method of shingle installation. Vertically installed shingles (i.e., racked) had vertical patterns of partial unsealing, while diagonally installed shingles had diagonal patterns of partial unsealing. Given the random nature of selecting roofs to survey these patterns are likely independent of shingle manufacturer and installer. The newest roof that contained the unsealing patterns was six years old, and the total percentage of shingle strips containing the unsealing patterns – for known roof ages – ranged from less than 1% for a six year old roof to over 79% for a 20 year old roof (Figure 3).

For three-tab shingles, the partial unsealing occurred on the extreme end tab of the strip where the end joint of the shingle course below aligned with the centerline of the tab (Figure 4a). Thus, only one tab of the three within each strip was partially unsealed. In general, the remaining two strips were well sealed along their entire lengths. As shown in Figure 4a, unsealing initiated from the shingle strip's end joint to end joint of the shingle course below – approximately 152 mm (6 in) was unsealed. Laminate shingles exhibited a similar pattern of partial unsealing with the unsealed length running from the end joint of the strip to the end joint of the shingle course below (Figure 4b). The resultant unsealed length for laminate shingles, therefore, was controlled by the horizontal offset that was selected to install the system – typically 102 mm (4 in) to 178 mm (7 in). In general, the unsealing ceased in both three-tab and laminate shingles at the end joint of course below; however, unsealing beyond this end joint was observed on older roof coverings. The failure mode for all field shingles exhibiting the noted unsealing patterns was a cohesive failure in the sealant.

Figure 3. Patterns of partially/fully unsealed three-tab and laminate shingles. (Note: blue tape denotes location of unsealing).

(a) (b)

Figure 4. Location of partial unsealing for (a) three-tab and (b) laminate shingle systems.

To evaluate the role of natural weathering on the observed unsealing, the age of each shingle roof surveyed was determined from publicly available building permit records and information provided by the homeowner. Unsealing statistics from surveys conducted on roofs with unknown ages were not included in this analysis. For each home, the total percentage of unsealed shingle strips – either fully or partially – was calculated by dividing the count of the total number of shingle strips with unsealing by the total number of strips installed on the roof. The total percentage of unsealed shingle strips stratified by roof age is shown in Figure 5. The plot indicates a general increase in the percentage of unsealed shingles as the roof age increases. Recall, unsealing patterns were not observed on roofs less than six years old. The total percentage of unsealing for all roofs with less than six years of aging is less than 1% while roofs with greater than six years of aging had up to 79% of the shingle strips with either full or partial unsealing. The variability of data set appears to increase with roof age as well.

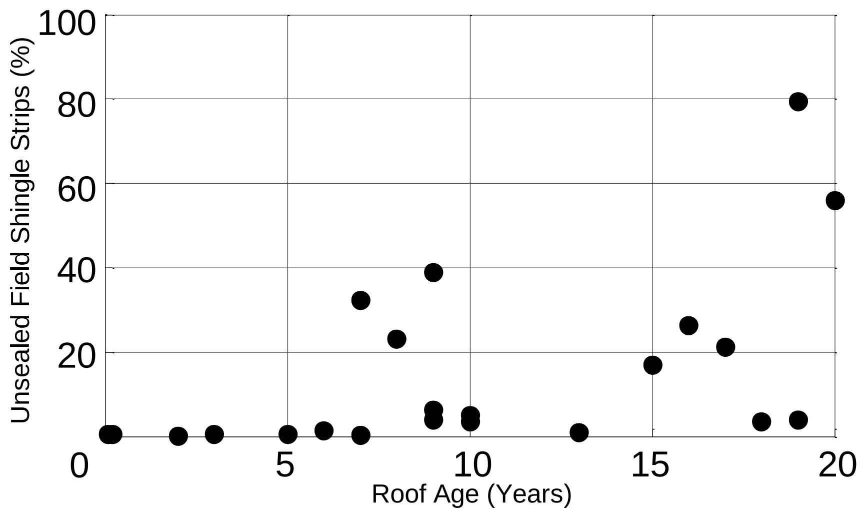

Figure 5. Percent of unsealed shingle strips located in the field of the roof verses roof age. (Note: fully and partially unsealed shingles combined)

Finally, the roofs were grouped into age ranges (0-6 years, 7-13 years, and 14-20 years) to evaluate the statistical significance of the perceived increase in unsealing with increasing roof age. The results of single sided t-test assuming unequal variances ($\alpha = 0.05$) indicates that a statistically significant increase occurred in both the 7-13 and 14-20 year old roofs when compared to the 0-6 year old roofs (Table 1). However, significance was not established between the 7-13 and 14-20 groups.

Table 1. Statistical comparison between grouped roof ages

Roof Age Range (Years) [No. of Roofs]	Mean Amount of Observed Unsealing (%) [σ]	Statistically Significant Increase Between 0-6 Year Old Roofs (P-Value)[a]	Statistically Significant Increase Between 7-13 Year Old Roofs (P-Value)[a]
0-6 [6]	0.7 [0.4]	--	--
7-13 [9]	11.8 [14]	Yes (0.017)	--
14-20 [7]	29.6 [28]	Yes (0.017)	No (0.080)

[a]Statistical significance determined using T-Test single sided test with unequal variance with $\alpha = 0.05$

Unsealing of Hip and Ridge Shingles

Unsealed hip and ridge cap shingles can be classified into two categories: (1) lack of sealant under the leading edge of the shingle cap (Figure 6a), or (2) adhesive failure between the sealant and underside of the cap near the cap's edge (Figure 6b). The lack of sealant can be attributed to the installation method of the shingle system, while the adhesive failures indicate that the cap shingles suffer from a weak bond between the sealant and underside of the cap. The adhesive performance of the sealant located directly on the hip/ridge line was superior to the adhesion towards the edges of the cap.

(a) (b)

Figure 6. Typical unsealed ridge and hip cap shingle conditions: (a) no sealant strip below cap and (b) poor adhesion on edges of cap.

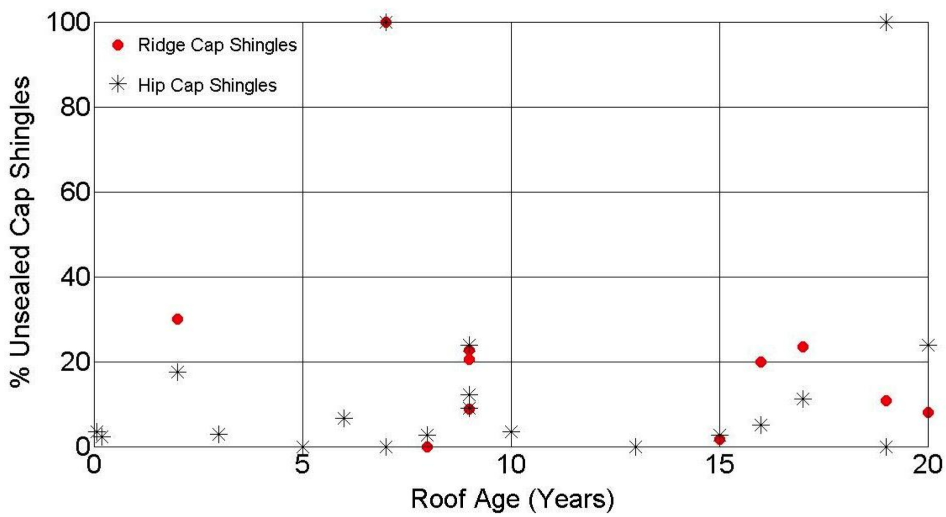

Figure 7. Percent of fully/partially unsealed cap shingles (hip and ridge) verses roof age.

Similar to the field shingles analysis, the total percentage of unsealed hip and ridge cap shingles was calculated for each surveyed roof. Placing this percentage in the context of shingle age it is apparent that no correlation exists between roof age and the percentage of unsealed caps (Figure 7). As expected, hip and ridge cap shingles are equally as likely to be unsealed. Aside from the cap shingles that did not have sealant below their leading edge, the total percentage of unsealing for caps ranged from 0 – 30%.

DISCUSSION

The results detailed above indicate potential issues in the long-term adhesive performance of the shingles sealant strip. This unsealing is likely a result of a systemic failure of the sealant, rather than a random loss of adhesion. Two questions arise: (1) what are the mechanisms that drive the partial unsealing observed in the field and hip/ridge shingles and (2) what is the wind damage vulnerability potential for asphalt shingle roofs containing this unsealing.

First, the mechanisms that drive the partial unsealing in the field shingles and hip/ridge shingles are likely different mechanisms. For field shingles, a statistically significant increase in the total percentage of unsealed shingles was established on older roofs when compared to newer. For hip and ridge cap shingles, no statistical significance between the newer and older roofs was established. Furthermore, the failure mode of partially unsealed field shingles – cohesive failure in the sealant – did not match the failure mode of the hip/ridge cap shingles – adhesive failure in the sealant. It is postulated that the partial unsealing of field shingles reported in this paper and in Marshall et al. (2010) is a result of long-term cyclical thermal movement of the shingle system causing an internal shear failure of the sealant strip material. For hip and ridge cap shingles, poor adhesion at the onset of service life is the most likely cause of their partial unsealing. Field-cut and pre-manufactured cap shingles are originally flat strips that are folded over the hip/ridge line to match the roof slope. Quick bond of the sealant strip is required once the cap has been installed to prevent the cap from reverting back to its original, flat, state. The adhesive failure between the sealant and bottom cap surface indicates that current shingle cap design may not adequately provide this early tack, leaving the edges of the cap vulnerable to unsealing.

Second, the impact of unsealed asphalt shingles on the wind performance of shingle roofs has not been addressed in previous literature. Post-storm damage assessment reports provide the most relevant information; however, their conclusions contain uncertainty as the condition of the damage roof prior to the storm is unknown. Reports by FEMA (2005a, 2005b, 2006, 2009) have consistently noted asphalt shingle wind damage patterns that have striking similarity to the partially unsealed shingle patterns observed in this study (Figure 8). These failures are most often attributed to a lack of fasteners on the end joint of the shingle due the racked installation method. However, as the sealant strip is the primary load path, unsealing of the sealant strip is required before nail placement becomes an issue. Hip and ridge cap failures are the most frequently reported asphalt shingle-related failures in post-storm reports (FEMA, 2005a). The failures are attributed to poor adhesion between the cap and the sealant strip (FEMA, 2005a) – echoing the findings of this study.

Figure 8. Potential link between (top) post-hurricane Katrina damage observed by FEMA (2012) and (bottom) observations of pre-existing unsealing during roof surveys.

CONCLUSIONS

In this study, 27 naturally aged asphalt shingle roofs located on single family buildings in Florida were surveyed in-situ to evaluate the presence of sealing along the asphalt shingles sealant strips. The age of the shingle roof coverings ranged from one month to over twenty-five years.

The study found significant, nonrandom, patterns of partial unsealing in both field and hip/ridge cap shingles. Partial unsealing for field shingles occurred near the end joint of each strip on both laminate and three-tab shingles. The failure mode of the unsealing was a cohesive failure in the sealant, indicating that the shingle was, at one time, fully sealed. The total percentage of partially unsealed shingles on a given roof statistically significantly increased with roof age. Damage patterns from post-storm assessments are similar to the patterns of partial unsealing discovered in this study, suggesting that partial unsealing may be the root cause of observed wind damage of field shingles.

The partial unsealing of hip and ridge cap shingles occurred on roofs of all ages with no correlation established between roof age and the amount of unsealed cap shingles. Partial unsealing occurred on the edges of the caps with good adhesion found on the portion of the cap directly over the ridge line. Failure of hip and ridge caps frequently occurs in below-design level wind storms and adhesion at the beginning of the caps in-service life may define the long-term wind performance.

The results gathered from this study are a critical step towards better defining the cause of asphalt shingle failures in below design-level wind storms. Future work by UF will focus on quantification of thermal movement in asphalt shingles and the expansion of roof surveys to other regions of the United States.

ACKNOWLEDGEMENTS

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Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors, partners and contributors.

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Critical Look into ®ISOMAX (Zero Energy Use Structures) Construction

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Abstract:

The intention of this paper is to discuss the opportunities of implementing in the ®ISOMAX Building Technology (Unknown, 2012 1) as a means to achieving Zero Energy Use Structures. ®ISOMAX is a fully integrated building system that collects solar heat energy and stores the heat in the earth just under the building. The system uses circulating fluid to transfer heat between the earth storage and the building envelope. The process allows the entire envelope of the building to take advantage of the collected energy by running the fluid, warmed or cooled, to move heat into or out of the insulated concrete wall and the roof. As Energy Reconsidered continues to prepare this technology for introduction into the American marketplace the team is engaging in dialogue with the construction industry to gather support for advanced modeling and prototype testing opportunities.

Summary:

The ®ISOMAX Building Technology as a whole furthers the notion of living building (Unknown, 2012 1) standards by integrating the building shell and conditioning components into an active system that can store or collect energy in response to the exterior weather conditions and the internal comfort levels of the occupants. The building shell becomes an active participant in occupant comfort and energy savings.

In the European market, this type of building construction has delivered an average heating load of approximately 24 kWh / (m^2/a) (Sturm, 2009) which is just above those of a passive house standards that have set the most restrictive benchmarks for the heating and cooling load of a structure not to exceed 15 kWh/(m^2/a) (Passive House, 2012)

The ®ISOMAX building system relies on two ideas that are different than those currently being used in a high performance buildings or passive house standards (Passive House, 2012 4)The first concept is the transformation of the exterior wall from a passive thermal resistance to one that can actively participate in the temperature control of the interior. This is accomplished by the heat transfer fluid which moves heat into and out of the walls and roof. The roof captures the naturally occurring solar heat energy for storage in the earth. The second concept is to utilize the earth as a thermal medium to provide cooling, heating, and storage to allow for temperature regulation of the building. The structure interacts with the earth-stored energy, allowing it to be stored and recalled as needed over time.

Introduction:

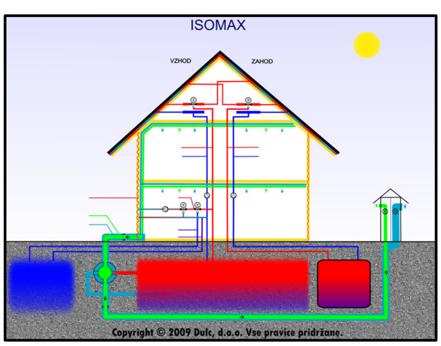
Several operational case studies have been built by international license partners, with the design guidance of Dipl.- Ing., Phys. Edmond D. Krecke. The previous case studies looked at the local european building technology to validate this construction approach as well as to engage the European research community to assist with further refinement in construction methods and further support the energy modeling of an active wall system. The European residential and small commercial building practices are different from US practices, and further proof of concept testing is needed to confirm the ISOMAX application in the USA.

Approach:

Our approach begins with a comparison of the performance of an ®ISOMAX home constructed in Slovenia by our international partners with a simulated home located in Philadelphia PA following PASSIV house guidelines (Passive House, 2012 4)The home was simulated using REM/Rate V13.0 (Rem Rate, 2012 5)software commonly used in residential applications to develop energy benchmarking in new and existing construction.

Slovenian Case Study:

The Slovenia case study home is a 170 m^2 size constructed about 100 km southeast of Ljubljana Slovenia and utilizes ®ISOMAX technologies as its only source of heating, cooling, and ventilation. The home is built with ICF exterior walls (U=.145) and standard wood framed roof with high insulation levels (U=.113). The walls and roof are energized using the ISOMAX system to create a thermal barrier between the interior conditioned spaces and the exterior unconditioned space. The home is built on an insulated concrete slab (U=.176). The system has a calculated total energy load of 61 kWh / (m^2/a) with an occupancy load of 4 people (Sturm, 2009)



This case study house is actively monitored and live data feeds can be seen via a web portal contact our office for further assistance as this information is proprietary to our Slovenian partners.

Philadelphia Simulation Data:

For our comparative data we have modeled a typical colonial style home employing passive house standards. In our model we simulated the weather conditions of the home in the Philadelphia, PA area. The house has 190 m^2 floor area and assumed an occupancy load of 4 persons. The exterior wall structure used insulated concrete forms (Berg, 2012) and included semi-conditioned crawl space and attic to house the mechanical equipment. As expected, the passive house based design performed well.

The Philadelphia house simulation model consisted of the following design components. The above ground-wall construction uses insulated concrete form consisting of 2 ½" extruded polystyrene, 6" concrete mass, and 2 ½" extruded polystyrene (Unknown, 2012 8) for an effective U = 0.210. The roof assembly has an effective U = 0.193. There is a sealed crawl space with insulated foundation walls throughout the entire footprint of the building. Both the attic and the crawl space are considered semi-conditioned space for the housing of the mechanical systems of the home. The simulated home has higher U values; however it is located in a milder climate.

Without the introduction of any alternative energy sources such as solar hot water, geothermal ground loops, or photovoltaic electricity the model required a total energy load of 562 kWh / (m^2/a) (Berg, 2012) which is comparable to that of the home in Slovenia.

The total heating and cooling load for the modeled house (16.4) (Berg, 2012) is lower than the Slovenian house (24.0) (Sturm, 2009) This is attributed to the milder climate in Philadelphia. The next challenge is to confirm that an ISOMAX building shell can regulate interior temperature given the local solar energy density and climate.

Table 1. Data Comparison Chart (including Passive House):

Description	Slovenia	Philadelphia	passive
Size m^2	170	190	100-120 ~
Air Tightness	0.6 ACH_{50}	0.6 ACH_{50}	0.6 ACH_{50}
U Wall (W/m^2K)	0.145	0.210	0.2-0.15
U Attic (W/m^2K)	0.113	0.193	0.2-0.15
U Floor (W/m^2K)	0.176	0.403	no requirement
U Windows (W/m^2K)	0.510	0.790	0.790
Ventilation Efficiency	98%	≥ 75% @.35 Wh/m^3	≥ 75% @.45 Wh/m^3
Total Primary Energy: $kWh/m^2/yr$	61.0	57.2	120
Total Heating /Cooling: $kWh/m^2/yr$	24.0	16.4	15

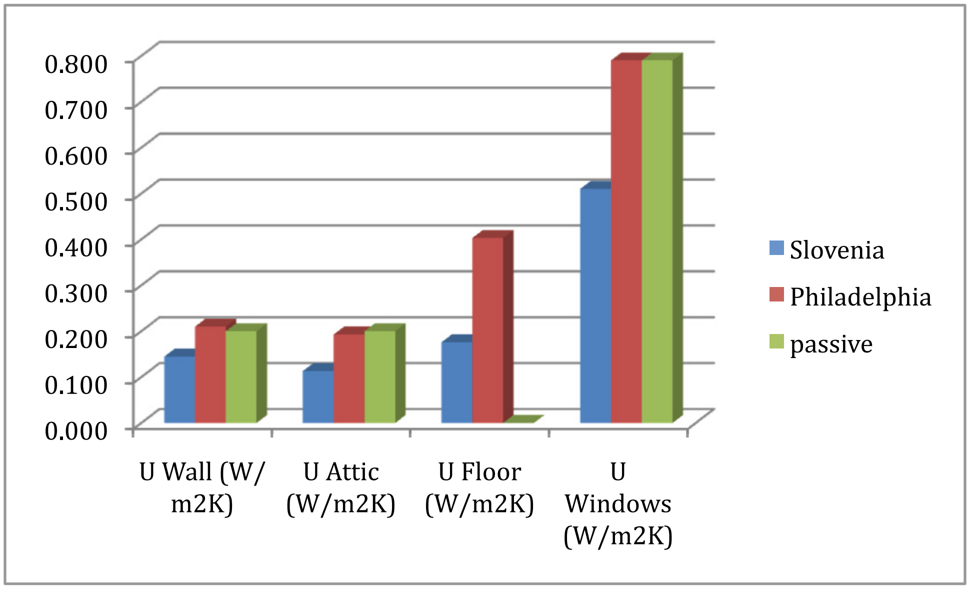


Figure 2. Chart comparing U-Values of Building Components

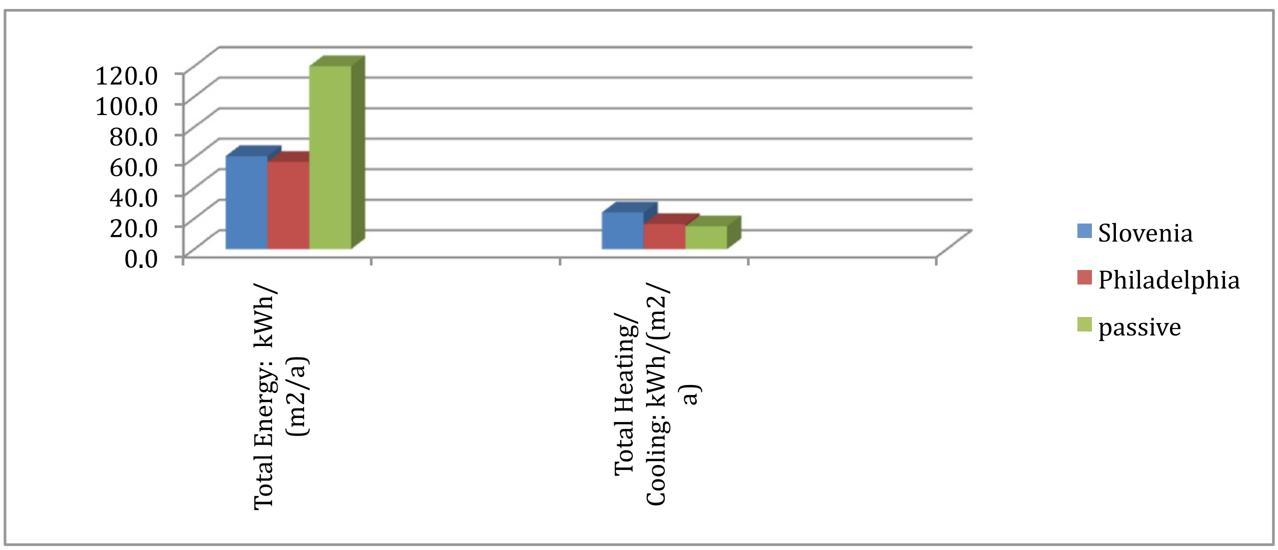


Figure 3. Chart comparing Energy consumption

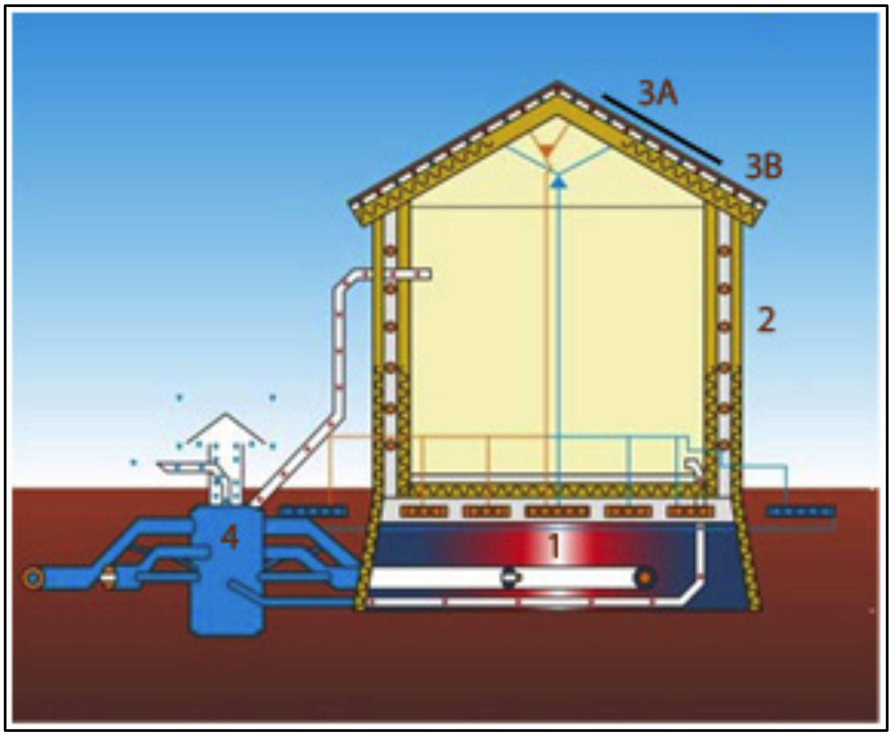


Figure 4: Conceptual Diagram of the Thermal Barrier

Figure 4: Notes
1. Underground storage system layout (energy reservoir)
2. Outer wall design with temperature barrier
3a. Solar Thermal Collection Panels
3b (Low Tech Alternative) Roof structure with solar absorbers
3. Pipe in pipe – ventilation

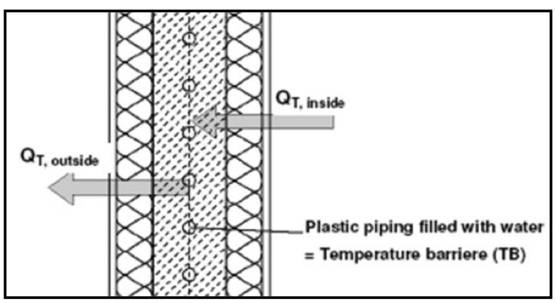


Figure 5: Science behind the Thermal Barrier

Figure 5: Notes
This diagram is the schematic diagram that we are looking to investigate in both a new construction and adaptive reuse condition. In the adaptive reuse setting we have a several alternative construction details. The primary scientific principle is to maintain the thermal mass of the internal wall and foam on each side to maintain a microclimate in the building envelope.

Evaluation Conclusions:

Overall the Philadelphia simulation was aligned with the performance of the case study home constructed in Slovenia. By looking at the data what became evident is that to some extend how to begin to understand the overall effectiveness of the ®ISOMAX system. During this evaluation we focused on the energy budget from four perspectives and using two of these sets of data derive a few conclusions help us understand the effectiveness of the ®ISOMAX system.

We determined there were four separate budgets that need to be analyzed.

- The first was an energy budget connected to the amount of energy that would be used to maintain the thermal mass of the envelope at a constant 68 F/20C.
- The second was the amount of energy storage needed to ensure the system is able to maintain the desired comfort levels and energy performance.
- The third item we need to look at further is the financial investment required to construct a home to these standards in the United States market.
- The fourth and final performance metric is the operating cost of to maintain this type of Zero Energy Use Structure.

When considering the first two "energy budgets" we look at the ISOMAX components integrated into a specific building envelope and building site. The energy required to heat / cool the thermal barrier and the ability for the soil below the building to store the energy required to maintain the thermal barriers constant temperature of 68 F/20C. Although not directly discovered within our energy model a partial confirmation has derived by the similarity in energy loads required by the house constructed in Slovenia and those by the simulated house located in Philadelphia. If we translate the information from our energy model the house located in Philadelphia will be required to capture, store and release approximately 16.4 kWh/(m^2/a) annually to maintain its temperature requirements. When modeled in the simulation the Philadelphia based house required 300 sqft / 500 gallon water heating system and an auxiliary 450 sqft / 6 kWh photovoltaic systems to balance out the energy demands, therefore, achieving a net zero energy use building.

Can a reasonably sized earth heat reservoir store the required energy? Additional questions also arise on the dynamic behavior of the system; can it moderate the heat transfer to maintain internal comfort levels without supplemental heating or cooling systems?

At this point we need specific building performance measures in a US climate zone to understand the local potentials for solar energy collection and the effectiveness of the ®ISOMAX techniques when implemented with our available building methods, materials, and controls.

Current Market Technology:

Despite the invention and integration of new and improved solar / geothermal technologies, conventional building design and construction (with or without these technologies) continues to address building design and energy design (efficiency) as separate non-engaging entities which consist of a static isolated shell and supporting mechanical components. While conventional practices include the installation of high performance / low energy consumption (Energy Star rated) equipment, triple insulated glazing, and super insulated perimeters, Energy Reconsidered's technology shifts this paradigm by transforming the envelope of the building into a computer monitored responsive barrier capable of maintaining a constant interior temperature regardless of the time of year or geographical location, therefore the technology reduces the size and cost of the PV inputs needed to achieve net zero.

Energy Reconsidered's (ER) technology has the ability to be a front runner in the energy technology industry given the current energy criteria being met in the market place today. ®ISOMAX has the ability to easily create Zero Energy Building (ZEB). This is significant because of the 31,800 LEED (Tweed, 2012) certified structures in the United States, only 60 of these meet ZEB or ZEC (Zero Energy Capable) requirements (Tweed, 2012). There is tremendous opportunity in the development and testing of dynamic building assemblies. Additionally, we can design a structure that has a provides us a greater ability to interface with the structure itself while maintaining connectivity to the naturally occurring solar irradiation and thermal storage capacity of the earth. This unique combination if proven will provide a new direction in the building industry and allow for Zero Energy Use Structures to become a standard where as they are currently a rare occurrence.

These investigations are important because it shifts the current construction methodology significantly by integrating a temperature control system into an envelope of a building, then providing an interface for the envelop into the earth and solar collectors, which allow for the collection and reuse of the solar energy. Increasing the ability of a building to reach energy neutrality while greatly reduces its supplemental energy loads is highly likely through the proper refinements of the ®ISOMAX system. Thus enabling a building's envelope to distribute natural energy collected (and stored) from the sun and earth, ER's technology substantially reducing the temperature fluctuations (ΔT) which occur between the interior and exterior surfaces of a building's envelope (wall), maximizes the thermal efficiency of the building, eliminates traditional mechanical equipment and its energy requirement, and greatly reduces the consumption of supplemental and off-site produced energy. This provides the potential for a highly responsive and energy efficient system to rely on for the construction of Zero Energy Use Structures.

Final Conclusion:

Because 95% of existing buildings in North America are three stories or less, which is a design limitation currently seen with ®ISOMAX [(1)] and because it is widely believed that forthcoming changes to National Building and National Energy Codes will greatly affect the minimum standards for new and existing buildings. It is our belief that it is time to reconsider the way buildings are constructed – especially with respect to energy efficiency and dependency. Energy Reconsidered's technology is significant because it transforms the way we build and energize our buildings. We strongly believe that implementing this and other technologies into the marketplace along with sustained research and development is critical to the progress of the building industry. Through this and other research into building materials and systems we will produce more flexible, universal, and cost effective dynamic wall, floor, and roof systems allowing us as a whole to further advance the science of dynamic construction assemblies.

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State-of-the-Art Review of Window Retrofit Options for Energy Saving in Single Family Dwellings

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ABSTRACT

The study presented here involved the investigation of several different window retrofit solutions for energy efficiency. The criteria used to compare each system were Thermal Improvement, Thermal Comfort, Condensation Potential, Impact on Daylighting, Air Leakage, Cost, Ease of Operation, and Aesthetics. This paper introduces various methods for retrofit of existing windows, presents their attributes, and compares various options based on the stated criteria.

INTRODUCTION

According to the 2011 Buildings Energy Data Book (US DOE, 2011), buildings use approximately 40% of the nation's energy consumption. Approximately 56% of this energy is used for space heating, cooling, and lighting applications, while 25-35% of this energy is wasted due to inefficient windows. All of these factors are directly impacted by the building envelope (Totten and Pazera, 2010). In addition to other functions (Kazmierczak, 2010; Sanders, 2006), successful building envelopes shield occupants from outside weather conditions, whether that be excessive hot temperatures in the summer or extremely cold temperatures in the winter, as well as provide a connection to the outside in terms of natural lighting and views.

Fenestration systems are a key element in achieving these goals, although they are always the weakest link in terms of thermal performance (Oldfield et al. 2009). This is primarily due to the extremely high U-value found in windows in comparison to wall systems. In addition, glazing systems can have a significant impact on energy savings through daylighting. For example, Johnson et al. (1984) found that fenestration can reduce total building peak demand by up to 14-15%.

One of the major challenges facing homeowners is the high capital cost associated with fenestration upgrades. This is particularly problematic since the energy savings associated with replacing windows with their higher efficiency counterparts is typically relatively small. The payback period for replacing single glazed windows with double glazed windows can be as long as 50 years for cold climates. This payback period will also increase as the quality of the existing windows increases. When double glazed uncoated windows are replaced with triple glazed units with argon fill and a low e coating, the payback period is typically around 100 years for cold climates (Guler et al., 2001). Another study conducted by Frey et al. (2012) demonstrated that high performance window upgrades have a return of investment (ROI) of only between 1.2-1.8% based on climate, which translates to a simple payback period of 55-83 years. Therefore, for most homeowners it is necessary to determine low cost methods of reducing heat flow through their windows.

The goal of this study is to evaluate retrofit strategies along with ratings of energy performance. The paper starts with an investigation of the performance of several different window retrofit solutions (a.k.a window attachments). This includes a description of each method as well as an indication of the cost of each method, the expected thermal improvement, as well as any potential risks that may be involved. A ranking will then be presented that can be helpful to aid homeowners in selecting a glazing system.

PARAMETERS OF THE STUDY

Several criteria are considered in this paper, including quantitative issues such as Thermal Improvement, Comfort, Cost, Condensation Potential, Impact on Daylighting, and Air Leakage as well as qualitative issues such as Ease of Operation, and Aesthetics.

Thermal Improvement

One of the most important criteria for energy management is the thermal improvement provided by a window attachment system. When considering thermal improvement, there are two basic aspects that should be considered. The first is the increase in U-value. The second aspect is how well it reduces solar heat gain.

The thermal performance of each window attachment is measured in terms of the improvement obtained in comparison to a double glazed window, based on manufacturer data or other scientific studies. Percent improvement is determined using the equation below.

$$\frac{Improved\ Performance - Orginal\ Performance}{Original\ Performance} \times 100\%$$

Comfort

The two components that will affect comfort are inside air temperature and the Mean Radiant Temperature (MRT). The MRT is determined by weighing the effects (by area, spatial relationship, and difference in temperature as compared to the skin of a person in the space) of each object in a space. When the MRT is warmer than the occupant's skin temperature, that person will "feel" warm. On the other hand, when the MRT is cooler than the occupant's skin temperature, they will "feel" cold.

The MRT of a window is a property that is based on variables such as room furnishings, the size and location of the window in that space, as well as regional climate characteristics such as outside temperature, humidity, and wind speed. For this study, the window attachments are rated as improving the thermal comfort, reducing the thermal comfort, or having no effect on the thermal comfort with all other variables being equal.

Condensation Potential

Condensation occurs when moist air contacts a surface with a temperature below its dew point. For fenestration, this will usually involve interior air condensing on the interior surface of a cold glazing unit, typically near the frame. Excessive condensation can result in mold growth or rot in the window frame and sill. In addition, condensate on windows in particularly cold climates has the potential to freeze the window shut, creating possible egress issues. Condensation typically occurs as a result of poorly insulated windows. Generally speaking, exterior window attachments that result in an increased glazing temperature will have a lower risk of condensation, while interior attachments that lower the temperature of the glazing will have an increased risk of condensation. Interior window treatments that either completely seal out moist air from the surface of the windows or allow for increased levels of ventilation will have less condensation. In this study, window attachments are rated as having an increased or a decreased risk of condensation.

Impact on Daylight

Most window attachments have some effect on the visual transmittance of the window assembly. When opaque attachments that significantly reduce the daylighting potential of an interior space are used, increased energy is required for lighting. This may offset any energy savings depending on the requirements of the space. Each window attachment is rated as having no impact, minimal impact, or significant impact on the daylighting potential of a space.

Air Leakage

There are two major routes in which outside air can infiltrate through windows. The first is between the sash and the jamb, while the second is between the jamb and the wall. The ability of a window attachment to reduce air leakage is judged based on how effective it is at preventing air leakage through each of these locations.

Cost

Since window attachments are all retrofit solutions for residential construction, the cost of all materials come from sources available to the common homeowner such as home improvement centers. When appropriate, installation costs are included.

Ease of Operation

The most successful window attachments will not become an inconvenience to the homeowner in order to operate. A window attachment that is difficult to use will be ignored by the occupant, rendering it useless, or may be used incorrectly, potentially resulting in an increase in energy use. Window attachments will be rated as requiring no work, minimal work, some work, or significant work.

Aesthetics

The aesthetic impact of a window attachment is the hardest criteria to weigh against the others. An exterior window attachment may affect the street appeal of a home or the interior feel of a room. The severity of any positive or negative impact is subjective on the part of the occupant. Therefore, each window attachment is rated as having "minimal to no aesthetic effect" or "substantial aesthetic effect."

EXTERIOR WINDOW ATTACHMENTS

OPERABLE SHUTTERS

Although exterior shutters on new homes are typically inoperable, existing primarily for aesthetic purposes, older homes typically have operable shutters. These shutters provide protection for the glazing as well as an effective means of solar heat gain prevention. They can fold from the sides, top, or bottom as well as slide into place on tracks. Shutter performance will vary based on material (wood, aluminum, and steel) and style (louvered, raised paneled, board-n-batten, bahama, or accordion type.)

Shutters with louvers can be an effective means of reducing the solar heat gain into the building as well as limiting the effect of night sky radiation. However, exterior shutters will be an ineffective means of insulation unless a mechanism is in place to provide sealing around the perimeter of the shutter. For best performance, light filtering shutters should be closed in daylight hours for solar heat gain reduction during the summer. In the winter, shutters should be open for passive solar heating during the day, then closed at night to prevent heat losses.

Bahama style shutters (e.g. www.shutterkings.com/extbahama.htm) are particularly effective at creating a shading effect for the window. A variation of this style of shutters could be designed with hinges at the bottom and a reflecting surface facing the window. This system would be used to reflect sunlight further into the building for daylighting and passive solar heat gain. A highly insulating material such as rigid foam insulation could also be used to reduce heat loss through the windows at night. A compressive seal could be utilized to insure that no air leaks through the windows when the shutters are closed.

INSULATING ROLLING SHUTTERS

Exterior insulated shutters (e.g. www.rollac.com) are a variation of the accordion shutters comprised of interlocking slats that completely cover the outside of a window when closed and retract to fit inside of a valence at the top of the window when open. The slats usually slide inside of weather sealed track and are operated with either an electric motor or a pulley system. Although they are primarily used for storm protection, units with an insulated core can also offer significant thermal improvement.

STORM WINDOWS

A storm window (e.g. www.larsondoors.com/storm_windows/) in its most basic form is an additional window system installed on the exterior of the existing window system. Storm windows are classified as Two-Track, Triple Track, Two-Track Sliding, and Basement. Storm windows can result in a substantial increase in thermal efficiency, which can be further improved when low- e coating is used, as well as reductions in air leakage and condensation risk.

WINDOW SCREENS

Insect screens are a common element of most residential window systems. Although the screens provide some shading effect; their presence is not taken into account with performance values for window systems. In addition to providing shading, they also slow the convective heat flow at the surface of the window.

PLASTIC WRAP ON WINDOW SCREENS

Plastic wrap can be used to cover the outside of window insect screens to create an inexpensive, easy to install alternative to storm windows. This method creates an additional airspace on the exterior side of the sashes. The thermal improvement in with this system would be greater than the 7% improvement obtained through using insect screens alone, but not as great as the 55% obtained through the use of exterior storm windows. A 20% improvement is assumed. This system does reduce air leakage, however drafts could seep between the edges of the insect screen and the jambs due to the lack of weather-stripping.

INTERIOR WINDOW ATTACHMENTS

CONVENTIONAL BLINDS

This system (e.g. http://www.levolor.com/products/metal-blinds/) uses individual flat slats, generally made of aluminum, wood, or vinyl, that can be adjusted to block light and solar heat gain While aluminum blinds are typically thin (6-9 gauge), wood and vinyl blinds can be as thick as ¼". In particularly humid climates, condensation may be an issue for wood blinds. Therefore, moisture resistant blind should be used.

INSULATING BLINDS

This system (e.g. www.levolor.com/products/cellular-shades/) uses a dual cell design that creates an air gap which provides additional insulation. Some more advanced models have edge tracks to limit the air movement around the blinds, which boosts the thermal performance of the system. Other designs have a reflective polyester layer on the side of the blind facing the window.

INTERIOR SHUTTERS

Interior shutters (e.g. www.horizonshutters.com/traditional-shutters) act similarly to blinds, except they are completely opened by swinging the shutter out of place. In addition, the angle of the shutters is adjusted manually or using an adjustment rod. The shutters are typically composed of wood or vinyl, with each slat being in the ¼" range. Although store bought models tend to be very expensive; do-it-yourself, highly insulated designs can easily be made for a low cost. However, as thermal performance increases, proper weather stripping is essential to prevent condensation.

ROLLER SHADES

The shades (e.g. http://www.levolor.com/products/roman-shades/) can be installed on either the interior or exterior of the building. The shades are pulled down as needed to block light and solar heat gain. They are stored in either a valence above the window or have a "Roman Shade" setup in which fabric folds up at the top. They are available in a variety of different materials and colors with varying transparencies.

CURTAINS AND DRAPERIES

Curtains and draperies (e.g. www.thermalwindowcurtains.com/) are common features of many homes. They are made with a variety of different materials in various styles and are typically used primarily for decoration. Although curtains will always be an effective method of shading, they will also be an effective insulator assuming the perimeter of the curtains can be sealed when closed, the fabric has an air barrier layer and is heavy enough to provide insulation (Langdon, 1980.) The use of a foil, reflective backing will result in additional savings. Condensation risk will be high, so a fabric should be selected which is effective at preventing moisture transport.

LOW EMISSIVITY FILMS

Low emissivity coatings (e.g. www.gilafilms.com/en/Residential-Window-Film.aspx) are usually applied to glass at the manufacturing stage for newer windows. However, many older homes still use uncoated glass. In these cases, a low emissivity film can be applied to the existing glass without the need for skilled labor. Although these films will not improve the insulation of the window, they will decrease solar heat gain as well as transport of long wave radiation (heat) from the interior pane outward.

PLASTIC WRAP AROUND WINDOW FRAMES

Plastic wrap can be used to cover the entire window frame on the interior of the building. Double-sided tape is used to attach the plastic to the outside of the window frames and a hair dryer is subsequently used to stretch the plastic tight. As an alternative, bubble wrap can be used to obtain even greater improvement in thermal performance, albeit at a greater loss to transparency.

DRAFT SNAKES

"Draft Snakes" are a fabric tube filled with rice or a similar fill. When placed along a window sill, they serve to block any drafts that are entering the space. They are only intended to prevent drafts that occur along the base of the window or a door. In addition, they will only be effective for leaky windows. Although they will not impact the sides of the sashes, they can effectively stop air leakage through the top or bottom sash of double-hung window.

DISCUSSION

A summary of the preliminary key performance characteristics of the retrofit options introduced is shown in Table 1. As can be seen, the thermal improvement ranged from 0 for systems that primarily focus on shading and SHG reduction, to 696% for custom made, highly systems which are capable of providing an air seal around the window. The cost for each system ranged from as little about two dollars to $600 for a 30"x60" window opening.

The systems were then ranked in order to compare the relative benefit of each system from a thermal improvement standpoint. The percent improvement for each system was divided by the cost of retrofitting a single window. This value was then normalized based on the worst performing system. Therefore, systems with a higher rank will perform better per dollar invested.

It was found that the rolling shutters ranked worst according to this criteria, whereas the custom made, interior shutters performed best. One of the more surprising results is how cost effective systems such as plastic wrap around window frames are. These types of systems also do not require any work on the part of the occupant beyond the initial installation.

Another important point to note is that many of the effective systems require some form of additional work to be done on the part of the occupant beyond basic installation. Systems such as curtains and draperies will be drastically less effective if measures are not taken to thoroughly seal around the edges. Many of these systems, including shutters, insulating shutters, curtains/draperies, and insulating blinds must be opened or closed throughout the day to allow for passive heating and daylighting as appropriate. If this effort is not taken with these systems, the true performance of the system will not be reached.

Table 1: Summary of performance characteristics for each window attachment

	Thermal Improvement	Comfort	Condensation Risk	Retrofit Cost for 30"x60" Window	Impact on Daylighting	Air Leakage	Ease of Operation	Aesthetic Impact	Rank
Shutters	up to 532% for custom designs[1]	Improved	Reduced	$100 [2]	Significant	Potentially reduced	Significant work required	Substantial	114.00
Roller Shutters	28%[3]	Improved	Reduced	$600 [4]	Significant	Reduced	Potentially significant work required	Substantial	1.00
Storm Windows	121%[1]	Improved	Reduced	$108.74 [5]	No Impact	Reduced by 5.7-8.6%[6]	Minimal work required	Substantial	23.84
Window Screens	7%[7]	Slight Improvement	Marginally Reduced	$5.04 [5]	Minimal	Ineffective	Minimal work required	Minimal	29.76
Plastic Wrap on Window Screens	20%	Improved	Reduced	$1.99 [5]	No	Potentially reduced	Requires work for yearly installation	Minimal	215.36
Conventional Blinds	Used for SHG reduction	Improved	Increased	$43-$151 [5]	Significant depending on use	Ineffective	Some work required	Substantial	N/A
Insulating Blinds	60%[1]	Improved	Increased	$110 [5]	Significant depending on use	Potentially reduced	Some work required	Substantial	11.69
Interior Shutters	up to 696% for custom designs[1]	Significant Improvement	Potentially Significant Increase	$21.29 (DIY) - $478 (High end wood shutters)[5]	Significant based on use and design	Reduced	Some work required	Substantial	700.53
Roller Shades	Used for SHG reduction	Improved	Increased	$128-$278[5]	Significant based on use and design	Ineffective	Some work required	Substantial	N/A
Curtains and Draperies	38%[1]	Improved	Potentiall Significant Increase	$29.98 [5]	Significant based on use and design	Potentially reduced	Some work required	Substantial	27.16
Low Emissivity Films	Used for SHG reduction	Improved	No effect	$12.60 [5]	Minimal	Ineffective	Some work for initial installation	Potentially substantial based on	N/A
Plastic Wrap on Window Frames	24% [1]	Improved	No effect	$1.99 [5]	No	Signficantly reduced	Some work for yearly installation	Minimal	258.44
Draft Snakes	N/A	N/A	N/A	$6.97 [5]	N/A	Signficantly reduced	Minimal work required	Minimal	N/A

[1] Craven et al., 2011
[2] http://architecturaldepot.com/louver0shutters.html
[3] ATi, 2009
[4] Personal Correspondance with Stefan Poetsch (Rollac)
[5] Lowes
[6] Drumeller et al., 2007
[7] Brunger et al., 1999

CONCLUSIONS

The study involved the review and comparison of several different window retrofit solutions. Five of these solutions are located on the exterior of the building, while eight are located on the interior. Each solution was investigated based on available information for thermal improvement, comfort, condensation risk, cost, impact on daylighting, air leakage, ease of operation, and aesthetic impact. Finally, each solution was ranked based on the percent thermal improvement per dollar cost. Several important conclusions can be reached based on this study.

- Interior window attachments are prone to have an increased risk of condensation, whereas exterior attachments are likely to have a reduced risk of condensation.
- For window attachments to be effective at improving thermal insulation, they must be made of a robust, highly insulative, non-air permeable material that can be sealed along the perimeter of the attachment and the window.
- When homeowners seek to perform energy saving retrofits, they should begin with simple low cost systems such as wrapping their window frames in plastic wrap.

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INFORMATION BARRIERS IN HOME ENERGY RETROFIT ADOPTION: RESEARCH IN PROGRESS

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ABSTRACT

Generally, buildings, especially residential ones, are a major consumer of energy. The majority of the housing stock consists of existing homes, a large number of which is energy inefficient. Retrofitting existing homes to make them energy efficient has huge economic, social, and environmental benefits.

Though the benefits and opportunities for home energy retrofits (HER) are fairly well established, its adoption has faced huge obstacles. One estimate of market penetration for HER programs puts it at less than 2%.

The research identified lack of information as an important barrier to the adoption of HER. It also identified two types of information barriers as quantitative information and expert knowledge. The need for information to accelerate HER adoption and promotion of HER among homeowners were also emphasized. Finally, the research explored the integration of various information categories for future development of an intelligent decision support system framework.

1.0 OVERVIEW

In general, buildings, particularly residential ones, are one of the major consumers of energy. Compared with other sectors such as transportation and industry, the building sector consumes a major share of energy. Buildings today are responsible for more than 40% of global energy used and a third of global greenhouse gas emissions both in developed and developing countries (UNEP 2009). In the United States, buildings consume 72% of electricity, 36% of natural gas and 40% of all energy use. The average household in the United States spends at least $2,000 a year on energy bills, over half of which goes to heating and cooling. Out of the total energy consumption in an average household, 50% goes to space heating, 27% to run appliances, 19% to heat water and 4% to air conditioning. The majority of the housing stock consists of existing homes and a large number of these homes are energy inefficient (EIA 2008 cited by USEPA 2009; Energy Star 2012).

Energy efficiency (EE) practice refers to increasing or maintaining a given level of service while decreasing the energy used to provide that service. Usually, an upfront capital investment in the use or installation of energy saving devices is required and savings usually pay off the initial expense. For instance, efficiency reduces the demand for electricity without reducing or interfering with the performance of an electrical appliance and without reducing the comfort or convenience that the appliance provides. Common instances of energy upgrades include the replacing of incandescent light bulbs with compact fluorescent lamps (CFLs); or buying Energy Star appliances, light fixtures, and windows (IEA 2011; LBNL 2012).

Increasing investments in EE in buildings is one of the most constructive, cost-effective ways toward addressing challenges with sustainability as it is can lower energy bills, reduce demand for fossil fuels, help control rising energy costs, enhance electric and natural gas system reliability, help reduce air pollutants and greenhouse gases, and increase the value and competitiveness of buildings (Johnson Controls 2012; USEPA 2006). Evidence from studies around the world continues to support the hypothesis that EE measures and programs result in highly cost-effective investments, using even the narrowest criteria (Clinch & Healy 2003).

1.1 Home Energy Retrofit (HER)

Retrofitting a building requires the replacement or upgrade of old building systems with new energy saving technology and processes. An EE retrofit by definition is any improvement made to an existing structure, which provides an increase in the overall EE of the building, or home. Examples of EE retrofits include air-sealing a building's thermal boundary, installing dense-pack cellulose insulation, loose-fill cellulose insulation etc. (Fulton *et al.* 2012; SME 2012).

The building sector has the most potential for delivering significant and cost-effective GHG emission reductions (UNEP 2009). Existing buildings consume more than 70% of electricity and produce more than a third of the greenhouse gas pollution in the U.S. Reducing the energy demand of buildings is vital to nurturing a clean energy economy that generates sustainable, high quality jobs and reduces our dependence on imported fossil fuels (EERE 2011). Investment in building EE, through retrofitting and other strategies, is emerging as a high priority in a growing number of cities and states throughout the U.S. because it simultaneously meets environmental protection, economic development, and social goals (ISC 2009). In addition, though there has been numerous research efforts related to EE in new home construction in the U.S., with over 130 million existing homes compared to an annual addition of about half a million to two million new homes, energy retrofit of existing homes can have a greater impact on saving energy (AHS 2009; BA 2010). This research concentrated on retrofitting existing homes to increase their EE.

2.0 LACK OF ADOPTION/ IMPLEMENTATION OF HOME ENERGY RETROFITS

Though the benefits and opportunities for HER are fairly well established, its adoption has faced huge obstacles. For instance, in 2007, the approximately 150 EE-related loan programs in the U.S. reached less than 0.1% of their potential customers (Fuller *et al.* 2010; Ho & Hays 2010). Generally considered a successful residential EE effort, a report by Fuller *et al.* (2010) on findings from a 1980–1992 Bonneville Power Administration Program that provided free audits and highly subsidized retrofits indicates that, the program only motivated 5 percent of eligible customers to have an audit. Evidence from the Residential Conservation Service, a subsidized audit program established in the late 1970s, suggests that of the audits offered by utilities to their customers at $50 or less, only 3–5% usually responded (Tonn & Berry 1986). Another estimate of the market penetration for HER programs is less than 2% (Neme *et al.* 2011).

The low patronage of EE and HER has led to what is referred to as the “efficiency gap” where the EE of buildings, equipment, and appliances in use is far less than what is technically attainable (OTA–U.S. Congress 1993). Even though unified and systematic information is required to perform effective retrofits, most of this information is scattered and difficult to find (PATH 2002). In a recent Pan-European survey, respondents agreed that neither cost nor technology was the problem, but rather a lack of information about the available technologies and their benefits to consumers (Commission 2005). Bonsall *et al.* (2011) posit that, results from the Commission's survey are by no means atypical and that of all the market barriers, information is continually cited as most influential to future uptake.

Research literature has shown that lack of information for retrofit decision making is one of the main reasons offered for the efficiency gap. The lack of information may be particularly important for owners of older existing buildings who do not have the expertise to assess HER options and may not know how to improve EE (Palmer et. al 2011). In order encourage the adoption of HER strategies in the U.S. this information barrier must be overcome.

The main objective of this research is to investigate the information related barriers leading to low adoption rates of HER and to explore the integration of various information categories for future development of an intelligent decision support system (IDSS) framework.

3.0 NEED FOR INFORMATION TO ACCELERATE HOME ENERGY RETROFIT (HER) ADOPTION

The Building America (BA) Program has identified the importance of information flow in HER as one of the key issues in its adoption. Having reached a consensus on the necessity of information flow, BA notes the following (NREL 2010b): (1) information is necessary to quantify EE in appraisal forms; (2) there is a lack of understanding of energy efficient terminology in the industry; (3) there is a lack of documentation to remove lead paint from exteriors; (4) information is out there, but it is not getting into the hands of the right people; (5) there is a lack of information to protect trade contractors from liability.

The following are some of the specific instances in the literature that point to information barriers to HER implementation thus necessitating the need for information in order to accelerate the adoption of HER.

Information for Stakeholders

BA has identified the skepticism of consumers and homeowners about EE claims due to market misinformation and false claims of EE as an important barrier to the penetration of market-ready energy solutions (NREL 2010a, NREL 2010b). In addition, regarding marketing and occupant behavior in retrofits, BA notes that, renovating and building energy-efficient homes is only part of the challenge and that convincing homeowners and investors to pay for energy improvements, and operate their homes efficiently, presents an additional challenge. Bianchi (2011) posits that, BA research is not accessible in a format that is most useful to stakeholders. An important conclusion drawn at a BA expert meeting on poor implementation of condensing boilers on a large scale was that, there was lack of information on optimum installation strategies and insufficient training for installers and designers (Aspen Publishers 2010).

Delay in Dissemination of Research Results

Though dissemination is an issue often raised by researchers, it is hardly seriously addressed (Crosswaite & Curtice 1994). According to Basch *et al.* (1986) dissemination can be described as deliberate efforts to spread an innovation. Ensuring the best possible use of research results is a means of demanding accountability from researchers (Crosswaite & Curtice 1994). Key reasons related to delay in disseminating/implementing research results into practice includes:

- Lack timely availability of information at the point of decision making (Haines & Donald 1998, Sorrel *et al.* 2004)
- Lack of understanding of the process of diffusion of innovation in the residential building industry (Koebel *et al.* 2003)
- Influence of powerful entities towards inhibiting the introduction of innovative cost effective solutions by smaller competitors (Golove & Eto 1996)

In a Pan-European survey, on the question of how funds could be targeted in supporting research towards investment in EE technologies, participants overwhelmingly responded that it would be better spent on demonstrating and validating the potential of current technology, thus avoiding the situation where good solutions stay in closed boxes without delivering results (Commission 2005).

Lack of a Standard Protocol and Unified Source of Information

A standard protocol is required to provide consistency in the means and methods used by home energy efficiency professionals, such as trade contractors and energy auditors. Standardized professional training programs, certification and an industry review/comment platform will support the growth of the energy retrofit industry by providing skilled and credentialed workforce (PATH 2002, EERE 2012, NREL 2012). One of the barriers identified to the large-scale implementation of EE in existing homes is the lack of standard protocol to dictate the methods used by home EE professionals, such as trade contractors and energy auditors, to retrofit a home. The process of overcoming this barrier requires conducting interviews with industry professionals and developing a standard protocol for retrofits (PATH 2002).

Need for Experts in Home Energy Retrofits

The involvement of experts in home energy retrofits is inevitable. Homeowners may not be aware of the inefficiency of their homes and the availability and benefits of energy retrofits. Specific opportunities for improving the EE of a building are typically more difficult for homeowners to evaluate on their own since they lack the expertise to do so. Thus, information provided by experts such as energy auditors is not only useful, but have an important role to play in filling the information gap that exists on building EE. Homeowners have a perceived distrust of energy auditors especially those with contracting interests. They are also confused about the conflicting information available in published sources and hence need the help of experts (Komor et al 1989; NREL 2010a; Palmer et *al.* 2011; PATH 2002).

The above noted discussion identifies the information related barriers. It also emphasizes the need to promote HER among homeowners and for information to accelerate HER adoption.

4.0 INFORMATION TYPES IN HOME ENERGY RETROFITS

To undertake a HER, homeowners seek information from a variety of sources such as: word of mouth, trade contractors, retrofit contractors, energy auditors, retail and lumber yard employees, how-to books and the internet, Federal and state government resources, television and radio shows, non-technical newspapers and magazines, utility companies, print advertisements, cost databases.

Based on literature review, these information sources can be put into two broad categories of information: expert knowledge/expert advice and quantitative /published information. These two information categories are utilized by stakeholders such as consumers, energy auditors, retrofit contractors, trade contractors, designers, developers, etc. for retrofit decisions (See Figure 1).

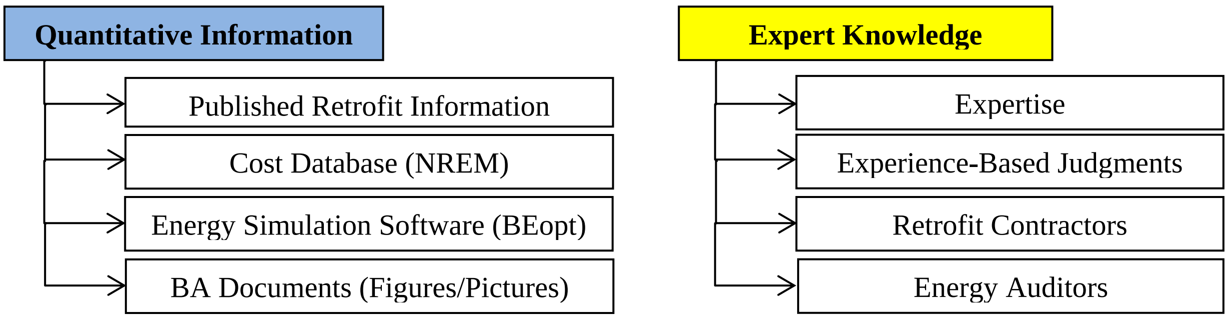

Figure 1: Two Key Information Categories/Sources

The first category has been termed as "quantitative information." This category includes information related to the task domain that is typically found in published sources and commonly agreed upon by those knowledgeable in the particular field (Palmquist 1996; Turban 2005; Syal 2011). Examples include: published information about retrofit technologies, cost information from databases such as the national residential efficiency measures (NREM) database, energy simulation reports from simulation software such as building energy optimization (BEopt), and information available in BA documents (NREL 2010b, USDOE 2010b).

The second category of information can be termed as "expert knowledge" and is also known as expert advice or qualitative information. This category includes information that can be defined as the knowledge of good practice, good judgment, and plausible reasoning in the field (Palmquist 1996; Turban 2005; Syal 2011). Examples include: expertise and experience-based judgment of retrofit contractors and/or energy auditors.

Within the context of the information categories identified and the lack of adoption and broad implementation of HER leading to low patronage of energy retrofits, the above-noted two information categories relate to the two barriers: "information barrier" and "expertise barrier". Understanding of the two information categories will help remove these barriers.

4.1 Sources of Quantitative Information

Several construction and home EE-related information portals and databases currently exist. This section summarizes the existing literature on information portals and databases used in the HER industry and other construction-related industries and a few examples are presented here.

National Residential Efficiency Measures (NREM) Database (NREL 2010a)

Developed by integrating several USDOE databases of building retrofit measures into a unified national database, the database is a public, centralized resource of home retrofit measures and costs. It is mainly designed to assist users decide on the most cost-effective retrofit measure(s) for HERs. It allows constant feedback from users to improve its effectiveness. The database obtains input from two sources: data from retrofit programs and data from public feedback, both of which are monitored by the database administrator.

Building America (BA) Portal

This was developed as a useful portal for providing information to the public. The layout of the BA portal mainly includes: (1) information about the BA program including research teams, current research, and future goals and deployment strategies; (2) technical and scholarly publications related to home EE; (3) links to building science educational institutions and curricula; (4) information related to EE technologies, measures, and best practices; (5) sources of EE incentives; (6) links to other EE databases such as the NREM database; (7) search portal useful for quick retrieval of specific data.

Energy Star Portal

The Energy Star Program is a joint program of the US Environmental Protection Agency and the US Department of Energy (USDOE). It was created to protect the environment through energy efficient products and measures (Energy Star 2010). The program's information portal contains the following information: (1) products and measure to increase home EE; (2) tool that assesses the energy performance of a home. Data required to run the tool are "location of the home" and "past energy consumption"; (3) tool that suggests retrofit strategies for increased energy performance, based on the location of the home and its typical features; (4) links to other EE databases; (5) search portal useful for quick retrieval of specific data; (6) scholarly and technical publications related to home EE.

Database of State Incentives for Renewables and Efficiency (DSIRE 2010) Portal

Established in 1995, DSIRE is an ongoing project of the North Carolina Solar Center and the Interstate Renewable Energy Council which is funded by the USDOE and the site is administered by the National Renewable Energy Laboratory (NREL). The database contains information related to renewables, and to energy efficient technologies and measures and provides three areas of information for both Federal and State resources: (1) Financial Incentives; (2) Rules, Regulations and Policies; and (3) Related Programs and Initiatives.

4.2 Sources of Expert Knowledge

Within the HER industry, many sources of expert knowledge exist and pursued by homeowners. This section discusses three main sources which include: HER professionals, homeowner's self-acquired knowledge, and knowledge from a prepackaged source such as an expert system.

HER Professionals

In order to make informed decisions about which energy retrofit measures to select, homeowners need the help of competent and trained professionals who are certified to give them accurate, trustworthy, and comprehensive information specific to their home (EnergyARM 2009). One way of obtaining this information is by conducting an energy assessment of the home. Energy retrofits employed without initial measurement and analysis can produce unacceptable results thus there is a need for energy professionals to estimate a proposed retrofit's energy savings and prioritize the retrofits in descending order of their cost effectiveness (Krigger & Dorsi 2009).

As a result of the need to have a standardized protocol and harmonized training for energy professionals, the USDOE in 2012 funded guidelines for home energy professionals. The certifications focus on the most common jobs in the home energy upgrade industry: energy auditor, retrofit contractor, and quality control inspector (EERE 2012).

Homeowner's Self-Knowledge

In order to perform energy retrofits, the needs, preferences, and budget of the homeowner is a major consideration. Homeowners who undertake energy retrofits have different levels of expertise and these ranges from novices to experts. The lack of access to information however generally inhibits how much knowledge the homeowner may possess. The level of expertise of homeowners range from doing simple tasks such as: installing light bulbs or installing wall insulation to difficult tasks including blowing insulation into an attic, performing an energy audit, or testing the home to ensure it meets the quality standard. Homeowners generally have limited self-knowledge and usually rely on the expertise of HER professionals.

Expert Systems (ES)

An ES is a branch of artificial intelligence that can be used to solve problems that generally require human expertise. The basic concept of ES is to capture and organize the enormous task-specific knowledge derived from the experts (expertise) in a computer. Users can recall the stored expert knowledge through the computer for specific advice in solving a problem. The computer can arrive at a specific conclusion by means of inferences and then provide advice or necessary logic in the same way a human expert would (Warzawski 1985; Turban et al. 2005).

5.0 INTEGRATION OF TWO INFORMATION CATEGORIES AND FUTURE PLANS TO DEVELOP INTELLIGENT DECISION SUPPORT SYSTEM (IDSS) FRAMEWORK

For effective HER decision-making, it is important that the above noted information categories – expert knowledge and quantitative information, work in an integrated fashion. Figure 2 shows the integration of the two information categories and the layout served as the early thinking for the proposed development of the IDSS framework.

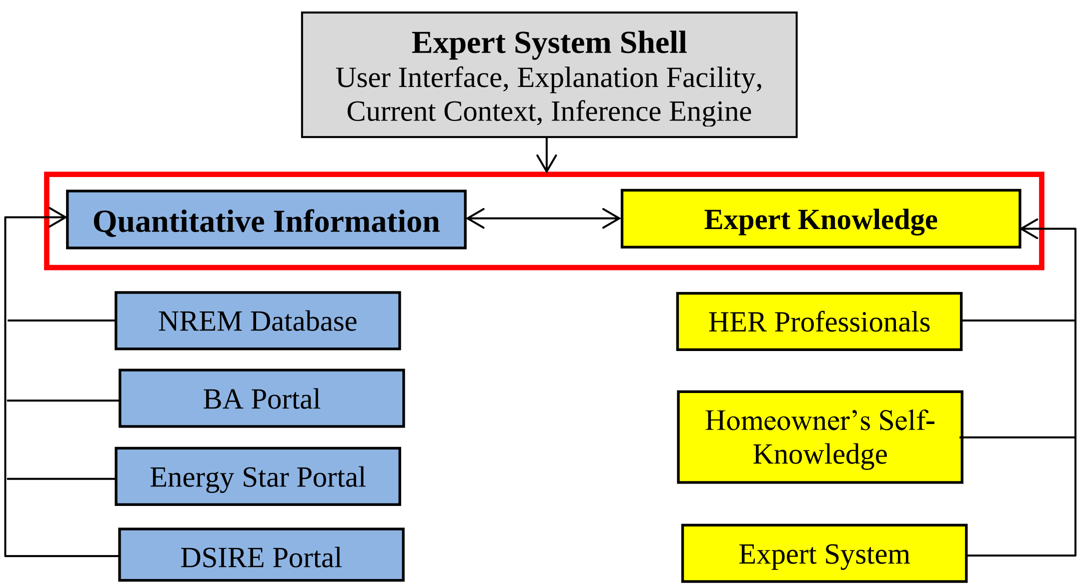

Figure 2: Integration of Information Categories – Early Thinking for Proposed IDSS

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Prefabricating Charles Moore: *Reinterpreted Saddlebags and Aediculae*

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ABSTRACT

Inspired by Charles Moore's strategy of the use of Saddlebags and Aedicule elements in residential design, this paper describes a design proposal for the retrofit of existing houses in a traditional suburban neighborhood with prefabricated Renewable Energy and/or Efficient Modules (REEMs). The conception and design of the modules is a response to two concerns:

- A 62% increase, between 1978 and 2005, in energy consumption in three of the primary components of residential energy demand: Water Heating, Air Conditioning, and Appliances and Electronics.
- The significant number of existing energy inefficient homes constructed prior to 2000.

Prefabricated Renewable Energy and/or Efficient systems are proposed as an effective means for reducing energy consumption in existing houses. These systems, comprised of (1) an array of Renewable Energy building skin systems (e.g., Solar PV, Solar Thermal, etc.) and (2) Renewable Energy and/or Efficient Modules (REEMs), are designed to decrease energy consumption—either by adding renewable energy capability and/or having more efficient energy systems. The prefabricated modules contain the equipment and components necessary to augment and/or replace the existing energy systems of the house.

The significance of the project, as distinguished from those proposals that focus on new construction, is the demonstration of a variety of design strategies for reducing residential energy consumption by retrofitting *existing* houses with mass-produced Renewable Energy and/or Efficient systems.

PROLOGUE

INCORPORATING FLEXIBILITY. The difference today that will enable modularization and mass production to succeed is its ability to be customizable. No longer does mass production have to produce the same repeated product; now flexible production methods allow for customization on a large scale.

—Stephen Kieran and James Timberlake
Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction (2004)

INTRODUCTION

Rather than focusing on new construction, this paper describes a design proposal for significantly reducing energy consumption in existing single-family houses constructed between the end of WW II and the last decade of the twentieth century. The strategy calls for a building retrofit that employs the principles and techniques of *prefabricated construction* and *mass customization*.

It is the contention of the authors that this proposal not only meets a functional goal, i.e., the reduction of single-family residential energy demand, but holds the potential for significantly improving and enhancing architectural value by creating new and significant residential spaces. The argument in support of the latter point requires a brief exposition of Moore, Allen, and Lyndon's ordering device of the Saddlebag and the Aedicule in residential architectural design.

Saddlebags and Aediculae

In their seminal work *The Place of Houses* (1974), Charles Moore, Gerald Allen, and Donlyn Lyndon describe their own version of the Vitruvian triumvirate of Firmness, Commodity and Delight, setting forth "the belief that houses must be special places within places," professing "…a special fondness for barns, which have a way of exhibiting …practical needs," and admitting an unabashed admiration for buildings that "display…the dreams and pretensions of their owners." Moore, *et al*, note that, though their clients' budgets were usually small and there was a great range in project scale and site, two essential formal ideas permeate the residential projects discussed: (1) the *Aedicule,* "a symbolic center in the midst of the specific demands of the household," and (2) Saddlebags, secondary and tertiary spaces for a specific use arranged about the central space. In the Bonham house (Santa Cruz County, California; 1961), for example, the tall central living space (with a large window with an expansive view to the surrounding redwoods) is flanked by kitchen, stairs, bathroom, and a "floating" bedroom loft. The house, small and inexpensive, "possesses great apparent size," in large measure due to the "juxtaposition of the spacious and the close" (Moore, Allen, and Lyndon, 1974).

The mutually reinforcing concepts of Aedicule and Saddlebag serve, in the present proposal, as the basis for a retrofit design strategy that improves energy efficiency while seeking to improve and enhance the architectural qualities of the houses.

PROBLEM STATEMENT

Two disturbing facts serve as the impetus for the design proposal described here:

(1) The 62% increase, between 1978 and 2005, in energy consumption in three of the primary components of residential energy demand: Water Heating, Air Conditioning, and Appliances and Electronics. Recent data on changes in total energy use in U. S. homes between 1978 and 2005 indicates that a number of factors (e.g., Federal energy efficiency standards for major appliances, improved energy efficiency of heating equipment, better window design, better insulation) have led to a reduction in energy use per household of 31%. However, while the number of occupied housing units has increased by 45%, total energy use in homes has remained constant (10.58 quadrillion BTU in 1978 compared to 10.55 quadrillion BTU in 2005). Unfortunately, the dramatic 38% reduction in energy consumption for Space Heating has been largely offset by increases in consumption in three areas: Water Heating, Air Conditioning, and Appliances and Electronics. Given the increase in the number of households with dishwashers and with central air conditioning, it is not surprising that the 2005 energy consumption for Water Heating and Air Conditioning was 3.0 quadrillion BTU, an increase of 62% over 1978 energy consumption levels.

(2) The significant number of existing energy *inefficient* homes constructed prior to 2000. According to the 2009 American Housing Survey National Tables, there are 73M occupied single family detached housing units in the United States: in excess of 60M of those units were constructed before 2000.[i] While improvements in the construction of building envelopes, more stringent energy efficiency standards, and the development of renewable energy systems for new residential construction are laudable, it is evident that some means must be found for reducing energy use in older homes in order to reduce residential energy consumption in the decades ahead.

A reduction of 8% per annum in residential energy demand (relative to the 2005 energy demand value) equates to a reduction of approximately .93 quadrillion BTU each year: for comparative purposes, this figure is equal to the energy consumption of the U. S. military in 2009 (Karbuz, 2010).

A DESIGN PROPOSAL

The design team recognized that, by employing the principles and techniques of *prefabricated construction* and *mass customization*, a solution could be developed that is both standardized (an energy efficiency module) and flexible: system components can be modified to respond to a multitude of criteria (e.g., owner preferences, project goals and budget, site constraints, solar orientation of the existing building, climate, building and zoning requirements). Furthermore, there are opportunities in some of the retrofit projects to provide Saddlebag spaces (e.g., bathroom, kitchen, carport) and Aediculae (e.g., an outdoor room, porch, or enclosed room) that will improve and enhance the architectural qualities of the house.

As part of the larger effort to reduce residential energy demand, the authors propose the design, construction and installation of prefabricated Renewable Energy and/or Efficient systems as an effective means for reducing energy consumption in existing houses. These systems are comprised of (a) an array of Renewable Energy building skin systems (e.g., Solar PV, Solar Thermal and even solar thermal air pre-heaters) and (b) Renewable Energy and/or Efficient Modules (REEMs) and connected to the existing building energy systems through an exterior wall). The prefabricated modules contain the equipment and components necessary to decrease energy consumption—either by adding renewable energy capability and/or substituting more efficient energy systems for the existing systems. When a southern exposure is not available, the REEMs will focus strictly on energy efficiency by using high performance tankless hot water heaters, next generation hybrid hot water heaters and fully integrated ultra-high efficiency HVAC units (both air to air and air to water units will be utilized). Regardless of whether the REEM is fitted with Renewable Energy capability, all modules will take advantage of highly efficient energy systems which are fully integrated into the module structure and require only electrical, plumbing, duct-work, and natural gas hookups. All modules, solar PV panels, and additional components will be prefabricated off-site at a single national or regional facility and shipped to a local distribution center or directly to the project site. Components will be designed to fit into 40foot high-cube shipping containers to allow for low carbon ship and rail transport in addition to the flexibility of truck transport.

An additional part of the retrofit strategy addresses energy loss related to antiquated fireplaces and chimneys. Older fireplaces are a continuous source of air infiltration. The development of highly efficient air to water heat pumps provides the thermal vehicle to remake inefficient chimneys as very efficient radiators and/or convectors that provide the functionality of thermal comfort and reinforce the understanding of hearth and living room as the symbolic center of the house (the Aedicule). The design has developed concepts that are compatible with most firebox designs which can provide both radiant and convective heat as required by the space and have the option for controlled release thermal storage using phase change materials.

Inspired by the concept of Saddlebags and Aediculae, the skin and energy module components of the system can be configured in a variety of ways:

1) As a stand-alone energy efficient module;
2) As an expanded energy efficient module with an energy and water efficient residential kitchen or bathroom [Figure 1];
3) As an energy efficient module with renewable energy capability (REEM) and a flexible array of solar photovoltaic panels (the array may be mounted to an existing roof or used to define a new outdoor room, carport, or porch); or
4) As an expanded energy efficient module with renewable energy capability (REEM), an energy and water efficient bathroom, and a flexible array of solar voltaic panels (the array may be mounted to an existing roof or used to define a new outdoor room, carport, or porch).

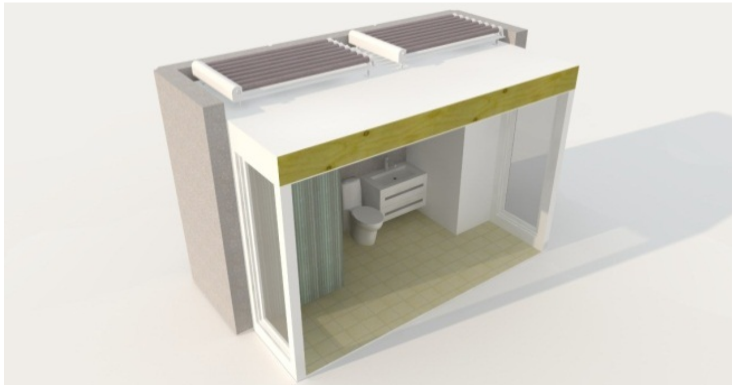

Figure 1: View of a Solar Thermal REEM as a modular component capable of being set in place with a small crane. The REEM contains a full bath that includes a vanity, toilet, and shower as well as a small mechanical room that houses the water heater and other Solar Thermal components, or can be configured as a laundry/mud room.

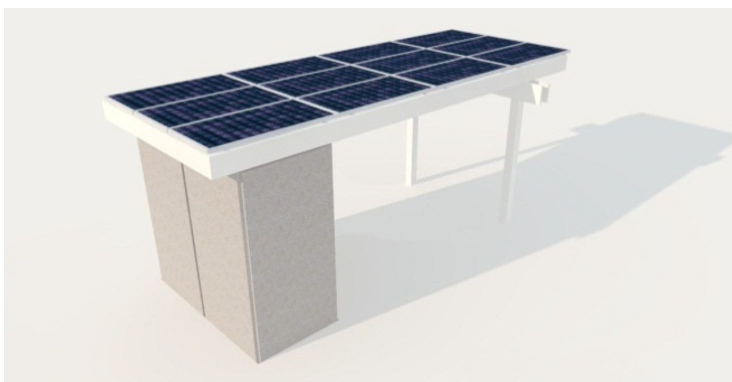

Figure 2: View of a Solar PV REEM as a modular component capable of being set in place with a small crane. The REEM contains posts, beams, a solar PV canopy, and a storage closet for PV components as well as general household items. Multiple modules of the REEM can combined to form various outdoor spaces, such as a carport or a porch.

Figure 3: View of a Solar Thermal Full Bath REEM and a Solar PV Carport REEM as modular components on a single flatbed trailer.

Figures 4 through 7 illustrate a retrofit that includes two energy modules/arrays: an expanded Solar Thermal REEM (with bathroom) and a Solar PV REEM (with an array of solar PV panels on the roof of a new carport).

Figure 4: Aerial view of a typical 3 bedroom, 1 bath ranch house facing north.

Figure 5: Aerial view of a typical 3 bedroom, 1 bath ranch house with a Solar Thermal REEM added as a full bath to the rear and a Solar PV REEM added as a carport to the side.

Figure 6: View of REEMs attached as saddlebags to a typical ranch house without obstructing the existing roofline.

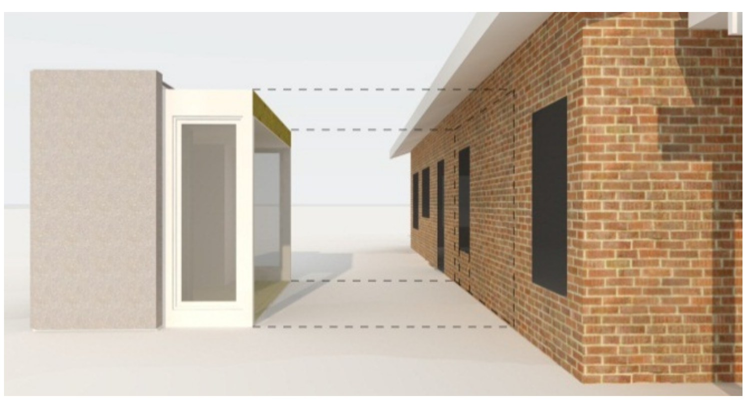

Figure 7: Exploded view of REEM-house attachment at an existing window with the sill removed to create a door to the new full bath.

Figures 8 through 11 illustrate a retrofit with two energy modules/arrays at the rear and front of the house: an expanded Solar Thermal REEM (with laundry room) at the rear and a Solar PV REEM added at the front of the house to create a new porch. The array of Solar PV panels is located on the porch roof.

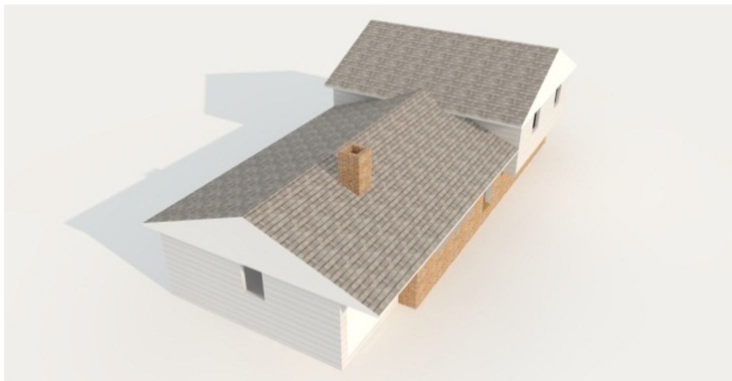

Figure 8: Aerial view of a typical 3 bedroom, 1 bath split-level house facing east.

Figure 9: Aerial view of a typical 3 bedroom, 1 bath split-level house with a Solar Thermal REEM added as a laundry room to the rear and a Solar PV REEM added as a porch to the front.

Figure 10: View of REEMs attached as saddlebags to a typical split-level house without obstructing the existing roofline.

Figure 11: View of Solar PV REEM attached to a new deck platform and overlapping the existing house roof without physical attachment.

CONCLUSION

This paper describes a design proposal for significantly reducing energy demand in older single family residences inspired, in part, by the formal and conceptual devices of Aedicule and Saddlebag in residential design. The proposal calls for a building retrofit that employs the principles and techniques of *prefabricated construction* and *mass customization,* simultaneously exploiting the economic advantages of repetitive unit production while developing design solutions that are adapted to owner preferences, project goals and budget, site constraints, solar orientation of the existing building, climate, and building and zoning requirements.

It is the contention of the authors that the proposal not only meets a functional goal, i.e., the reduction of single-family residential energy demand, but holds the potential for significantly improving and the enhancing architectural value of the existing houses.

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Lessons Learned from the Process of Retrofitting Existing Housing for Energy Efficiency

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ABSTRACT

This paper discusses lessons learned from the design and retrofit of two existing homes for improved energy efficiency. Principle findings include the necessity for providing cost-effective, replicable solutions for the energy efficient retrofit of existing homes that address both up-front expenses and the long-term energy costs carried forth by the resident. One major conclusion is that process matters; although there are essential principles for retrofitting existing homes for improved energy-performance, actual solutions must be project specific and should be undertaken through a comprehensive process that engages the contractor from the very beginning of the project.

INTRODUCTION

Residential energy use accounts for 22% of the total energy consumed in the US (EIA 2001). Over the last 10 years, energy prices in the United States have risen on average by 45% (EIA, 2012) and specific to the residential sector electricity prices have increased 37% from 8.6 cents/kWh to 11.8 cents/kWh (EIA, 2010; U.S. Energy Prices, EIA, 2012). With prices ascending annually, improving energy efficiency in homes could potentially save the nation hundreds of billions of kilowatt hours of energy and billions of dollars every year (Electricity End Use, EIA, 2010). Cost-effective measures for the energy-efficient retrofit of existing houses have the significant potential to "save energy, lower utility bill costs for homeowners, and create jobs" (NREL, A Method for Determining Optimal Residential EE retrofit Packages, pg. 1). Retrofitting existing homes can drastically improve the home energy rating while minimizing up-front construction costs and maximizing energy cost savings for the resident. Further, improving the energy performance of existing homes can significantly reduce greenhouse gas emissions from single-family homes (Tracey, 2009). Notably, according to the United Kingdom Department of Energy and Climate Change, "Carbon Emissions from existing homes represent as much as 25% of total emissions in many countries (Hamilton, 2010). The Housing Authority of Union County (UCHA), located in central Pennsylvania, has introduced an initiative to demonstrate the importance of energy efficient home building through its Energy Efficient Housing Program (EEHP). This paper describes the methods applied to retrofit two existing single-family homes as pilot projects for the Energy

Efficient Housing Program and summarizes the lessons learned in the interest of providing a model that can be replicated by other housing authorities, builders or homeowners.

PROJECT BACKGROUND

The Union County Housing Authority Energy Efficient Housing Program was established to reduce utility costs as a way to make homes affordable and more environmentally responsible. UCHA's goal for the Energy Efficient Housing Program (EEHP) is to produce affordable model housing in Union County, Pennsylvania that is highly energy efficient using cost effective current technology. Union County Housing Authority received a $500,000 HOME grant from the U.S. Department of Community & Economic Development to design and construct a new energy efficient duplex and to retrofit two existing homes with energy saving improvements. These homes were constructed and rehabilitated for purchase by income eligible, "Prime Time" home buyers, that is someone age 55 or older that earns less than 80% of the area median income (currently $33,150 for a single person; $37,900 for a couple). The total budget for each home, including new construction and the purchase cost plus costs of renovations and retrofits of the existing homes, was $150,000. Emphasis for the projects was on long-term energy efficiency and energy cost savings as a first priority, "green development" as a second priority, and minimizing the costs associated with the rehabilitation and retrofit of existing homes as a third priority. The new and retrofitted homes were designed to meet ambitious goals for energy performance (exceeding EnergyStar Home Energy Rating System (HERS) scores) and to assure recognized and verified status for green buildings (achieving a minimum of a "Silver" rating using the NAHB Green Building certification system). A building-science oriented integrative design process, engaging the design team and the building performance specialist / home energy rater, was employed from pre-design through construction. All four homes, and the design and construction process, were intended to provide a replicable model for homebuilders, homeowners, and other housing authorities.

The first pilot project for the EEHP, the new duplex in Lewisburg, Pennsylvania, was completed in the summer of 2010 meeting high standards for energy performance using modular construction. To assure that EEHP could be a model project where the lessons learned could be applied to the broadest audience, The Union County Housing Authority (UCHA) purchased two existing single-family homes in Union County, Pennsylvania. These existing structures were evaluated for energy efficiency and retrofit design solutions were applied in order to 1) improve the energy performance of the building envelope and 2) renovate the homes for 'aging in place'. Energy efficient improvements were undertaken by a local contractor to earn a HERS Index score of 85 (to comply with minimum expectations for EnergyStar version 2.5 performance) or better and a NAHB Green Home rating of "Silver."

Existing Conditions. The existing homes acquired by UCHA each fulfilled goals for "green development" in that they were located in existing neighborhoods, with some resources within walking distance, and would contribute to a sense of community and could enhance living conditions for the new residents. Each of the two homes had the major living spaces on a single level and therefore, with minor modifications, would accommodate residents' needs as they aged (Fig.1).

Figure 1: Existing Homes for retrofit as part of Union County's EEHP (Mifflinburg on left and Lewisburg Home on right) were selected because they were located in established developments and could accommodate single floor living.

Overview of Approach. For benchmarking purposes, an initial energy audit and baseline energy simulation model was prepared based on actual energy bills that were collected over the period of about one year prior to the retrofit of the existing homes (homes unoccupied at the time). The design team, including the project architect and a home energy rater, were selected based on an RFP for the EEHP, including the new duplex and the retrofit of the existing homes. A systems integrated approach based on building science principles and testing via energy simulation tools was employed during the design process. Because UCHA is a public agency there were rigorous requirements for a public bid process, including affirmative action goals for female and minority participation and bond requirements for the contractors. Very basic drawing documentation, a single 11"x17" sheet to convey the scope of work for the renovation of each property, and basic specifications were prepared for each retrofit home. The contractor was responsible for surveying the properties to obtain quantitative information for bidding and to coordinate construction with the verified field conditions. Basic work was performed in each home to insulate and isolate the existing basements from the living space of the homes and to replace existing electrical wiring with new code-compliant systems. Minor interior renovation work was completed to update the homes, assure that spaces were reasonably ADA adaptable and complied with *Visitabilty* standards, and to maximize views and daylighting while minimizing extraneous openings in the building envelope. Retrofit of the homes included building envelope and fenestration improvements, replacement of HVAC systems, installation of EnergyStar certified electric appliances and replacement of existing lighting fixtures to accommodate low-energy lighting sources. Aerators were installed on existing sinks and new water efficient roll-in showers and water closets were installed. Materials and equipment selected for the EEHP projects were based on three criteria: cost, performance (energy performance and durability), and locally manufactured and/or supplied.

Energy Efficiency Retrofit Strategies Specified. Although constructed about 40 years apart, both homes had framed exterior walls with little or no insulation, unfinished full basements and open attic space above the living space. The specified retrofit measures applied to the homes were consistent with "best practices" for the U.S. industry and summarized in an international report prepared by the UK Department of Energy and Climate Change:

> *Blower-door guided draught sealing is typically the most cost-effective measure and is applicable to virtually all existing homes. Draught sealing in lofts [attics] is deemed necessary before adding insulation. Blown-in cellulose (recycled) has been found to be widely applicable, effective and inexpensive for both loft and wall-cavity insulation. Heating and cooling system efficiency is approached to address not just equipment efficiency, but also quality installation, controls, and distribution systems efficiency.* (Hamilton, 2010, p.20).

<u>Building Envelope</u>:

Attic: Specifications called for existing fiberglass insulation to be salvaged and reused in the attic space. 1" of closed cell insulation (zero ozone depletion potential blowing agent) was to be installed between joists on top of any ceiling material and at the top plates. Where the condition of any existing fiberglass batt insulation was acceptable for reuse the facing paper was to be removed and the insulation reinstalled over closed cell foam insulation. Vent baffles were to be installed at the roof eaves and blown cellulose insulation was to be installed over the entire attic space to bring the total assembly to a minimum R-60 rating.

Basement: 1-1/2" of closed cell foam insulation (min. R-10) was to be installed on the foundation wall and thermal barrier paint applied as needed. Closed cell foam insulation was to be installed at the Rim Joists (min. 3") and sealed to the foam on the foundation walls.

Exterior Walls: In both homes the exterior siding material were to be retained and exterior walls were to be sealed and insulated through holes that were sawcut in the interior wallboard. Any existing fiberglass batt insulation was to be removed and

100% of the wall cavities were to be filled with dense pack cellulose insulation (min. 3.5 lbs / cu. Ft density). Holes in the drywall were to be patched, sanded and painted.

Changes to the specified building envelope strategies will be further explored below. The following systems were realized more or less as specified, but required active coordination between the contractor, the design team and the Home Energy Rater:

HVAC: The existing furnaces were removed and chimneys removed and sealed. Efficient mini split heat pumps were installed to heat and cool the living spaces of the homes.

Plumbing: Heat pump boosted EnergyStar electric tank water heaters were installed, with a condensate drain provided. New insulated 3/8" pex tubing hot water lines were installed and connected through a manifold.

Lighting: New EnergyStar fixtures were installed in the kitchen, bath, bedrooms and living room. Fluorescent bulbs were installed in all remaining fixtures.

Doors and Windows: All exterior doors were replaced with insulated doors and advanced weather-seal accessories. Patio doors in the Mifflinburg home were replaced with double-glazed EnergyStar-rated argon filled low-e doors with a U-factor of 0.30. All windows were replaced with locally produced dual glazed windows with a 0.29 u-value (triple-glazed windows with a u-value of 0.20 were specified as a bid alternative, but rejected due to an imbalance between the cost and improved efficiency).

Monitoring: Since overall energy performance and resident electricity use patterns are important to both the long-term understanding of how the retrofit measures are functioning and to establishing high-performance results, inexpensive but effective energy monitoring devices were installed in each home. The devices provide real-time feedback to the home occupants on how much energy is being consumed and trends can be followed with the web-based interface.

PROJECT SPECIFIC REALIZATIONS & REALITIES

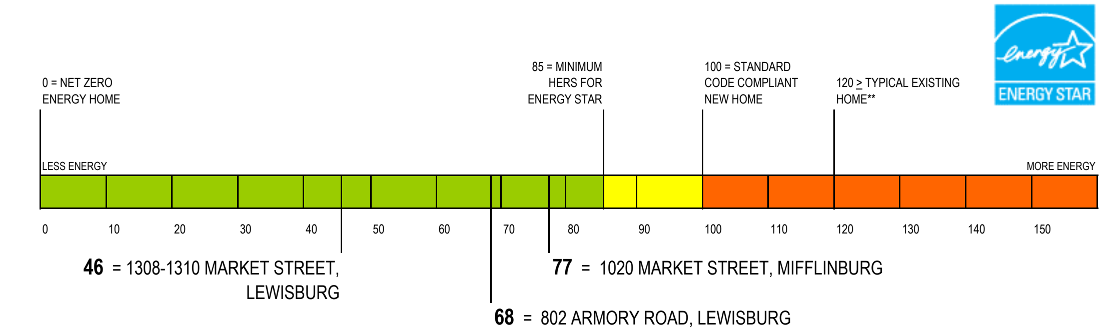
Mifflinburg Home

The first home to be retrofitted was a ranch located in Mifflinburg, Pennsylvania, and most likely constructed in the 1980s. The 1,163 square foot home consisted of three bedrooms, a kitchen, bathroom and living space with an open rear deck and an unfinished basement. The largest expenditure of time and adversity went into the wall insulation and how it was to be installed. Because of the contractor's preference and supplier relationships, dense-pack fiberglass insulation instead of cellulose was blown into the openings in the drywall to fill the inner-wall cavity. As planned, horizontal slots were cut in the drywall, about half way up the wall, so that old insulation could be removed and the new dense-pack insulation added. However, because of horizontal blocking in the walls, this technique proved to be ineffective and, except at the brick-clad front façade, was abandoned in favor of removal and replacement of the worn existing vinyl siding. This allowed for an additional layer of rigid insulation below the exterior siding. There proved to be insufficient space in attic to insulate as specified. Therefore the rim band was sealed and 2" thick polystyrene rigid board insulation was installed in between rafters in the ceiling. This rigid insulation was cut ½ inch smaller than the space between the joists and the edges were sealed with polyurethane expanding foam (proving a better seal than cutting the insulation to fit tightly). The original drafty windows were replaced with double-glazed windows filled with inert Krypton gas. To cut costs, Fiberglass batts were installed in the basement ceiling to thermally isolate the basement from the rest of the house instead of insulating the foundation walls; a wall enclosure and new insulated door were installed at the basement hatch providing a thermal barrier between the basement and rear yard. The building envelope and fenestration improvements helped retain a great deal of heat in the home and contributed significantly to its overall energy performance. However, the home was so tightly sealed that it had to be mechanically ventilated and a heat recovery ventilator (HRV) was installed. The HRV ultimately proved problematic in the small town where neighbors heat with wood, because in certain climatic conditions smoke was drawn into the living space (a solution to this problem is an ongoing effort. Note: avoid venting toward the prevailing wind direction when installing an HRV.). These modifications to the Mifflinburg home improved its HERS rating from approximately 135 to 77; 23% better than code compliancy for new homes (fig.2).

Lewisburg Home

The Lewisburg home was built in 1941 and had very little insulation and extremely poor energy performance. The main living space of the home was 887 square feet with a 160 square foot enclosed porch, attached garage and an unfinished basement. Lessons learned from retrofitting the Mifflinburg home informed the process of improving the energy performance of this home. Here, the plaster interior wall finish was completely stripped off to facilitate proper sealing and thorough insulation of the exterior walls. In removing the wall finish a layer of tin siding underneath the external clapboard was discovered. The layer of tin on the interior surface would create air leakage and moisture problems if insulation was applied directly to the wall cavity. To circumvent this problem, one-inch (1") polystyrene rigid foam insulation board was placed in the wall cavity between the framing members. Blown-in dense-pack fiberglass insulation was then installed to fill the rest of the void and the walls were sealed and finished on the interior with new drywall. Like in the Mifflinburg house, the old windows were replaced with double-pane windows filled with inert Krypton gas and fiberglass batt insulation was installed to the basement ceiling. To save labor and material costs, the attic was isolated from the living space at the ceiling; the existing ceiling insulation was left in place and new insulation was blown overtop. A smart fan, instead of an HRV, was installed for ventilation. These upgrades improved the home's HERS rating to 68; 32% better than standard code compliant new homes and significantly better than the original HERs rating of nearly 160 (fig.2).

UNION COUNTY HOUSING AUTHORITY
HOME ENERGY COMPARISON (HERS INDEX*)



	ADDRESS	HOUSE TYPE	YEAR BUILT	CONDITIONED AREA	ENERGY SOURCE	ESTIMATED MONTHLY ENERGY COST ($0.21/KWH)	ESTIMATED ANNUAL ENERGY COST	ESTIMATED ANNUAL ENERGY CONSUMPTION	HERS RATING	BETTER THAN CODE
1	1308 MARKET STREET, LEWISBURG, PA (NEW CONSTRUCTION)	DUPLEX, SINGLE UNIT	2011	2025 SF	ELECTRIC	$134	$1,609	34.4 MMBtu/yr	**46**	54%
2	1310 MARKET STREET, LEWISBURG, PA (NEW CONSTRUCTION)	DUPLEX, SINGLE UNIT	2011	2025 SF	ELECTRIC	$134	$1,609	34.4 MMBtu/yr	**46**	54%
3	802 ARMORY ROAD, LEWISBURG, PA (RENOVATION)	SINGLE FAMILY, DETACHED	1944	911 SF	ELECTRIC	$157	$1,881	42.6 MMBtu/yr	**68**	32%
4	1020 MARKET STREET, MIFFLINBURG, PA (RENOVATION)	SINGLE FAMILY, DETACHED	1981	1120 SF	ELECTRIC	$121	$1,450	31.0 MMBtu/yr	**77**	23%

* ENERGY STAR VERSION 2.5
** PER ENERGY STAR ENERGY RATING CERTIFICATE

Figure 2: Comparison of EEHP home performance.

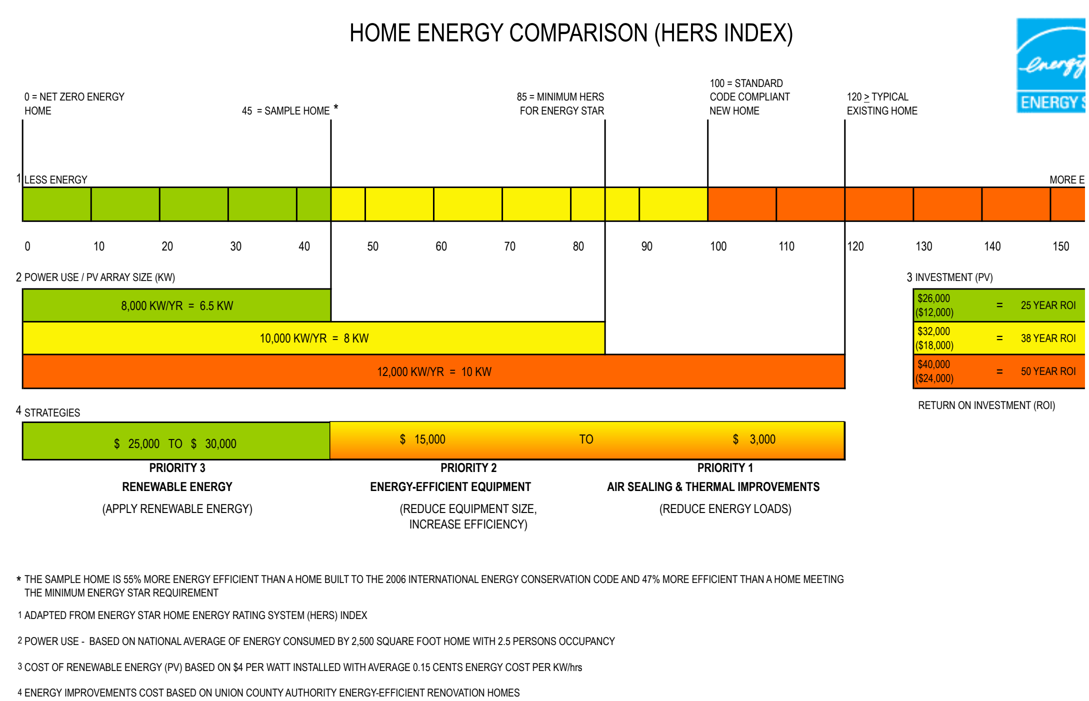


Figure 3: Comparison of EEHP expenditure for energy improvements.

LESSONS LEARNED

Costs. The general trend realized was that a $10K (between $3,000-$15,000; see fig. 3) investment specific to energy improvements was necessary to bring homes from performing as much as 60% worse than minimal code to performing 23% and 32% better than code (2006 IECC) for the Mifflinburg and Lewisburg homes respectively. For the EEHP, cost constrains were based on the project budget ($150k / project), but all expenditures were weighed against what might be deemed a viable undertaking by a homeowner. Estimated costs for retrofit improvements (building envelope, HVAC, lighting, DHW / appliances, doors and windows) was approximately $30,000 with an additional $30K invested in essential renovations to bring the homes up to current living standards and requirements for aging in place. $60,000 was considered a reasonable expenditure undertaken as a home improvement project or equity loan budget. The project cost was also thought to reflect a reasonable "street" or appraisal value for the completed home. However, despite findings from a majority of home remodelers that buyers are willing to pay more for green homes (McGraw-Hill, 2012), in reality the comparative appraisal methods used do not value energy improvements. During a de-briefing meeting the project team speculated that once more EnergyStar and retrofit projects hit the market the "true value" would be realized in assessments. It was speculated that finance options could begin to absorb the cost of energy efficiency improvements since any added cost would be marginal in the overall loan. From a regulatory standpoint, legislation could be passed to include energy efficiency standards in code compliance for new homes. Comparable information will provide for more realistic ideas about actual cost of energy improvements, the payback times associated, and the market for valuing energy performance.

Process. The EEHP operated under a design, bid, build method as stipulated by the federal grant that funded the project. This occurred in different ways for the duplex and the retrofits due to the inherent differences in the projects. In the duplex, the architect was able to completely design the homes and prepare full documentation for the project to be bid by contractors (both conventional construction and modular builders). After the low-bidder – a modular builder - was selected the homes were built and the entire project was carried out relatively seamlessly. The design, bid, build process was not as effective for the retrofitted homes. Although careful evaluation and coordination of the retrofit measures was important, the size and scope of the projects did not warrant and could not support full project documentation. It is important to note that the retrofit projects were bid separately from the new construction project of the EEHP. Perhaps as a result of this, or for other unknown underlying factors, there were issues in acquiring competitive bids for the retrofit projects. Initially the drawings and specifications for the Lewisburg home were completed and put out to bid without response. Thereafter the project was combined with the second renovation / retrofit home and bid as a single job. This yielded a single bid by a small local contractor who had the enthusiasm but not the experience for energy-efficient building. The bid was also significantly over budget. One issue identified was that small contractors are not familiar with the bidding process and normally are not in a position to address the hefty bond requirements for the public project. In response the UCHA assisted with the process and paperwork and as a result the contractor felt that the experience would be beneficial for future projects. To address project budget, negotiations between the contractor, UCHA, and the project design team ensued to fully explore project intents and associated costs, ultimately realizing a favorable solution for all parties. Throughout construction, as the result of existing conditions or expense, some changes had to be considered. Direct and time-consuming team involvement and coordination between the contractor, the architect's construction administrator and the energy rater was necessary throughout the retrofit process. The project was valued and changes were coordinated to maintain the overall project performance goals on a weekly basis as field conditions were revealed. Dialog with the contractor, based on his expertise and local connections, provided insight into more cost effective material choices. It is important to note here that the local economy had a huge part to play in realizing cost-efficiency for this project; if prevailing wage had to be applied the retrofit projects probably would not have been realized. The primary lesson learned was that there is significant benefit to be realized through contractor involvement from the beginning of the project. Such early involvement would have reduced the amount of contract modifications that had to be made during construction process. This may seem a fairly straightforward process issue, but it is complicated by the public bidding requirement since this would have given the contractor involved an unfair advantage. Essentially a primary difference between the new and retrofit EEHP projects was that a front-loaded design process, centered on a coordinated building science approach, was necessary for the new construction whereas the expertise from the design team was desirable during retrofit construction for oversight and coordination. Both cases illustrate a need for the traditional design project fee structure to be readdressed.

Project Time. The time frame for the two retrofit projects could have been more than cut in half by refining the process and changing the bidding requirements. The unscientific conclusion from these retrofits was that "design-build" involving the contractor from the beginning would have taken one quarter of the project time. Contractor experience gained during the retrofit project contributed to streamlining the time on the second retrofit project and would likely reduce time on any subsequent projects. Once again, overall project time could have been reduced by involvement from the contractor in early project decisions and throughout the design process.

CONCLUSIONS

Because of the enormous existing housing stock and energy-use implications, the market for energy-efficiency needs to be focused on retrofit over new construction. In many ways the lessons from the EEHP retrofit homes illustrate significant opportunity. However, in some ways the EEHP retrofit projects are not an ideal model.

According to the 2009 Federal Recovery Act, building energy efficiency would result in job creation and a competitive edge for existing small contractors and businesses - ambitious and advantageous goals in today's economic climate. In green building generally, and with energy-efficient retrofits specifically, there is the necessity for a committed party dedicated to making it happen, therefore there is an "act of will" factor at play. Fortunately, predictions show that "despite the downward pressure of home prices, discriminating consumers have helped to keep green in the forefront" and that builders and remodelers have realized several business advantages related to green homes (Mcgraw-Hill, 2012, pg. 1). These findings did not fully prove true on the EEHP retrofit projects. While working on the retrofit projects the contractor became an EnergyStar certified remodeler (small contractor). As a result he received discounts on some materials and became a wholesale distributer for energy efficient products, including HRVs. Unfortunately his EnergyStar status was compromised due to the requirement that each contractor complete two EnergyStar certified projects per year to retain certification; Even though he was the only EnergyStar contractor in four counties he was unable to fulfill this requirement.

Often improvement of the building envelope for energy performance is not enough, and it is important to acknowledge that existing homes must also be updated for contemporary living. In part because the existing wall assemblies for the EEHP homes ended up being significantly modified, they have only limited application to other older housing found in most walkable neighborhoods. The energy performance of historical windows and horsehair plaster walls are difficult and expensive to significantly upgrade without compromising the home's character. Further programmatic changes needed to make older housing stock consistent with today's market may reduce the economic logic of such projects.

Finally, an expensive design-bid-build process including extensive construction phase services by the architect and energy rater proved necessary in realizing the EEHP homes. This was possible only because of money committed to making the EEHP a demonstration. In order for this to be replicated in the market, specialized and expert contracting teams need to emerge so that the design can be simplified a set of performance goals. Realistically, there may be limited potential for these teams to emerge entirely from the existing pool of renovation contractors.

In the end anything that is available for "mass consumption" overly simplifies the issues. However, it is important for projects and stakeholders to try and address policy / transformation of the market. An emphasis on public information regarding the benefits of energy-efficiency and reduced energy use remains an important cause. Despite limitations, the EEHP projects are significant achievements in this regard. UCHA's support of ongoing research and dedication to dissemination of knowledge gained from the EEHP projects has promise to propel the practice of small projects that maintain high standards for long and short term energy expenses and community-oriented development goals.

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Adoption of Innovative Products in the US Housing Industry: Builders' Practices 2000-2010

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Abstract

Researchers and policymakers have struggled with the lack of technological innovation in the US housing industry (Koebel 1999). While housing is arguably no different in nature than other industries, several unique factors have been established as causing risk and uncertainty in the context of innovative construction technology (McCoy et al. 2009). Previous intervention strategies borrow from other industries to explain prior adoption and diffusion patterns and do not address the divergence of recent residential construction technologies. Where homebuilding innovation has traditionally experienced slower rates of adoption, some green building technologies exhibit accelerated patterns. In order to understand underlying reasons for resistance, it is important to not only understand uncertainty and risk, but also articulate use of innovation in the residential built environment. Towards this goal, the authors examine and highlight broad patterns of innovation use (adoption) by builder firms within clusters of products (i.e. traditional versus innovative) for six energy efficient (EE) products, across recent years.

Introduction

Definitions of green building remain broad and do not necessarily reflect the needs of the residential construction industry, According to the fifth edition of The Dictionary of Real Estate Appraisal Sustainability (2010), green design and construction is "the practice of developing new structures and renovating existing structures using equipment, materials, and techniques that help achieve long-term balance between extraction and renewal and between environmental inputs and outputs, causing no overall net environmental burden or deficit." In 2007, the United States Energy Independence and Security Act defined a high performance building as one that "integrates and optimizes, on a lifecycle basis, all major high performance attributes, including energy [and water] conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations" (EISA 2007).

In residential construction, High Performance Homes (HPH) can include a variety of proven energy-efficient features that: 1) contribute to improved home quality and comfort, lower energy demand and reduce air pollution; 2) include features such as design strategies and installation methods; and 3) use innovative green products (Lukachko et al. 2011). Such features have been suggested as significant in achieving green, high performance buildings, with green product technology offering solutions that reach across all features of green construction, design and HPH, including the green strategies and categories of accepted certification systems. As a result, HPH green product technologies contain broad implications for the Architecture, Engineering and Construction (AEC) industry.

Despite the increasing worldwide concern for the environmental impact of buildings, the residential construction industry is often seen as a laggard industry or one adopting innovations only after the products or techniques are clearly established (Dibner and Lemer 1992; Laborde and Sanvido 1994). Homebuilding firms are also perceived as laggard and resistant to the benefits of technological innovations (Tatum 1987). Researchers and policymakers have struggled with the lack of technological innovation in the US housing industry (Koebel 1999). While housing is arguably no different in nature than other industries, several unique factors have been established as causing uncertainty and risk in the context of innovative construction technology. Reflecting on the "Laggard industry" assumption, Koebel et al. (2004) identified barriers and impediments to innovation for firms in residential construction. Based on these barriers and others, McCoy et al. (2012) consolidated uncertainty and risk into the following categories: site variability, one-off nature, longevity of warranties, supply chain variability, path dependency and stakeholders.

However, previous studies on innovative practices do not address the divergence of recent residential construction technologies. For example, in place of path dependency and resistance to innovation, numerous industry studies point to a widening awareness and likely use of innovative practices and techniques that support environmental goals (Bodie et al. 2008). Where homebuilding innovation has traditionally experienced slower rates of adoption, some green building technologies exhibit accelerated patterns. In order to understand underlying reasons for resistance, it is important to not only understand risks, but also articulate use of innovation in the residential built environment.

Towards this goal of articulation, the authors examine and highlight broad patterns of innovation use (adoption) by builder firms within clusters of products (i.e. traditional versus innovative) for six energy efficient (EE) products, across years 2000-2010. The paper first reviews literature on uncertainty and risk that might hinder innovation in housing, building construction and green building. Second, we examine data from the National Association of Home Builders' Builders Practices Survey from 2000-2010 and describe the diffusion trajectories of the following six energy efficient, HPH product technologies in residential construction: 1) insulated concrete forms, 2) structural insulated panels, 3) cellulose and spray foam insulation, 4) PEX tubing, 5) programmable thermostats and 6) air infiltration barriers (housewrap). Each product is analyzed within a cluster of their substitute products, and based on the survey questions asked.

Literature Summary and Review

Research shows that innovation in construction in general and in the residential construction industry, specifically, has been slow to be adopted. While relatively few innovation studies are specific to uncertainty and risk in residential construction, researchers have attributed resistance to adoption and diffusion to many factors.

Beginning in the 1990's, researchers investigated innovation broadly, while some recognized the need to focus at the product level. In 1993, Slaughter investigated the product case of "stressed skin panels" and discovered that most of the innovation occurred at the builder level rather than at the manufacturing level. Slaughter later investigated unique elements of the construction industry and how they informed categorical models of innovation (Slaughter 1998). She suggested that theories of innovation should be modified when applied to construction due to the complexity, long lasting facilities. These facilities are created and built by a temporary alliance of disparate organizations within an explicit social and political context (Slaughter 1998). A 2004 survey of builders indicated that national and regional homebuilders, multi-family builders, modular, and custom builders are more likely to adopt innovations than other firms (Koebel et al. 2004). Koebel et al. (2004) also identified innovative firms as likely to: have a technology advocate in the firm, stress creativity, use a technology transfer program (e.g., PATH), and use union labor at least some of the time. These innovative builder firms also recognized the importance of demand for innovative products (from homebuyers) as well as the ability of a manufacturer to stand behind the quality of their product (Koebel et al. 2004).

Koebel et al. (2004) also identified several barriers and impediments to innovation in residential construction for large, production builders: R&D expenditure shortfalls, liability, cyclical market, disaggregation (many small firms), diverse building codes, and financial/insurance concerns that can and do inhibit the adoption of innovation in the construction industry. Larger firms relied on advantage/cost of products, while smaller firms required: high product awareness, an innovation's lower price to its replacement, and a change in the home production process. In addition, firms building in locations where increased awareness of innovative materials existed were more likely to adopt, while areas exhibiting path dependency and resistance to new technology contained limited potential for adoption (Koebel and McCoy 2006; Koebel et al. 2004).

Since the early 2000's, several trends have also emerged that could affect innovation adoption and diffusion for residential construction firms, including: homebuilding firm consolidation and growth of national, publicly traded homebuilding firms, increased industry concentration in high growth metropolitan markets, migration of technical/management talent from outside industries, decreasing supply of developable land for medium density development (increasing restrictions on land development), increasing energy costs, decreasing supply of craft labor, and Systems integration tools for design, modeling, and processing (Koebel and McCoy 2006).

While an understanding of general industry risks for residential construction exist, it is also important to understand uncertainty and risk for areas of the industry prone to adoption. Where homebuilding has traditionally experienced slower rates of innovation adoption, some specific green building technologies exhibit accelerated patterns. General innovation research on green building products has focused on user behavior, termed ecological consumer behavior, while recent work in residential construction focused on the performance characteristics of the product itself (McCoy et al. 2012). Common attributes affecting diffusion of green products in residential construction include (McCoy et al. 2012):

- Timing of Commitment,
- Compatibility/Special resources,
- Supporting Innovation,
- Complexity,
- Simplicity,
- Trialability,
- Observability,
- Relative Advantage/Cost,
- Risks,
- Supervision Competency,
- Consumer Resistance,
- Trade Resistance,
- Regulatory Resistance, and
- Coordination with Project Team.

Energy efficient, HPH construction is gaining acceptance as a sign of excellence in the trade, limiting the options in the market for firms who cannot bring these skills to a building project. Other factors, such as energy prices, regulation, and health or safety concerns, also increase the need for the adoption of energy efficient and 'green' practices in the building construction field. Similar types of evidence for price premiums have been found in certain housing markets and given certain types of green attributes of housing (Aroul and Hansz 2011; Bloom et al. 2011).

Nevertheless, few studies have been able to articulate statistically significant patterns of use for green products. According to a National Association of Homebuilders (NAHB) poll (Hudson 2011), almost 80 percent of respondents mentioned actions and products within the 'green' portfolio. Building industry professionals provide ample testimony that green building is not a trend or a passing phase (McCoy et al. 2012). Instead, energy efficiency and related HPH building practices are becoming the state of the art in the building industry and the ability to deliver these services to clients are increasingly important to maintaining a successful business. This work therefore aims to increase the significance of understanding for levels of firm adoption, and in the innovation literature, through an analysis of use for six EE HPH products (adoption), across builder firms (diffusion) and among substitute products within its cluster over time.

Methodology and Research Steps

This paper utilizes data from the 2000 to 2010 National Association of Homebuilders' Builder Practices Survey (BPS) on the annual use of high performance products (and related substitute products) by builder firms. The BPS survey data includes approximately 2 to 3 thousand firm responses, at FIPS county, state and regional levels, per year and over 1100 total products. Usage data for this paper only reflects a binary level of use and non-use, as opposed to percent use by firm, while percent use is available. To begin, the authors explored the survey, identified EE HPH products and classified them into 20 major innovation clusters (e.g. Engineered Wood, Air Sealing/Cement Board Siding/Insulation, Home Electronics, Insulation, and Plumbing). Some of these clusters had subdivisions, for instance, Engineered Wood Cluster includes types of wood floor framing, types of exterior wood/steel frame walls, and type of roof framing. Based on these clusters, this work draws on 6 high performance products and identifies their usage patterns during the time period of 2000 to 2010. The total use of these EE HPH products, across builder firms and across clusters of products, is plotted by product in the following findings section. Figure 1 describes the process of creating these use plots.

In order to produce the first group of graphs, a summary sheet was extracted which includes the number of firms and their responses to whether or not they have used the product across 10 years from 2000-2010. The relative use of each product within its cluster was determined by calculating the total number of firms using each product in each year and was called n_{ij}, where *i* represent each product within the cluster and *j* represents each year from 2000-2010. Then, the total use of all products in each year, n_{tj} was calculated. Finally, index S_{ij} was determined by the following equation:

$$S_{ij} = \frac{n_{ij}}{n_{tj}}$$

The resulted indices (i.e. S_{ij}) were then plotted using JMP software. The plot of each cluster, in the coming findings section, shows the percentage usage of each product relative to other products within that cluster during 2000-2010. Note that plotting years were often due to the availability of data for certain products over time.

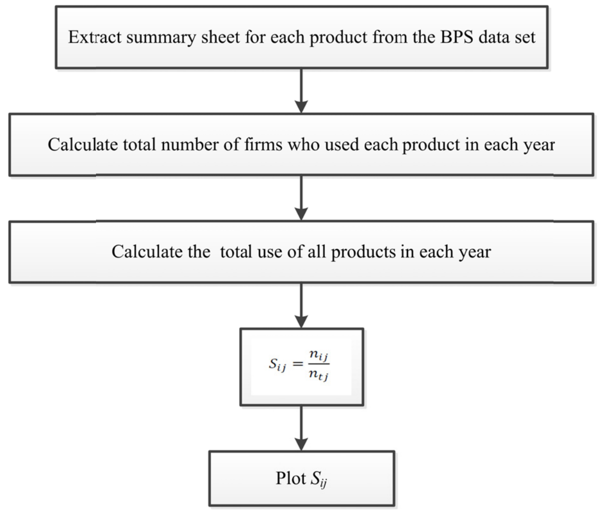

Figure 1. The process of producing graph 2-7.

Findings

Fig. 2 describes materials used by builders in basement or crawlspace walls. Poured concrete and concrete block are the two market leading building materials with block taking market share over the last five years. Interestingly, insulated concrete forms (ICF) has made a very small penetration in the market and appears to be sensitive to market conditions, with a somewhat increasing share in economic expansions and decreasing share in contractions. ICF represents a systems innovation that requires changes in how the house is built, different contactors, and potential disruptions in other contractor, supply chain, and regulatory networks. HPH innovations of this sort will have to overcome the inherent resistance of path dependency and the equilibrium reinforcing effects of networks.

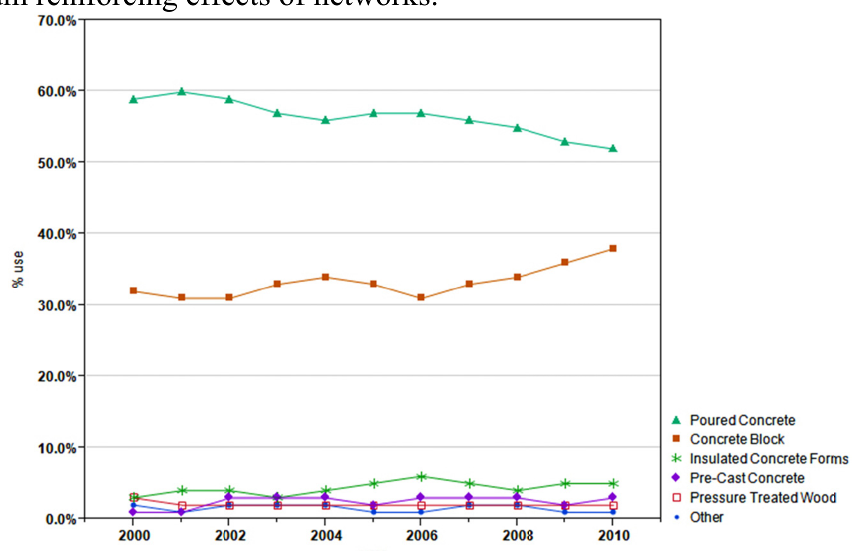

Figure 2. Basement/crawl space wall material vs. year.

Figure 3 depicts the cluster of exterior wood/steel wall products and includes Structural Insulated Panel Systems (SIPs). Site built walls with dimensional (2 x X) lumber dominate the market with nearly 90% use from 2000 to 2010. Panelized light frame systems comprise less than 10% of market share. Similar to findings in McCoy et al. (2012), SIPs walls represent a consistent 2% of the above grade wall market. Similar to ICF, SIPs represents a building systems technology innovation that requires some changes to the home construction process. Most of these changes focus on acquisition via the supply chain and movement/installation strategies due to panel weights. However, unlike ICF, SIPs panels do not represent a significant interruption to the construction process from knowledge, scheduling or tooling standpoint. More research on the obstacles and drivers of SIPs is needed to determine why a technology with significant insulation value occupies so little of the wall market.

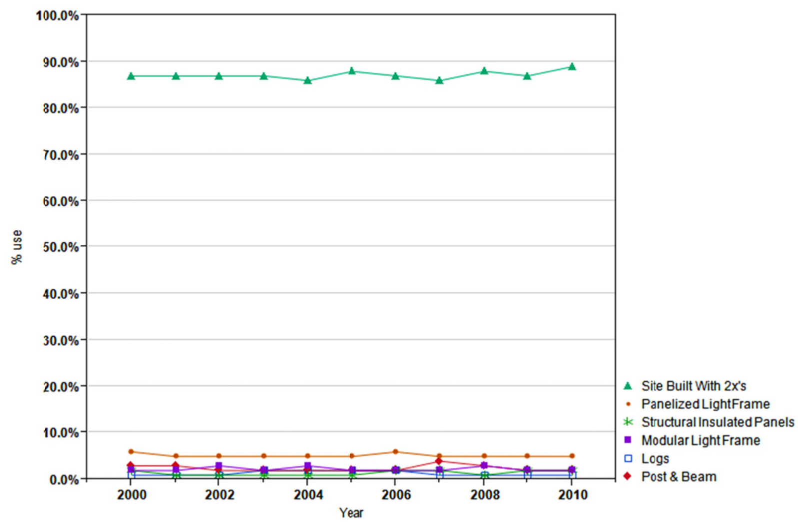

Figure 3. Types of exterior wood & steel walls vs. year.

Figure 4 characterizes wall cavity insulation material use over the study period. Fiberglass batt insulation is the market share leader capturing nearly 60+% of use. However, with it declining in use from 80% to 60%, other insulation technologies have gained share. Blown cellulose and spray foams have grown to capture a combined 20% of the market. Interestingly, spray foam popularity spiked in 2007 indicating potential market displacement of other economic substitutes and will be targeted for further research. Blown cellulose and spray foam insulations represent material innovations but not system innovations. They require very little out of the ordinary for a general contractor in terms of new skills, tools, labor, scheduling, or supply chain knowledge and provide higher levels of building energy performance.

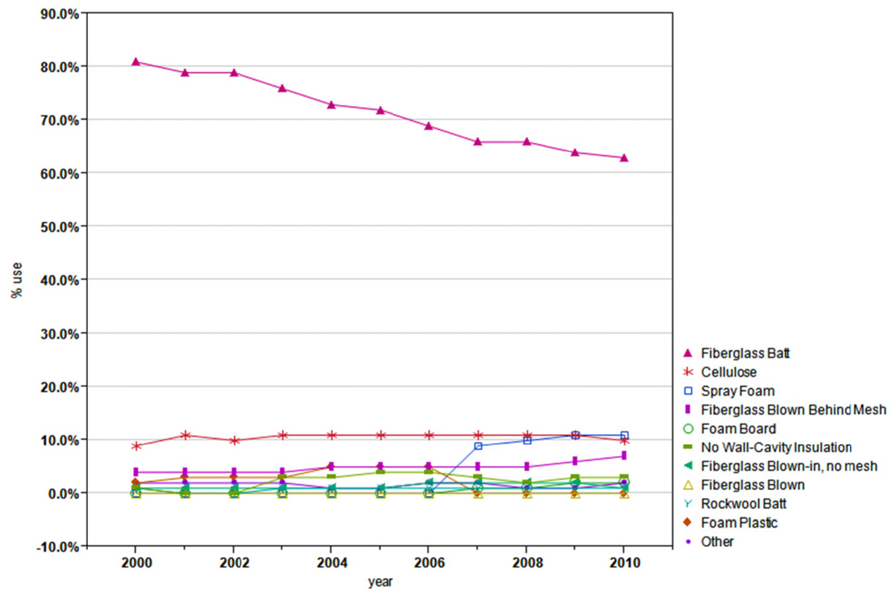

Figure 4. Wall cavity insulation material vs. year.

Figure 5 describes use of various types of water pipes from 2000-2010. Copper pipes dropped from nearly 65% of the market to 30% in 2010. Part of this decline can be explained by the five-fold increase in the retail price of copper/lb during the study period though certainly other factors contributed. Use of PEX piping grew from substantially from 2000 to 2010 when nearly 55% of builders reported use. PEX represents an innovation in piping, as it does not corrode like metal. Further, it is resistant to both scaling and build up and some contractors report reduced installation time due to the product's flexibility. PEX piping is an energy efficiency innovation in that the plastic does not conduct heat or cold so conductive loss or transfer is minimized when compared to metal substitutes.

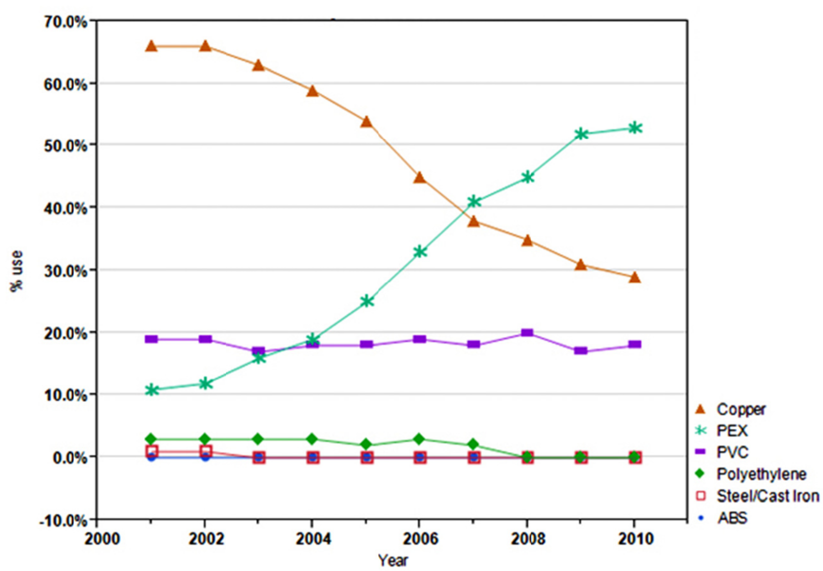

Figure 5. Water pipes vs. year.

Figure 6 shows the use of 13 Home Electronic products during 2000-2010. Programmable thermostats dominate the market with between 65% and 85% use. Easily installable, programmable thermostats allow occupants to more precisely control the interior temperature of their homes. Though occupants have long had either analog or digital control over their HVAC systems, programmable thermostats are a system innovation that allows the occupant to customize temperature settings based on time of day and other factors. Though not included in the survey data, the Nest thermostat represents the next wave of programmable thermostat innovation. Nest is a system that both communicates with smart phone and other mobile technologies but also detects occupant behavior patterns and adjusts temperatures accordingly. While not an energy efficiency technology, it was interesting to observe the decline in multi-line phone systems over the study period. In the context of increased smart phone sales and in mobile only consumers, this decline is not much of a surprise.

Figure 7 represents a slightly different chart type than Figures 1-5. This figure summarizes use of a single technology vs. non-use of the same technology—air in-filtration house wrap. The BPS question structure did not provide a set of economic substitutes for synthetic house wraps. So instead of the use of a product compared to others in its cluster, we show use vs. non-use to provide a second reference line on the chart. Non-use is defined here as the difference between total respondents and respondents indicating use. The pattern of house wrap use is intriguing in that it shows a decline over the study period. Given the increase or at least static nature of use in other energy efficient building technologies, this small decline is somewhat of a surprise. However, where we combined all building types SFD, SFA, and MF to create the graph, there is the potential for some noise as not all SFA and MF buildings require the use of a house wrap (building height, skin, and other design factors contributing).

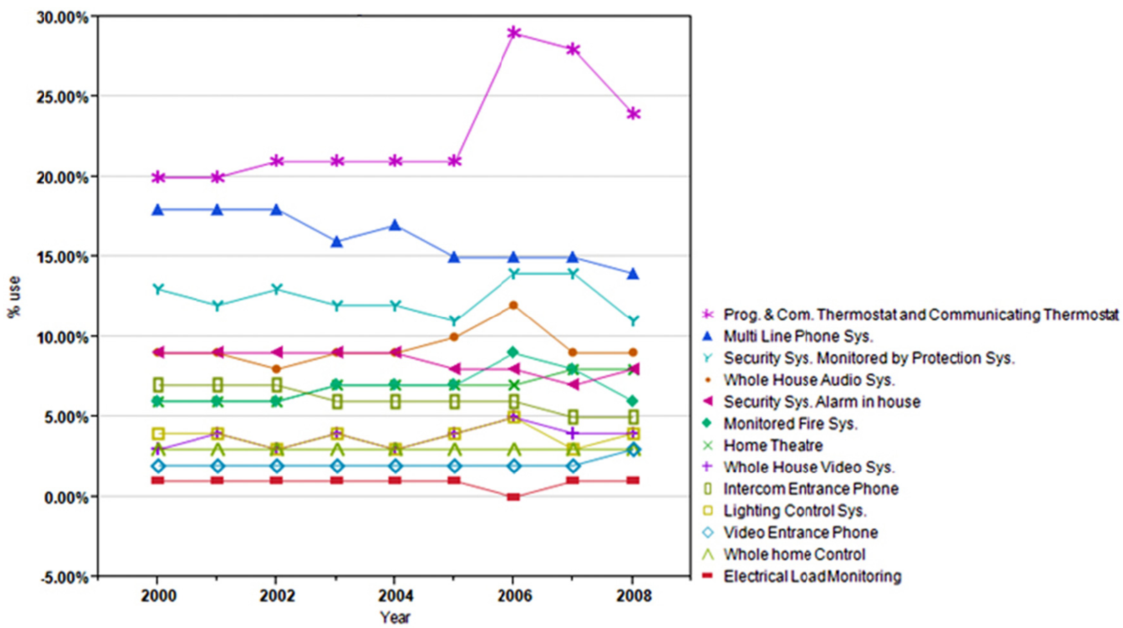

Figure 6. Home electronic systems vs. year.

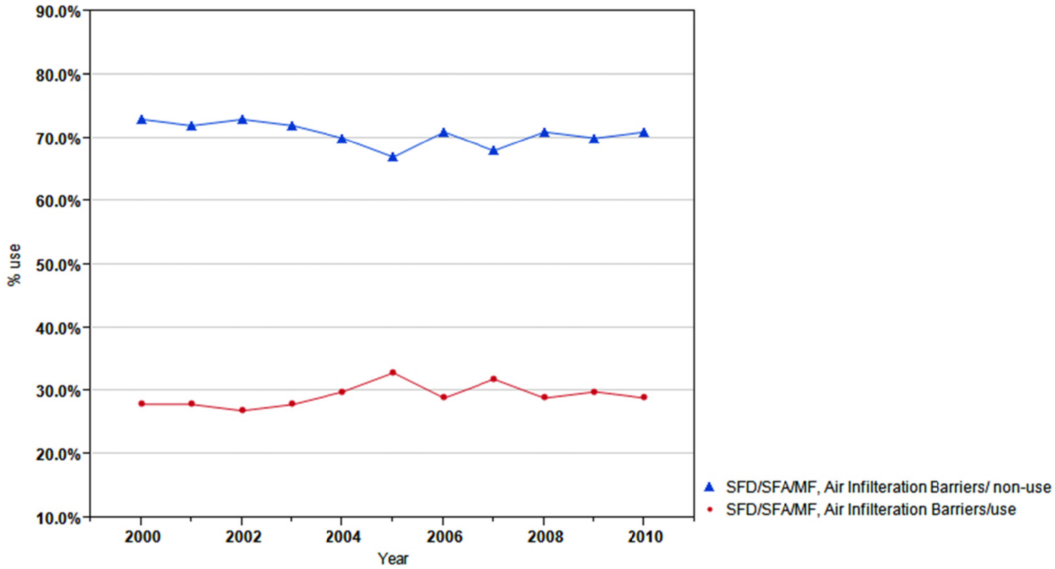

Figure 7. Air infiltration vs. year.

Implications of Patterns

From 1980 to 2009, the number of housing units in the United States grew from 81.6 million to 113.6 million. During the same period, the average consumption of energy per housing unit dropped from approximately 114 million BTUs to 89.6 million BTUs (Energy-Information-Administration, 2010). Similarly, there are now nearly 15,000 LEED certified homes and more than 130,000 homes were certified under the Energy Star rating system in 2011. When combined with the above data suggest that the housing stock is becoming more energy efficient and that there are building technologies and processes used to create or contribute to increased environmental performance. These data appear to confirm preliminary and literature based evidence that energy efficiency and green building are growing trends the residential construction and real estate sectors. But some aspects are puzzling and require further investigation.

Conclusion

To analyze the underlying reasons for resistance, the authors examined and highlighted broad patterns of innovation use (adoption) by builder firms within clusters of products for six energy efficient (EE) products, across recent years. The plots point toward an increase in the adoption of innovations in residential industry over time. Although homebuilding innovation has traditionally experienced slower rates of adoption, some green building technologies such as Programmable Thermostat and PEX piping exhibit accelerated patterns. The plots also indicated that some products such as ICF, SIPS, cellulose and spray foam have to overcome the inherent resistance of path dependency and the equilibrium reinforcing effects of networks.

This study attempts to prepare the ground for further study and exploration of current patterns of adoption in the residential industry. These preliminary explorations of the BPS data helps us to identify potential the underlying reasons for resistance, as well as to identify the risks and uncertainties associated with residential built environment.

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Innovation in Residential Construction Systems in Sweden

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Sweden stands out as the foremost innovator in homebuilding process and energy performance in Europe. 96% of Swedish Housing is built using an off-site process, and on average Swedish houses consume less than 50% of the energy of American Homes. Yet Sweden and the United States share a heritage of wood framed residential building, a result of the timber resources common to both countries. As recently as the 1970s the way houses were built in Sweden and the US was largely the same. But the global oil crisis of the late 1970s set the two countries on divergent trajectories. Sweden entered a period of rigorous innovation, improving the quality, construction efficiency, and energy performance of their houses. Their example is relevant to builders in North America because there remain many areas of commonality both in construction methods, consumer expectations, as well as the challenges presented in cold climate regions. One could consider Sweden as a "crystal ball", showing what American House Building might look like if we had spent the past 40 years committed to improving efficiency.

Our investigation into the Swedish housing industry has occurred both in factories and construction sites in Sweden. We have documented and analyzed our observations in order to understand the Swedish common building process, and determined how key components have been altered across their industry to support these techniques. We have examined construction drawings and technical documentation from dozens of houses from multiple factories to come to an understand of key characteristics of Swedish residential building system conventions. And finally we have systematically applied these principles to wall and framing prototypes based on American building products in order to lay out a road map to implementing these techniques in the US. These are manifested in a series of prototype wall systems we generically call Nordic Layered Walls, and in a next generation development of Western Platform Framing which we have come to call Swedish Platform Framing.

We will present a photographic overview of the Swedish approach to offsite construction and discuss the defining features of both job site and factory process and practices. We will explain how these processes contribute to the superior average energy performance of Swedish houses. Last we will look in detail at the Swedish Wall itself, and our application of their concepts in Nordic Layered Walls and Swedish Platform Framing.

This presentation will cover three areas.

- How Swedish houses are built: a brief overview of the site assembly of a typical house.
- Overview of the Industrial Production Process: innovations in off-site fabrication.
- Application to US Practices: adapting key innovations to American building.

How Swedish houses are built

Almost all Swedish homes are built with some form of off-site construction. It is a very lean process, everything arriving on site at the time it is needed, and in the quantity required, with very little waste of time, effort, or material. In contrast with American site building, which you are all familiar with.

We are going to watch a time lapse video of the site assembly of a Swedish house, but first I'd like to mention a few things you are going to see. The house perimeter is fully scaffolded, which means the workers can quickly and safely access the construction without ladders, and without the time needed to carry and move ladders. There are going to be four men working on this house, two on the ground staging and feeding the crane, and two on the house placing and securing the panels, plus the crane operator. In the US you may see 4 or 5 carpenters on an American home building site. They will be there for a few weeks framing a house. The Swedes will be done the same day they started, minus lunch and a few coffee breaks.

A short video will be presented here documenting a house installation. This will be followed by more images of the assembly process to highlight key points from the video.

This shows a floor panel being lifted into place. The cross furring is a typical technique used to facilitate passing wiring without boring holes through the framing. We will look at this more closely later in the presentation.

Here a floor panel being placed. I'd like to call attention to the top of the exterior wall, and note that the floor is being placed flush with the top of the wall, and not on top of the wall. We can also see the sill plate of the second floor wall which forms the "tongue" side of a tongue and groove joint that aligns the second floor wall when it is placed. Also visible is the gasket under the sill plate that will form the seal between the 1st and 2nd floor walls. So, before the wall is placed, it has already been precisely positioned, and sealed. There will be no need to carefully align the wall when it is dangling from a crane, the worst possible moment to need to be precise, nor will a worker need return to this joint with a caulk gun to seal it. When the second floor wall is placed, the joint is complete. By placing the floors inboard of the wall, they have reduced two field joints to one, and eliminated the need to finish an exterior band corresponding to the floor thickness. There are also energy performance ramifications to this configuration which we will cover later.

Another close-up of this wall panel joint.

Here we can see the racking used to transport the wall panels, and hold them in the vertical orientation. Temporary strapping is attached to the walls to protect sill and flashings from damage.

These braces which prop up the wall panels until everything is secured are also innovative. They adjust in length by twisting a grip in the mid section. This adjustability allows a single worker to quickly plumb the walls before they are secured permanently in place.

The blue plastic visible at the tops and sides of the panels is the heavy plastic vapor barrier sheet used at the interior side of all Swedish walls. We will look more closely at the composition of these walls later in the presentation.

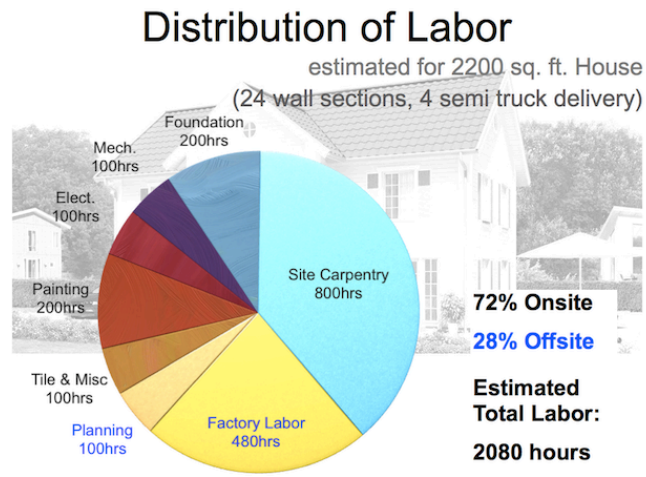
Here we see the second floor walls in place, and the materials needed to complete the framing, gypsum wall board, and floor finishes all staged for the completion of the house. None of these materials will need to be carried in and up the stairs.

Here the roof assembly which was built on the ground the previous day has been moved into position to be lifted on to the house. You can see another roof assembly underway in the distance. These are also built of off-site fabricated elements - trusses and end wall panels.

The roof is lifted and guided into position, then secured from the inside.

The last major operation is the staging of the roof tiles by one of the workers with the assistance of the crane. This man will do very little carrying, primarily lifting tile off the palette to distribute them to the final location.

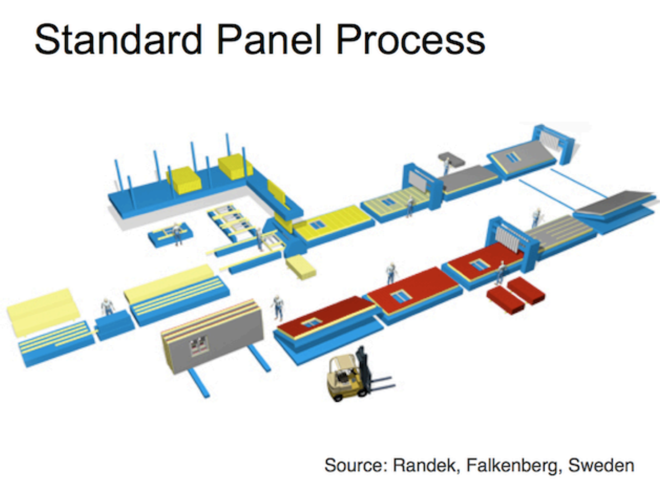
At the end of the day the house is "closed in", and for the most part water tight, the exterior walls were painted in the factory, all windows and doors installed and sealed, and a good deal of the wiring and plumbing is already complete. In this case an attached garage remains to be finished, as well as some interior partitions, finishes and painting. The house is roughly 75-80% complete.



A sample of the data from a single manufacturer indicates that the total amount of time spent on off-site construction is only about 28% of the total time it takes to build a typically sized 2000 sqft house.

Overview of the Industrial Production Process:

The assembly process we just watched used what we would call closed or both-sides-finished wall panels. This is the almost universal way in which walls are built in Sweden. In the US the predominant off-site method for houses is Modular. Modular also exists in Sweden, it is called Volume Element building, and it represents a smaller percentage of homes built than Panel, or Wall Element building. However modular builders in Sweden build their modules from closed finished-both-sides wall panels. And both Modular and Panel builders build walls using the same manufacturing process.



The Standard Production Process can be highly automated, or completely manual. It can be a linear assembly line, or a static work-station model. All of these scenarios share key characteristics:

- Wall panels are fabricated on the flat.
- Panels are flipped to finish both sides.
- Completed panels are racked and transported in the vertical.
- Work goes from 2d to 3d at last possible moment.

Working on the Flat provides numerous benefits to the building process.

- Working with gravity, not against it.
- Workers stand on the floor working waist high.
- Tools and supplies are always immediately at hand.
- No ascending/descending ladders.

This facilitates the efficient manufacture of complex high value assemblies. Swedish walls are sophisticated multi-layer assemblies that achieve high energy performance. This lends itself to interwoven trade sequences, such as carpentry-insulation-carpentry-insulation. Because there is little time or cost penalty for making walls with components in an assembly sequence that optimizes performance, they are able to invest more value into the wall assembly for less relative cost.

The mature process we see in Swedish home manufacturing is the result of a strong commitment from the entire industry. Almost all building components have been modified or adapted in some way to facilitate the manufacturing process.

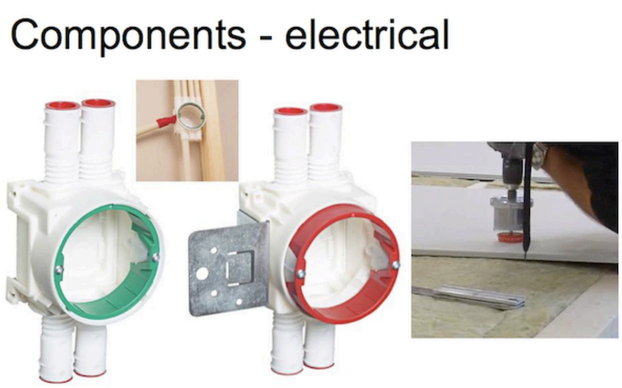
In this example we look at the window installation process. On the right is a window being installed in an American modular factory. The process is essentially the same as site building, except it is taking place indoors. Once the window is in place the worker will be up the ladder we see in the background to sink fasteners into the nailing flange of the window. It will be taped to flash it to the house wrap layer. Later another worker will apply caulk or inject foam sealant.

On the left is a window workstation in a Swedish factory. The first step is for the worker to apply a butyl gasket around the perimeter. The window unit is then clamped into the jig with precut lumber for jamb studs, head, and sill members which are then nailed together. The window is fastened to this subframe with adjustable fasteners that allow adjustment and squaring of the window unit.

Here we see staged window assemblies waiting to be incorporated into the wall panels as they are framed. What has just transpired? Essentially this window is installed, and sealed, and the wall has not even been framed yet. Nobody has to return to this assembly to finish it, or seal it, and if subsequent handling leads to any misalignment the unit is easily adjusted via its fasteners. This is a very lean process that has been totally reinvented for off-site fabrication.

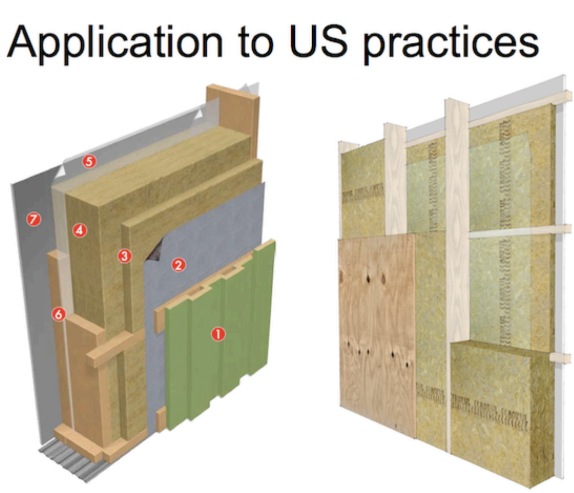
Similar innovations have taken place with other major systems. Pex tubing for plumbing is something we are familiar with here in the US but less familiar is that this was a Swedish innovation. With PEX, the flexible plastic piping can simply be left in a small coil where it exits the panel and easily passed through a hole in adjacent work to be connected later. Because of this it is possible to plumb and ship the walls with the piping in place, and to easily connect the piping after wall panels are installed.

Electrical systems have also been adapted to off-site building in Sweden. The key issue is making connections between panels rapidly when the house is being assembled on site. American residential wiring relies on plastic shielded wire which is inexpensive, but it binds together the conductors and the protective casing. This prevents any panel to panel connection from happening without a junction box.



The Swedes instead have a light weight plastic conduit system, that conceptually works more like our metal shielded commercial conduit systems. It simply snaps together easily in the field allowing joins to be made wherever needed. The conducting wires are simply pulled through later where conduits have crossed panels. Junction boxes have also been rethought to speed installation. Their circular openings work with a magnetically centered saw to quickly locate and cut box openings in wall board.

This kind of innovation is pervasive throughout Swedish house building and not limited to these few examples. All contribute to more efficient manufacturing process, better energy performance, and higher levels of quality.

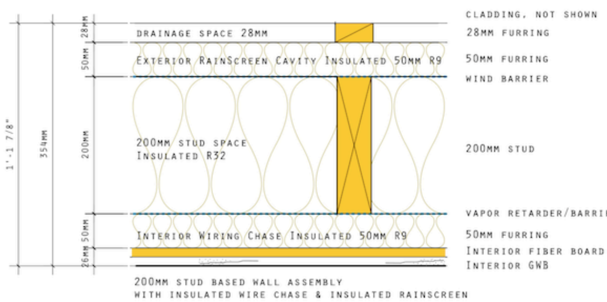


Application to US Practices

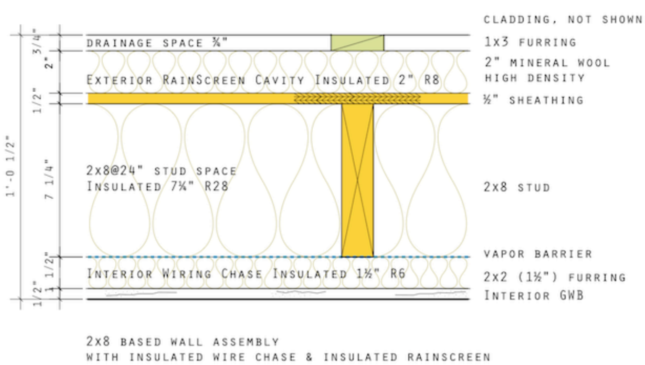
These building innovations are very transferrable to the US. Both countries use a stud framed house building model, and as such these Swedish innovations can be looked at as a natural evolution of practices here in the US. Demand for better energy performance is just emerging in the US, and market pressure for gaining efficiency through off-site construction is also growing. In that context we have studied how to apply elements of these Swedish techniques to American building practices. Today we'll look at prototypical wall assemblies, and also at a slightly larger scale whole house framing strategies.

This diagram represents a typical Swedish house wall, distilled from studying the standards of numerous Swedish factories. While there is some variation between factories this represents the major components of a typical wall. The main stud space is 200mm deep, just shy of 8". This is fully filled with stone wool insulation of approximately R32.

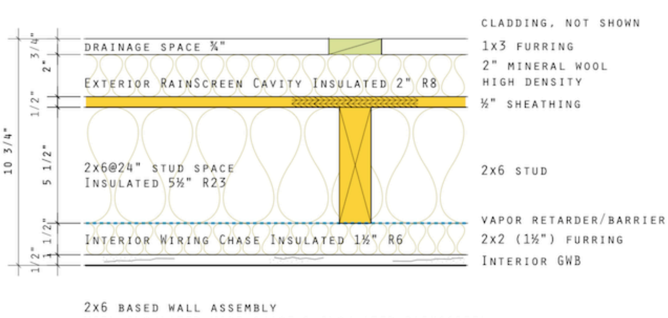
Typical Swedish Wall



USA New Wall 2x8



USA New Wall 2x6



To the interior there is a heavy vapor barrier layer, which is then covered with 50mm furring to create a wiring chase. This is insulated with a 50mm batt of R9. This layer breaks the continuity of the framing to overcome thermal bridging. Over the furring is a particle board layer that adds bracing, and last Interior wall board. Note that wiring is kept completely within the Vapor Barrier layer which also serves at the primary air-tight layer for the house.

At the exterior the studs are covered with a wind-break barrier. Then with a continuous 50mm semi rigid stone wool insulation layer of R9. Over this is furring and last is heavy wood siding.

Our goal was not to recreate the Swedish Wall, but rather apply the energy efficient characteristics to a wall built with standard American materials, using the same trades and skills currently common here.

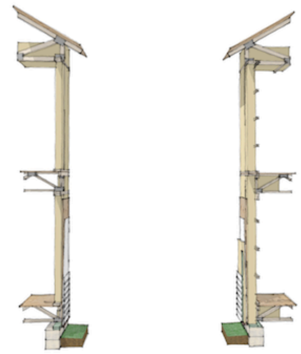
These are heating climate walls which we generically refer to as Nordic Layered Walls. There are 2x6 and 2x8 versions, both with a *Good/Better/Best* paradigm that applies these innovations in graduated steps. The purpose is to allow builders to step up performance as comfort level and market allows. We are going to look at the *Best* version of these walls.

At the core of the Nordic Layered Wall is a conventional stud wall with exterior sheathing. In the 2x6 version the stud space is insulated with 5.5" of stone wool of R23. In the 2x8 version the stud space has 7.25" of stone wool of R30.

To the inside we first cover that stud wall with a vapor control membrane with variable permeability which allows the wall to respond favorably to the flip of the vapor profile in summer. This is important because air conditioning is so common in the US. This vapor control layer forms the primary air tight layer for the house. Over this is 2x2 furring for the wiring chase which is insulated with 1.5" of stone wool of R6. Interior wall board last.

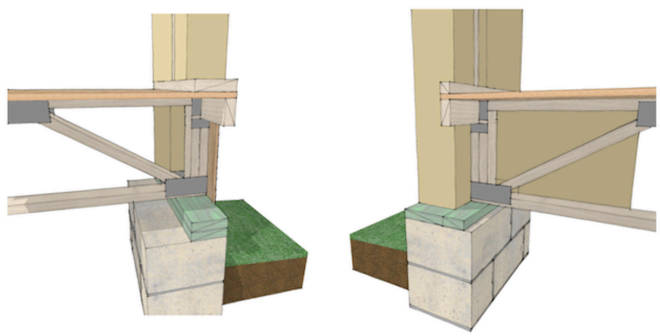
On the outside of the sheathing the typical american house wrap or building paper layers are installed, which are then covered with 2" of semi rigid stone wool insulation of R8 value. Over this is furring forming a drainage space, and siding panels mounted over that furring.

Platform Framing Innovations



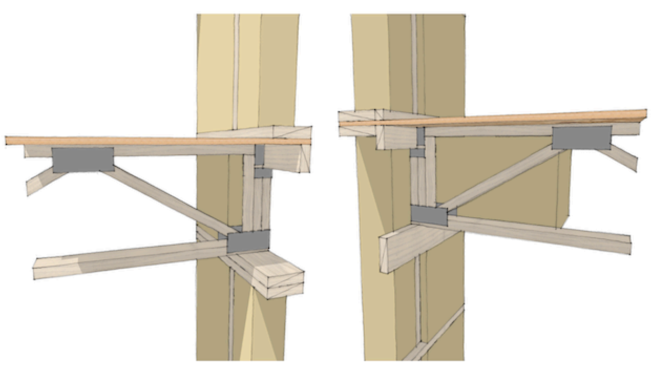
Western Platform Framing   Swedish Platform Framing

Ground Floor Condition



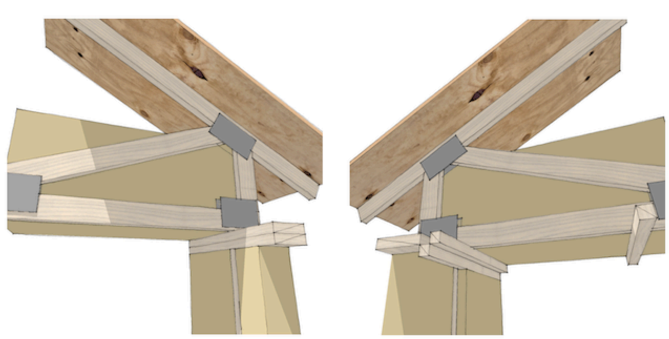
Western Platform Framing   Swedish Platform Framing

Second Floor Condition



Western Platform Framing   Swedish Platform Framing

Roof Condition



Western Platform Framing   Swedish Platform Framing

The second part is about whole house framing strategies. The predominant framing model for stud built houses in the US is Western Platform Framing. The Swedes have made several distinct changes to the Western Platform Model in order to facilitate off-site building, as well as resolve shortcomings of the energy performance and air-sealing characteristics of Western Platform Framing.

We've again translated this to American materials. It is referred to as Swedish Platform Framing.

At the ground floor of the Western Platform Frame the spaces between joists are difficult to insulate and air seal effectively, and the joist ends form a thermal bridge into the house. Sill Plates and wall sole plates form additional thermal bridges from the exterior.

The Swedish Platform Frame is configured differently. Wall studs extend all the way down to the foundation top, and floor joists are moved inboard of the wall. The interior vapor control layer can extend all the way down to the top of the foundation wall for better air sealing. Multiple sill plates are eliminated, and thermal bridging of the assembly greatly reduced.

At the second floor the Western Platform Frame wall terminates under the floor joist with a double top plate, and resumes again above the floor with a single sole plate. Again the space between the joists is difficult to insulate and air seal.

In the Swedish Platform Frame the wall extends up to the second floor level, again allowing the wall insulation to pass outside of the floor framing. The vapor control/air tight membrane extends up to the second floor deck maintaining the integrity of the air tight envelope. This is made possible by the floor joists being supported on a ledger located within the depth of the interior wiring chase. The overall quantity of wood members forming thermal bridges is reduced, and the air tightness of the wall maintained.

At the roof the Western Platform Frame uses a double top plate to top the second floor wall. The Swedish Platform wall in 2x8 configuration will often be able to suffice with single top plate which reduces the thermal bridging. The furred wiring space continues here across the ceiling which reduces the thermal bridging from the roof trusses, as well as continues the vapor control and air tight layer across the ceiling completing the envelope.

The State-of-the-Art Application of Modular Construction to Multi-Story Residential Buildings

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Abstract: Modular construction methods show great potential as an alternative to traditional site-built methods and could be a means of providing much needed affordable housing in the dense, land deprived urban areas typical of US cities. The evolving field of modular construction will require significant investment in research to successfully integrate these powerful concepts into mainstream construction practice and provide the industry with the resources and tools it needs to use these cost, time, and material saving construction methods effectively in future designs. This paper aims to review both the current state-of-the-art of multi-story construction and promote its utility for high performance, sustainable multifamily dwellings in U.S. urban areas, particularly for moderate income, one- or two-person families.

Introduction

The use of modular construction has been gaining momentum and popularity in the construction industry slowly over the last decade. Large statistical reporting agencies such as FMI Corporation and McGraw-Hill Construction are promoting the modular construction industry a growth opportunity (MBI 2011). The resurgence of these methods is largely in response to the need for high performance buildings and construction cost savings in these down economic times.

Figure 1. Proposed B-2 Modular High Rise (image by ShoP Architects, 2012)

A study carried out by McGraw-Hill (McGraw-Hill Construction 2011) reports the current state of the market regarding the use of prefabrication/modularization in the building construction industry. According to the study, with almost universal interest, a remarkable 98% of the surveyed professionals expected to be using prefabrication/modularization on at least some of their projects by 2013. For those not currently using these methods, the primary reason cited was that they were not specified by the architect. The primary reason architects reported not specifying the use of modular methods in their projects was owner resistance to the idea.

One of the challenges the modular market faces today is overcoming social stigmas from the past. Many people associate modular construction with unattractive, low quality, industrialized structures. This may not be the case, however, with today's advanced manufacturing technology and BIM modeling capabilities. The variety of applications for modern-day modular methods seem to be only limited by the creativity of the designer.

It is important to note that modularization is not appropriate and cost effective for all projects. Economy is achieved primarily in terms of scale. Large cellular building types such as multifamily dwellings (i.e., condominiums, dormitories, hotels, and apartments) educational, correctional and health care facilities are all prime candidates. Structures that have many repeatable units can typically be modularized efficiently with positive results.

Modular Construction

In their 2011 annual report (MBI 2011), the Modular Building Institutes (MBI) defines modular construction as follows: "Modular describes a construction method or process where individual modules stand alone or are assembled together to make up larger structures." MBI classifies modular construction into two different categories: Permanent Modular Construction (PMC) and Relocatable Buildings.

PMC methods are subdivided into 2D panelized construction and 3D modular construction. 2D panelized systems, or cassette type assemblies, are frequently used in the construction market today. Panelized systems are complete flat assemblies that can be craned into place and set. Wall, roof, and floor systems are good candidates for panelization. Panelized systems are typically constructed from wood, light gauge steel framing, or concrete. Structurally Insulated Panel (SIP) wall and roof systems, panelized wood framed or light gauge steel walls, and panelized thin reinforced concrete foundation and above grade walls are popular assemblies used in modern residential construction. 3D modular construction, or volumetric modular construction, refers to 3D modules or units typically constructed from 2D panelized components. The modules are often completely assembled and finished on the interior. They can stand alone or be used in conjunction with other modules to form a complete structure (AMA Research Ltd. 2007). In this paper we will primarily discuss volumetric modular construction.

3D Volumetric Modules

A typical volumetric module used in the construction of a multifamily dwelling is approximately 11'-14' wide and 20'-30' long and has a floor area of 270 ft^2 – 375 ft^2. One module is appropriate for a small single-person accommodation, two modules for a slightly larger 2-person apartment and three or four modules can be used for a family-sized accommodation (Lawson et al. 2012). There are three basic types of modules used in mainstream construction today (Lawson and Ogden 2008).

1. Load-bearing modules that use corner and intermediate posts (Figure 2) to transmit gravity loads. When using this type of construction the posts would be aligned vertically throughout the building height.

2. Load-bearing modules that use the exterior walls to transmit gravity loads. The modules are stacked on top of each other, and the side walls are aligned vertically to form a straight load path throughout the building height (Figure 3).

3. Non-load-bearing units also called Pods. This type of module is typically used as an infill unit and is set on a floor framing system.

Structures that are less than four to six stories in height that use load-bearing modules can transmit lateral loads through diaphragm and shear wall action to the ground. A structure that exceed four to six stories will be considered a high-rise structure in this paper and usually require a separate lateral bracing system. It is common for high-rise structures to use steel framing systems or concrete cores to resist the increased lateral loading.

Figure 2. Corner Supported 3D Module (image by Lawson and Ogden, 2008)

Figure 3. Load Bearing Wall 3D Module (image by Lawson and Ogden, 2008)

Benefits of Modular Construction Methods

In a recent report the MBI (MBI 2010) points out that almost every U.S. industry has experienced growth over the last few decades except the construction industry. The National Institute of Standards and Technology (NIST) recently formed a committee of experts to investigate ways of improving productivity and competitiveness in the construction industry. The committee identifed the increased use of BIM and modularization as keys to increases in productivity. The U.S. Department of Housing and Development (HUD) has one of its mandates to support manufactured housing, and at a May 2012 meeting of experts in Washington D.C. organized by the HUD's Office of Policy Development and Research, development of multi-story modular construction was identified as one approach toward creating affordable and energy efficient housing. The primary benefit of using modular methods is the gains in construction productivity. Additional benefits are as follows:

- Factory-built products benefit from the controlled environment of an indoor facility, which can be managed more efficiently than an outdoor jobsite.
- Productivity increases can be recognized in time or cost savings for the developer. Lawson and Ogden (2008) estimate 10%-20% cost savings may be available and 30%-40% time savings may be achievable in larger construction projects. Cost and time saving items include:

  a) Fabrication of modules concurrent with site improvement activities.
  b) Simultaneous module erection and site remediation efforts.
  c) Reduced individual building subsystem construction.
  d) “Just in Time Deliveries”.
  e) Reduced need for equipment, labor and stockpiling space.

- The benefits achieved through the construction process lead to an overall reduction in site and community disturbance. This can be advantageous for student housing projects or those in dense urban settings.

- A benefit of modularization is the recyclable nature of the modules or panels. 3D volumetric modules can be deconstructed offsite and recyled or reused whole if possible.

The implementation of modular methods can benefit both the project owner and the future dwelling occupant. The owner realizes the cost saving through productivity increases and the shortening of the construction schedule can lead to early occupancy of the structure. The owner can gain a competitive edge in the market by providing much needed affordable housing to the occupant without sacrificing quality. Additionally occupants benefit from reduced utility bills and maintenance requirements that result from a high quality factory produced unit.

Challenges Facing the Modular Industy

The most significant challenge facing the modular industry is the social acceptance of modular products. McGraw-Hill points out that the primary reason cited by industry for not using modularization in their projects was that the architect did not specify it. (McGraw-Hill Construction 2011). Architects will be instrumental in initiating a strong modular integration effort in the main stream construction market. If they accept and adopt modular technology, architects have the opportunity to influence clients when developing potential design options for a project. Additional Challenges facing the industry are listed below.

- Modular construction projects have physical constraints that apply and limit the ability to modularize some projects. Consider the feasibility of modularization at the conception stage of planning:

  a) Will the dimensional constraints of using 3D modules be acceptable?
  b) Is there site access for crane assemblage and delivery of the modules?

c) Can the modules be successfully transported and staged at the site?
d) Is there a modular facility within a reasonable distance of the project?

- Standardization across the industry seems to be essential. In order to successfully implement cost-effective design, standard dimensions and standard communication protocols should be established.

- Drafting systems used by designers are outdated. Once drafting systems are updated and BIM is incorporated into the discussion, the benefits of modularization will become more apparent to both owners and architects.

- The assemblage of interdisciplinary, colloborative, model based design teams along with increased design time allotment in the project schedule is needed to improve the productivity of the design process and construction management of projects that use modular methods.

- Building codes are slow to develop and could hinder the integration of modular methods. Restrictive codes may hamper new ideas and make it difficult to integrate much needed new building design philosophies into society.

Multi-Story Modular Design

Stackable Modular Units

The most common method used to construct low rise modular structures is stacking. Similar to building blocks, load bearing modular units (Modules) can be stacked and bonded to form a complete structure. Modules are typically arranged in a story floor plan such that they border a central corridor or common area. This allows easy service connection and common access for maintenance of modules or module connections (Lawson et al., 2012). The structure shown below (Figure 5) is an example of a typical low-rise modular design.

Figure 5. SoMa Studios, a 23-unit apartment building in San Francisco's trendy South of Market district (image by MBI, 2012)

Concrete Core Construction

Concrete cores are used to transfer lateral loads and provide story access in mid-rise and high-rise structures. Modules are typically arranged around a core in one of two ways. They can be clustered around the central core, with modules attached to the core via embedded connections, or they can be bordering a common corridor and attached via bracing elements. Typically, gravity loads are transferred through the modules. Module connections and bracing elements are designed to transfer lateral loads from the module to the core or corridor (Lawson et al. 2012).

Concrete core construction is the most common structural system used for modular high-rise construction. An example of a 19-story modular high-rise concrete core design is shown in Figure 6 (MBI 2013a). Cores can be constructed onsite with reinforced concrete or can be prefabricated and assembled onsite.

Figure 6. Concrete core construction Victoria Hall, UK ; Core visible on left, rendering of completed structure on the right (images by MBI, 2013a)

Hybrid Modular, Panel and Primary Steel Frame

A hybrid moular design incorporates the benefits of a primary steel frame with the benefits of 2D and 3D modular components. The primary steel frame is typically used as the stabilizing structure and provides the designer flexibility when planning internal spaces. 2D modular panels can be incorporated to make up open areas in the floor plan, and the 3D volumetric modules can be used for the core use spaces or highly-serviced spaces such as bathrooms. Two generic forms of construction are typically used with a hybrid modular design (Lawson et al. 2005):

Podium Structure – These structures are intended for mixed commercial/residential use. The first one to two stories are steel or concrete framed and are used to provide commercial space. Load-bearing modules are then stacked on top of the podium and used for accommodations.

Skeletal Structure – This type of structure is used to provide flexibility of floor planning to the owner. A steel skeleton is used for the superstructure and to frame out any intended open areas. Modules are then placed as needed. Both load-bearing and non-load-bearing modules are used with this type of design.

Shown in Figure 7 is a student housing project for Manchester University, in the UK. This 7-story building was constructed with a primary steel frame and a two-story podium. The first story was constructed below grade for parking. The second story has retail space, and the remainder of the stories contain 3D modular student housing units. A total of 1425 modular units were used for the construction of this building. The Steel Construction Institutes (SCI) claims a construction time reduction of 60%, for this project, over site-intensive construction methods (SCI 2003a).

Shown in Figure 8 is a housing project located at Lillie Road, Fulham, in the UK. This particular hybrid design incorporated light steel framed 2D cassette panels for wall and floor systems with 3D modular bathroom units. The apartments are a maximum of six stories, and 16 weeks were saved from the overall construction period of 68 weeks (SCI 2003b) for this project.

Figure 7. Podium Design Manchester University (Image by Lawson and Ogden, 2008)

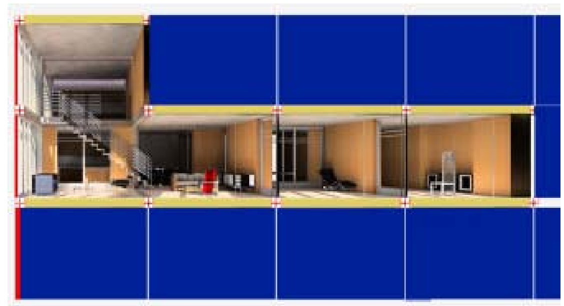
Figure 8. Hybrid structure, Lillie Rd. Fulham (Image by Lawson and Ogden, 2008)

Open Building Systems

The concept of "open building " originated in the Netherlands in the 1960's (Cuperus 2001). The philosophy of open building systems strives to decouple the base-building (support) and fit-out (infill). This concept can be seen in the construction of modern day leasable office space. Modular methods are at the heart of the open building philosophy and can be implemented in many ways. Many of the hybrid steel-framed structure types discussed previously are based on elements of this philosophy (Lawson and Ogden 2008).

Many forms of open building systems exist. The Swedish system known as "The Open House 3D Modulus system" is based on a "flexible mass production idea"(Birgerrson 2004). Flexibility comes in the form of many available arrangements of the modules, whereas mass production is a result of modularization. Figure 9(d) shows a module from this system being placed. The modules are placed between steel columns spaced on a grid pattern. The system can be used for structures under eight stories. Figures 9(a) and 9(b) illustrates a concept from the Massachusetts Institute of Technology (MIT) open source alliance housing program ("MIT House_n" 2012). Architectural firm ANDO has a innovative idea labeled by architects as "the mutant vertical city" (Parkins 2012). Figure 9(c) shows a rendering of the concept.

(a)



(b)

(c)

(d)

(e)

(f)

(g)

Figure 9. (a) MIT test case modular chassis system, (b) MIT sample five unit apartment (images by MIT House_N Contortium, 2012), (c) Proposed "Mutant Vertical City" (Image by DesignBuild Source, 2012), (d) 3D Modulus System (Image by Lawson and Ogden, 2008), (e) Victoria Hall Wolverhampton student housing, (f) Wolverhamton under constuction (Images by MBI, 2012b, (g) Murray Grove housing project (Image by CABE, 2012)

Current Application of Modular Technology

McGraw-Hill identifies healthcare facilities as the number one current user of modular methods, while Commercial warehouses, Hotels, and educational facilities show potential for future growth (McGraw-Hill Construction 2011). Developers of multi-family residential buildings are users of modular methods as well. Seen in Figure 9(f) is the Murray Grove residential project constructed in London (CABE 2012). The high-rise building shown in Figures 9(e) and 9(g) is another example of a residential multifamily project constructed in the UK (MBI 2012b). While the UK dominates the landscape, there are also large-scale residential projects in the US; Figure 1 displays the Proposed B-2 high-rise slated for construction in Brooklyn New York. This 32-story building will be the tallest modular high-rise in the world if constructed. The building will be used primarily for housing units

A survey was administered to a group of experts in the field of residential housing to gage the demand and acceptance level for modular technologies in the local construction industry. The table is still a work in progress but the initial results from a limited portion of the group of experts are summarized in Table 1. The objective of this stage was to identify major criteria for comparison of different systems. In follow up parts of the study, a comprehensive survey will be carried out that will include more extensive criteria for comparison and a broad group of experts.

Table 1. Assement of benefits and opportunities for select modular construction methods

Criteria:	*Stackable Low to Mid-Rise*	*Concrete or Steel Core High-Rise*	*Hybrid Structures*
Aesthetics:	Low	Medium	High
Flexibility of Floor Planning:	Low	Medium-High	Medium-High
Level of Off-Site Construction:	High	Medium-High	Medium
Opportunity of Time Savings in Construction Schedule:	High	Medium-High	Medium-High
Opportunity for Overall Construction Cost Savings:	High	Medium-High	Medium
Natural Disaster Resistant Design Challenges:	Medium	Medium	Medium-High
Building Envelope/Waterproofing Design Challenges:	Medium	Medium	Medium
Energy Efficient/High Performance Design Opportunities:	Medium-High	High	Medium-High
Current Level of U.S. Use:	Low-Medium	Low	Low
Projected Level of U.S. Use:	Medium	Medium	Low-Medium
Current Level of European and Asian Use:	Medium	Medium	Low-Medium

Closing

Bringing modular technologies to the forefront of the modern building construction market is a necessary evolutionary step toward energy independence and prosperity in the construction industry. Many new and innovative technologies already exist, but require integration and interoperability advances in order to become effective in our future structures. There are currently many opportunities for use and increasingly positive attitudes toward modular methods, but the preparedness level of the industry is low. In order for modular methods to reach their full potential in the construction market, key technology sectors such as BIM must become established. The interoperability of high performance building subsystems in part will lead to improvements in efficiency. The continuing development and standardization of BIM protocols will be essential as a platform for the integration efforts.

Although many opportunities for modular construction exist in the construction market, many barriers also exist. In addition to the technological barriers discussed above the general public has negative preconceptions regarding modular construction that may slow down the large scale adoption of these methods. It is important to look at examples of past modular construction projects and identify the successful elements and failed portions of the projects. Applying the lessons learned from past designs will improve the chance of success for future designs.

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Identification of Structural Issues in Design and Construction of Multi-Story Modular Buildings

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ABSTRACT

As the modular construction industry tries to find new markets in multi-story buildings, additional challenges are faced along the way that needs to be addressed. This paper initially introduces different types of modular multi-story or high-rise construction systems. The structural systems including gravity and lateral load resisting systems are then discussed. The challenges that structural designers face in addressing load path continuity and gravity and lateral load transfer between adjacent structural components are reviewed. Approaches for system and building modeling needed for structural analysis as well as relevant building code requirements are discussed. Furthermore the challenges in design and detailing of different structural members and components/systems are evaluated. The paper also provides an overview of any special structural safety issues for design and construction. Finally, the paper outlines the R&D needs for advancing the technology of multi-story modular building design and construction.

INTRODUCTION

Modular construction is known for its economic advantages and high construction quality of the modules because of the factory construction environment. Despite the simplicity of the construction of modular single-family dwellings that brings about speedy erection at the job site, the same thing cannot be stated for multi-story modular buildings. With increase in the number of stories, the construction method and structural engineering issues become more complicated, in particular when lateral loads also need to be considered. There is lack of good or sufficient understanding of the structural behavior of such multi-story construction. Nonetheless, interest exists in multi-story low-rise, mid-rise and high-rise modular construction, in particular in urban and metropolitan areas. However, because this technology is relatively new with limited understanding of structural performance under extreme loading conditions, most applications of multi-story modular construction are currently in low-rise buildings or in areas with minor natural hazard potential. However, construction of multi-story modular buildings in the United Kingdom has shown significant progress in developing and advancing this construction technology.

By improvement of technology, the methods of construction can be changed. As shown by the popularity of the use of panelized components in commercial and industrial construction, there are various benefits in shifting from all site construction to more

panelized and modular construction of residential buildings. Lawson and Ogden (2008) mention the following three major benefits of the modular construction of buildings:
(a)Lower construction cost—as the number of plant fabrication increases, the constant cost of the plant will be shared by more fabrication, thus reducing the total cost; (b) Shorter construction time—because of reduced jobsite activities; (c) Higher quality production—because of better plant fabrication and inspection.

In recent years, numerous mid-rise and high-rise modular buildings have been built around the world (MBI, 2011). Due to lack of specific code or standard for construction of multi-story modular buildings, different innovative structural systems are used in these buildings, and general building code requirements are normally considered for safety-related issues; for example in United States, most of the multi-story building are designed according to International Building Code (IBC, 2012). As for each new innovative system, multi-story modular buildings with their own characteristics pose unique challenges for prediction of their behaviors under structural loads; there is very limited research available on different types of such systems. In particular, there are no specific design criteria for this type of structural system. In addition, due to the complex nature of structural components and connections of modular buildings, structural modeling and analysis are more complicated in comparison with conventional (non-modular) buildings. In this paper, for each multi-story modular system type, some important structural aspects are discussed that needs consideration for structural design and modeling purposes.

IDENTIFICATION OF DIFFERENT STRUCTURAL TYPE OF MULTI-STORY MODULAR BUILDING (MSMB)

By considering structural aspect of these buildings, we can categorize them in the following six major groups: 2D, 3D, Open Building System, Hybrid Cored-Modular, Hybrid Podium, and Framed Unit systems.

2D systems

In 2Dsystems, prefabricated floors and walls are installed and assembled to create a whole building. First, columns and walls of each story are installed, followed by installation of floor cassettes on these columns and walls (Lawson et al., 1999).A good example for this system is a 30-story hotel in China near Dongting Lake where it was erected in just 15 days. As depicted in Figure 1, the structure has two main components, which are roof/floor cassettes and columns (Jackson, 2012).

Floor diaphragm system is strongly related to the type of modular building. Generally, in 2D

Figure 1. Dongting Lake Hotel with 2D structural system using floor cassette-column- connection example (Jackson, 2012)

systems and Open Building systems, panelized floors (e.g., floor cassettes) are supported by walls or a framed structure (as shown in Figure 1) requiring constraining of floor joints in these systems. The main function of connections between 2D panels is integration of panels and load transfer between them. Connections must have adequate strength to transfer gravity and lateral load between panels. An example of connections in 2D system is also depicted in Figure 1 (Jackson, 2012). As shown in this figure, these connections consist of rigid bolt fasteners. In addition, a shear key is considered at the top of the column, which goes to the floor cassette and gives rise to uniform movements of the joints at floor level. Furthermore, due to the use of wings for the column, a rigid connection is achieved between the column and the cassette. The behavior of this structural system under lateral loads, resulting from wind loads or earthquake induced drift, will depend on whether such resistance is relied on stair tower walls or elevator shafts, or whether some bays employ certain bracing system. In general, in such construction, emulation of conventional rigid frame behavior in analytical modeling may not be the most appropriate approach, and innovative systems may need to be employed. In particular, for use in high seismic regions, appropriate energy dissipating systems need to be developed.

3D Systems

In this modular system, the structure consists of many 3D modules, which are stacked vertically and attached horizontally to create the 3D building. Each module can be part of a unit, one complete unit, or even more than one unit. The size of the modules is related to the location of the module in the building, construction equipment and transportation limits. Usually modules in this system are in the range of 100 to 600 square feet (Lawson et al., 2010). Based on the study of load paths for this type of structure, 3D system can be divided into two main subcategories, which are “Wall-Load Bearing” and “Corner-Supported” systems (Lawson et al., 2010).

Wall-Load Bearing systems

In wall-load bearing systems, gravity loads (live and dead) are transferred to the walls, which will then transfer loads to the foundation. Load bearing elements of these modules are walls and usually consist of many repetitive C section (light gage steel studs) profiles along the wall. Lateral loads within the module are resisted by bracing elements and/or sheathing. Another structural system that is common for these walls is steel sandwich panel. The spacing of these profiles or the strength of panels depends on the amount of gravity loads, location of the module, and lateral load magnitude. In Figure 2, a module with load bearing walls is depicted (Lawson et al., 2005b).

Figure 2. Wall-Load Bearing module with steel C-section profiles (Lawson et al., 2005b)

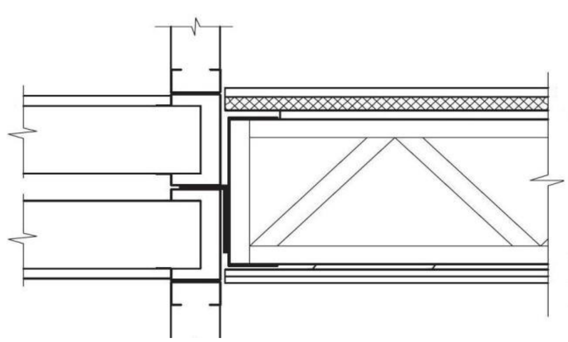


Figure 3. An example of entire building floor diaphragm in stacked modular construction (Lawson et al., 2008)

Figure 4. Individual module diaphragm of a module (Lawson et al., 2008)

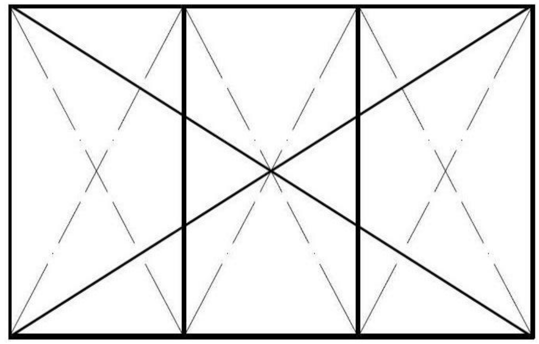


Figure 5. Difference between entire building diaphragm (continuous lines) and individual module diaphragm (dashed lines)

Generally, in 3D systems and their combinations, the floor of the building consists of many discrete floor elements (unit diaphragms). Therefore, the integrity of these discrete units, which is provided by the diaphragm, is very important in these systems. There are two diaphragm systems that need to be differentiated. The entire building floor diaphragm is a structural system that distributes lateral story loads to lateral load bearing elements of the structure; an example of this diaphragm is presented in Figure 3. The building floor diaphragm helps floor joints to have uniform lateral movement. This diaphragm constrains top joints of the lower modules and bottom joints of upper modules by tying them together at each story for horizontal movement of the floor. This diaphragm also helps bring about integrity of the modules and ensure uniform lateral movements of modules in each story. It also functions to distribute horizontal floor loads to vertical lateral load resisting structural elements. In 3D systems and their combination with cluster and podium systems, floor panels of the stacked modules and the connections between modules cannot sufficiently constrain floor joints together; therefore additional diaphragm system would be required. Figure 4 shows an example diaphragm system for 3D modules (Lawson et al., 2008).

In addition to the entire building floor diaphragm, each module should have its own individual module diaphragm. The module diaphragm constrains the joints of a module together in the floor plane at the top as well as the bottom of the module. As shown in Figure 4, the module diaphragm can consist of a crossed cable diaphragm bracing, which constrains opposite corners of the module together (Lawson et al., 2005a). In addition, the difference between module diaphragm and building floor diaphragm is shown in Figure 5.

Module diaphragms in these systems perform different functions during construction and after the construction. During the construction phase, this diaphragm helps increase rigidity and stability of the module, especially at the time of erection and installation when it enhances twisting and buckling resistance of the module. After completion of the building construction, the module diaphragm forms a part of the building diaphragm to distribute loads among structural elements, especially under lateral loads.

Corner-Supported systems

In this system, the corners of the modules support the gravity loads, which are transferred by edge beams of the modules. The columns and edge beams (normally deeper than those in wall-bearing modules) in this system carry gravity loads, while some bracing elements or

Figure 6. Corner-Supported module (Lawson et al., 2005b)

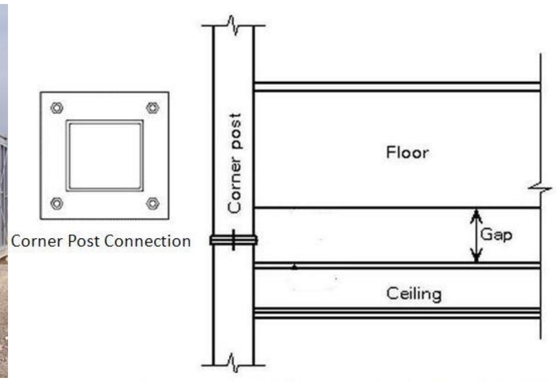


Figure 7. An example for connection of two stacked 3D models (SteelConstruction.info website)

sheathings resist the lateral loads. Steel Hollow Sections (SHS) are the most common profile types for use as the corner column sections. One example of a corner supported module is shown in Figure 6 (Lawson et al., 2005b). A critical performance aspect in such system would be the lateral load response of the building made up of stacked modules. Depending on the relative stiffness of the floor and ceiling beam and their connections to the corner posts, the behavior of the post at post-to-post connection can be different. In any case, such behavior will also be dependent on the type of entire building lateral load resisting system. In Figure 7, an example of connections between two stacked corner-supported 3D modules is illustrated.

The Open Building System

The Open Building system is developed to enhance the flexibility of space planning and may consist of various combinations of framing and module systems as appropriate. In one type of such systems, two integrated framing systems transfer both gravity and lateral loads to the foundation. The interior structure of the module is one of these frames. The second frame is the exterior frame, which consist of columns on exterior edge of the structure (or some in the middle rows) at a constant spacing. The procedure of the construction of the Openhouse system (one type of the Open Building system) has three main steps. First, the job-site fabricated columns are erected. In the second stage, the modules are installed between the columns of the first stage; as depicted in Figure 8, the columns are positioned in the hollow spaces within the modules. In the last stage, by installation of a uniform roof system, all of the module elements and the columns of the first stage will be integrated together for the lateral movements. In Figure 8, two photos from different stages of construction are shown (Bengt Birgersson, 2004).

Figure 8. Two photos from two different stages of construction of an Openhouse building (Bengt Birgersson, 2004)

As in conventional building structures, roof and floors behave as diaphragms of the structure at each floor level, and these diaphragms integrate interior and exterior frames for gravity and lateral loads resistance.

When a multi-bay structure is loaded in the lateral direction, the columns or walls in adjacent bays tend to slip with respect to one another if not tied together properly. In conventional building construction, the connections of horizontal and vertical elements are designed for combination of gravity and lateral loads. Therefore, the continuity of load path between horizontal and vertical elements exists and the integrity of the system is provided. However, due to discontinuity between modules in modular building construction, the modules must be connected to one another in the vertical direction to resist vertical shear forces (caused by lateral loads) between modules. In Open Building systems, the columns that are installed at the first step should be structurally connected in the vertical plane to the adjacent modules. Figure 9 shows the difference in deflection modes between the two systems when the adjacent vertical load carrying systems are not tied to one another and when they are tied. In the figure on the left, there is no vertical deformation coupling between adjacent components, while the figure on the right shows the vertical shear transfer between such components.

Hybrid Cored-Modular Systems (Cluster)

As the height of a structure increases, the magnitude of the total lateral and gravity loads increase and therefore, the size of load-bearing elements in lower modules will have to be larger beyond what is needed just for gravity loads. In cluster systems the size of these elements are limited by considering a core for the structure.

Generally, due to erection and installation issues, prefabricated modules should be kept light (e.g., by using light gage steel) and as a result they have lower lateral stiffness in comparison with regular (e.g., rolled steel) framings. However, conventional concrete shear walls and frames, braced steel frame, and steel moment frames have higher lateral stiffness in comparison with prefabricated modules. By installation of one or more of these stiff systems between modules as the core, lateral deformations of the whole structure can be reduced. Under lateral loads, the diaphragms at the floor levels will transfer most of the lateral loads to the stiffer (core) parts of the structure. Therefore, the connection between the core structure and the modules should be strong enough to transfer tension-compression and vertical loads between these two structures. As depicted in Figure 10, the stacked modules rely on a braced steel frame to resist lateral deformations. In Figure 11, the

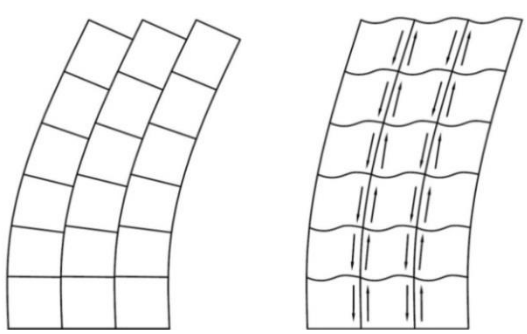
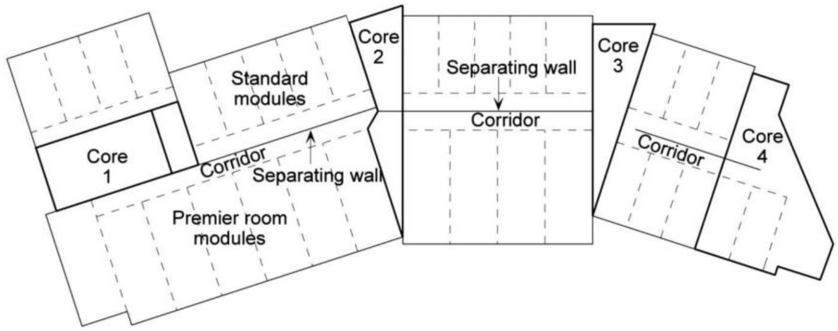


Figure 9.Vertical Shear transfer between stacked units: (left side) No vertical shear transfer; (right side) Coupled at vertical joints

Figure 10.Stacked modules, supported by steel frame (Lawson et al., 2005)

Figure 11.Arrangement of cores in the plan of a 12-story building (Lawson et al., 2010)



plan of an 11-story modular building is depicted. This is a student residential building In Bristol. As shown in this Figure, there are 4 steel braced cores in the plan that resists lateral loads applied on the structure (Lawson et al., 2012).

Hybrid Podium-Modular Systems

One of the limitations of modular buildings is short bay spans for lower stories normally desired for retail or parking spoce. The hybrid podium-modular system is normally used in structures that need longer bay spans in lower stories. In podium-modular systems, some of the bottom stories (usually two stories) are built using conventional structural steel or concrete frames with long spans. Then, the modular part of the building would be installed on top of the podium. In other words, the podium is like a foundation for the modular parts. The modules transfer their uniform load to the beams of the podium. In addition, a podium structure with long spans behaves as a soft story for the structure leading toan increase of the period of the structure, which results in a decrease of design earthquake forces.

A schematic drawing of a 2-story podium system is shown in Figure 12 (Lawson et al., 2010). As shown in this figure, the edges of the modules are aligned to the center of the podium beams to omit eccentricity of the loading on podium beams and columns. In conventional structural models, one usually assumes that all elements at a given floor level are located in a single plane, which is the diaphragm level. But, as depicted in Figure 7, in some types of modular buildings such as 3D systems, the bottom of the upper modules do not lie in the same plane as the top of the lower modules; they are just linked together at some points. In other words, there is an elevation difference between the ceiling of a story and floor of the next story; and this should be addressed in the model. This difference is more distinguished when the designer wants to model the interface of the podium and the modules. Therefore, the designer must consider two

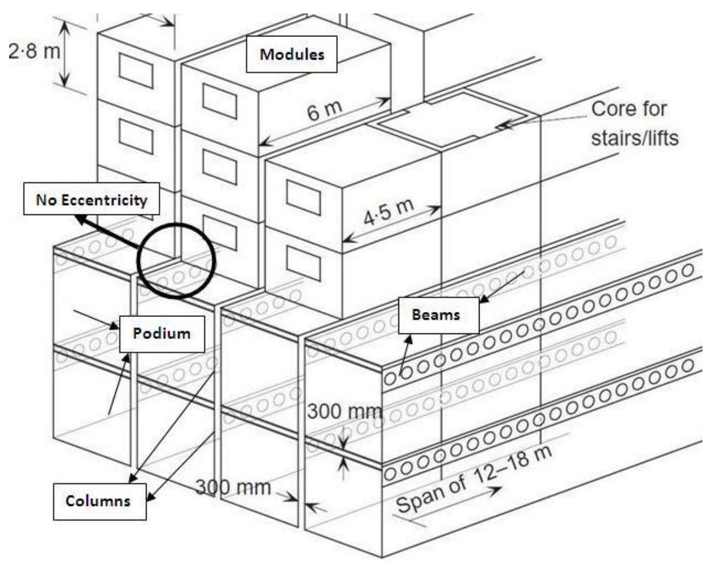


Figure 12.A 2-Story podium beneath a multi-story modular building (Lawson et al., 2010)

different closely spaced planes for floor and ceiling to link upper and lower joints of these elements at sufficient number of points to ensure continuity and integrity of these separate modules. An example of the finite element model to represent the diaphragm in such systems is depicted in Figure 13.

Framed Unit Systems

In this system, the main structure of the building is not constructed as modular. As depicted in Figure 14, the main structure of this type of construction is a conventional structural frame. After erection of the main structural frame, prefabricated units will be placed and fitted between beams and columns of the structural frame. Figure 14 shows the Contemporary Resort Hotel of Disneyland, built in 1971 (Walt Disney Drawing Board website). The main structural frame is a braced steel frame. The modular units of this structure are made of wood and cannot therefore bear large deformations as much as steel frames do. This is one reason for the use of braced frame, which increase the stiffness of the structure and control the the deformation of the frame under lateral loads.

One of the most important benefits of this system is that the properties of module elements are not dependent on the plan shape, number of stories, and wind and earthquake loads, and due to the fact that the main structural frame bears the loads, all of the units can be identical. In addition, the elements of the modules are designed just to carry their own gravity loads and construction loads; therefore, the weight of the modules is lower than the weight of the other types of the 3D modules. In spite of the fact that the main structural frame carries the lateral loads, the connection between the modules and the frame should be strong enough to be able to transfer the gravity loads and the earthquake loads, which result from the acceleration of the mass of the modules. In modeling such a system, a suitable diaphragm should also be considered in order to properly model the integration of the modules and structural frame. In addition, to avoid unbalanced loading of the structural frame during construction, a detailed and exact construction procedure should be presented by the design groups to avoid failure of the structure at the time of the modules installation.

ISSUES COMMON TO MOST TYPES OF MULTI-STORY MODULAR SYSTEMS

In addition to specific challenging issues related to each structural system of multi-story modular buildings, there are some common issues that should also be addressed in all

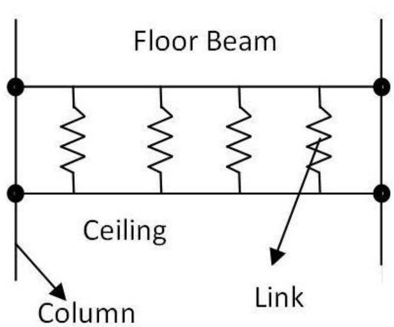


Figure 13. An example of floor finite element model for module

Figure 14.Contemporary Resort Hotel in Disney land (1971)

different types of these modular structures. In code-based design of structures to resist earthquake loads, one needs to determine the response modification factor (R) value. As for any new structural system type, it is a challenge to determine a reasonable R factor value, and as a result, without extensive analytical studies or experimental testing, specific value for R factor cannot be obtained. Further challenging in the determination of R value is the fact that due to the difference in lateral resisting systems, R factor would have different values for different types of modular buildings.In nonlinear design of conventional construction, plastic hinges that form in members near the connections help dissipate the seismic energy. In modular construction however such plastic hinging in members is not expected to occur because of the existence of various flexible joints in the system. Therefore, the designer should think of alternative approaches to develop appropriate systems or components that will dissipate energy.

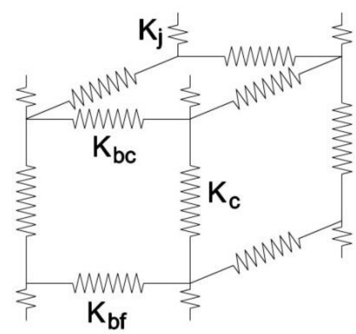


Figure 15. A 3D Finite model for a 3D module

Detailed finite element modeling of entire modular buildings is complicated because of the variety of joint and support types with unknown load-deformation properties. For practical application of finite element modeling of modular systems some simplifying modeling assumptions are necessary. For example, a two-tier modeling approach will be one option where for tier one, each module can be simplified and assumed as a 3D sub-frame as shown in Figure 15 to represent the modules shown in Figure 6 and 7. K_c, K_{bf}, K_{bc}, and K_j represent, respectively, the stiffness of vertical members, floor level horizontal elements, floor level horizontal elements, and joints. Once the entire building is modeled using 3D sub-frames, the structure can be subjected to applicable loads and analyzed. The forces the sub-frame experiences can then be used for a more detailed second tier modeling. Using the forces resulting from the analysis of the entire building model (first tier modeling) and applying them in a second tier more detailed finite element model of each module, we can then design internal elements of the modules such as beam, columns, ceiling beam, floor beam, bracing or shear walls, etc.

Safety and robustness of the structures are important factors that designers must take into account in the design of the structures (Lawson et al, 2008). There may be many situations that could bring about the failure of some modules. Some of these situations are faults in the factory where modules are assembled, damages during erection or transportation, failure due to fire or explosion, terrorist attack, and plain collision. Therefore, elements and connections must have enough redundancy to prevent repetitive failure or progressive collapse of the structure, when some of the modules fail. Accordingly, the modules must have a reliable integrity and the continuity needed to be able to bear the loads transferred from failed modules. Furthermore, contractors cannot prevent all of the installation problems and eccentricities during the sequence of module installation, and therefore, the designer must consider installation problems and provide allowance in their design calculations and drawings. Some internal forces must be added to the module elements or alternatively the factors of safety increased.

SUMMARY AND CONCLUSION

As for any relatively new system, unknown structural behavior and lack of sufficient specific design and construction guidelines and code requirements are two main reasons that designers or contractors may not be inclined toward selecting modular construction building. In order to make multi-story modular building more popular and reliable system, challenging issues for the structural aspects have to be carefully addressed.

In developing computer modeling, the following issues should be considered: load definition, modeling of modules overlap, element definition, and identifying loads during construction. Furthermore, there are some important challenges in structural design of the building, including the following: Individual module horizontal diaphragms, whole building floor diaphragm, continuity in vertical plane, and connection of units. The importance degree of the above mentioned challenges can vary based on job site condition and natural disasters in the region to be considered in design; for example in places that are not exposed to storm and earthquake load, the importance factor of some elements such as diaphragms and vertical connections reduces. Finally, it should be mentioned that studying existing modular building systems, evaluation of their performance, and discussing pros and cons of each system can effectively be helpful to address the above mentioned challenges.

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Chicago Flat Type Planning: Sustainability and the 1902 Tenement House Ordinance

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ABSTRACT

This paper examines the planning flexibility and the passive ventilation and day-lighting potential of the various multi-unit apartment types developed in response to the 1902 Tenement House Ordinance in Chicago. Instead of thinking about the future of sustainable multi-family housing design as built upon current planning strategies, this paper examines a historic planning precedent that may be more applicable, or appropriate, based upon the criteria of the new sustainability paradigm. Beyond explaining the history and requirements of the Ordinance, this paper illustrates how basic planning strategies adapted from the Chicago two-flat apartment building could be combined and repeated to form ever larger, taller and complex apartment buildings. Today, many "sustainable" multi-unit apartment buildings are planned in a manner that requires constant mechanical ventilation and artificial lighting even during daylight hours. This is done without asking whether a building that requires energy to be habitable should even be considered sustainable. Air-conditioning for housing was not technically or economically feasible until after 1930 so these Chicago flat type apartment buildings relied upon passive planning strategies to ventilate and light each unit. In an era of increasingly expensive energy, the advantages of planning every unit to accommodate the passive ventilation and lighting strategies inherent in these pre-air conditioned designs becomes apparent. Historical resources and field documentation were utilized to explain and illustrate the Chicago flat type planning strategy. The paper concludes that the sustainability paradigm shift is an opportunity to rethink the planning models upon which we base our multi-unit apartment building designs.

INTRODUCTION

I like Chicago courtyard apartment buildings. I like that these buildings are based on a simple planning strategy that can be manipulated to respond to a variety of building sites of different size and configuration (Figure 1). I first became aware of this multi-family apartment building type in the fall of 1984 while on an academic internship at SOM in Chicago. In 1990, as a graduate student, I prepared a research project on Chicago courtyard apartment buildings and I came across a period article published in Architectural Record in 1907 that described the Chicago courtyard type. "It will be noticed that … these lower buildings are arranged around courts so liberal in size that even the rooms on the bottom of the court obtain an abundance of light and air. It is of course, these courts which give the buildings their character …" [Croly 1907] The author clearly understood that the apartment buildings he had seen in Chicago were unique compared with those he was familiar with in New York City.

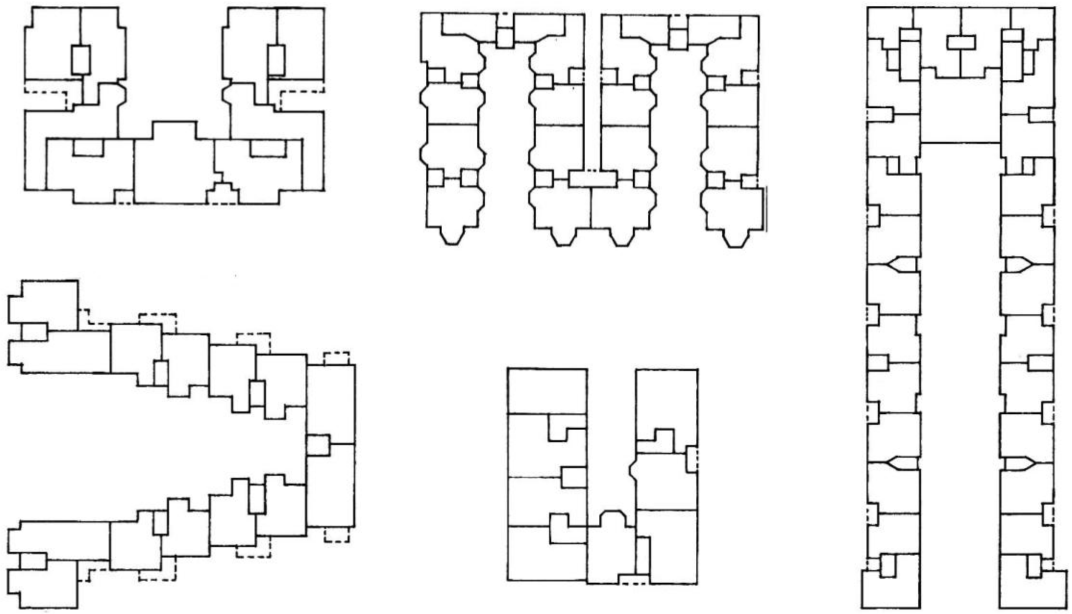


Figure 1. Various Chicago courtyard building plans drawn from Sanborn maps

With this article, I had the first confirmation that the buildings I had seen in Chicago years before were unique. After years of studying courtyard buildings, I started to analyze these buildings in order to see if there were some sort of underlying planning principles that could be diagrammed and explained. Eventually, I came across references to the 1902 Chicago Tenement House Ordinance. After reading the Ordinance, I realized that courtyards, and the other multi-unit apartment buildings developed and utilized during this period in Chicago, were all based upon the planning principles outlined in that document.

PROGRESSIVE ERA SUSTAINABILITY

How would you plan an apartment building if air-conditioning and electric lights were extremely expensive, not an option, or if access to electricity could not be consistently relied upon? As we plan housing that is to be considered sustainable, I think these are some of the most significant questions a designer might ask. I should add that I don't think it is necessary to build buildings without air-conditioning but if we want to give the end user the choice to utilize passive ventilation when the weather permits then we need to plan buildings in a way that maximizes passive ventilation potential. If we agree that this is a valid goal, then the next question we should ask ourselves is what are the multi-unit apartment building precedents we should draw from?

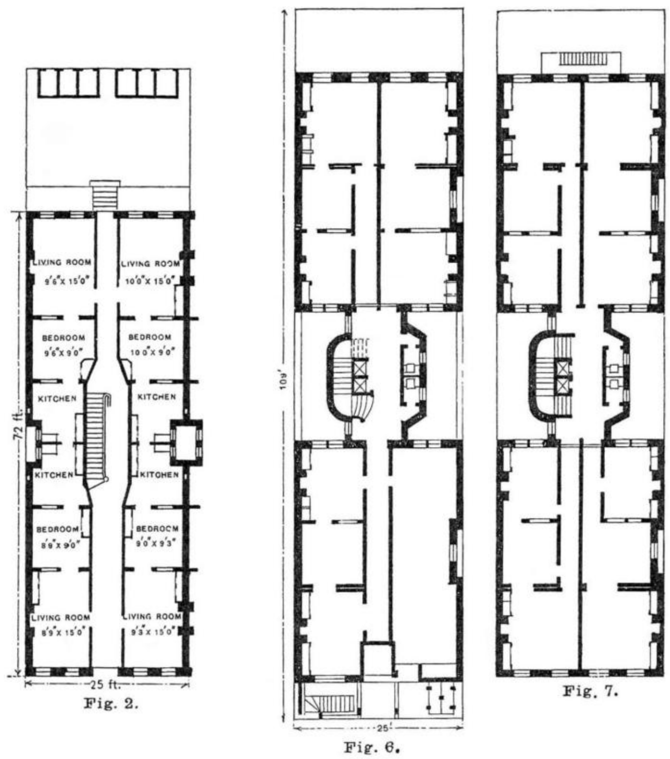
Should we look to apartments that were planned in a period of inexpensive energy utilizing planning and design strategies that could ignore the environment and weather since (with enough energy and technology) any conditions, no matter how extreme, could be overcome? Should we look to historic precedents developed by ancient civilizations that lacked many of the modern amenities that we expect today? Or rather, should we look back, just far enough, to a time when most buildings included all of the amenities that we are accustomed to and expect today but were planned without air-conditioning because the technology did not yet exist for residential applications? This was a period when codes did not just delineate minimum requirements but prescribed planning and design principles that could be relied upon, when competently implemented, to generate decent passively day-lit and ventilated spaces. I believe the 1902 Chicago Tenement House Ordinance, which was derived from the 1901 New York State Tenement House Act, is one such document. Even though the Ordinance was developed more than one hundred years ago, it might be the most advanced guideline for planning sustainable multi-unit apartment buildings today.

TENEMENT PLANNING PRINCIPALS – NEW YORK CITY VS. CHICAGO

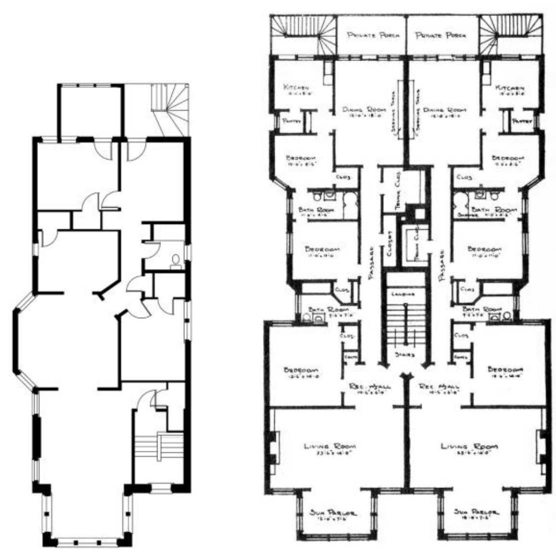
There are many historical, political, social, cultural, contextual and economic reasons why tenements developed differently in New York City than in Chicago and this paper could not even begin to address all of them. However, there are a few obvious planning strategies that are the basis of the differences between the New York City and Chicago tenement types. First, there is a preference in Chicago to organize multi-unit apartment buildings around pairs of vertical stair halls. This circulation scheme distinguishes Chicago tenements from the preference for central corridor type tenements in New York City (Figure 2). Richard Plunz in his book *A History of Housing in New York City* does an excellent job of describing how the pre-law, old-law, and new-law tenements types had evolved from the row house type that had been common in lower Manhattan since colonial times. [Plunz] Second, physical context was a factor since Chicago did not have the same physical limitations that existed on the island of Manhattan and the population of Manhattan was more than double that of Chicago in 1901.

Third, Chicago has alleys. Because Chicago's street grid was laid out to include alleys, all types, and scales, of housing in Chicago could have front and rear entries. Manhattan had a block configuration that turned out to be too shallow for alleys so that is why trash must be collected from the street. Alleys allow even the most modest residential unit planned with the flat type strategy to have a formal and informal entry sequence. This was important historically because, for example, these buildings were built before refrigeration was common and so block ice could be delivered, at any time, from the rear stair landing even while the home owner, or apartment dweller, was away. The rear entry also allowed the owner, or tenant, to take the trash from the units, and ash from the coal fired boiler, out to the alley without having to go through the front entry.

And finally, Chicago, unlike New York City at that time, did not have a significant number of substantial tenement houses or extensive previous tenement house regulation. Unlike The 1901 Tenement Act in New York City which rendered many earlier New York City tenements non-conforming and no longer habitable. The 1902 Chicago Tenement Ordinance became the guide for how new multi-unit housing



NEW YORK CITY TENEMENTS WITH CENTRAL COORIDOR SCHEME



CHICAGO TENEMENTS WITH VERTICAL STAIR HALL SCHEME

Figure 2. New York City and Chicago Type tenements

types could, and should, be designed to meet the latest standards of health and hygiene for multi-unit apartment buildings.

CHICAGO 1871 TO 1902 - FROM THE CONFLAGRATION TO THE TENEMENT HOUSE ORDINANCE

When we think about multi-unit housing precedents in Chicago it is important to remember that the densest portion of Chicago had been completely destroyed by fire in 1871 and the wooden buildings that had been used to quickly rebuild after the fire were rendered redundant as the Central Fire District was implemented and expanded in the years after the fire. [Adams 1903, Hall 1920] There seems to be few significant advances in multi-family housing design in Chicago during the period of 1871 to 1902. However, there were a few important precedents that were built during this period that helped to define the Chicago flat planning approach.

The earliest significant example was the Mecca Flats building which opened in 1891 in time for the World's Columbian Exhibition (Figure 3). The Francis Apartments and the Francisco Terrace apartment building (Figure 3), both from 1895 and designed by Frank Lloyd Wright, are two other important local precedents. All of these local precedents featured courts but only the Francis Apartments also featured vertical stair hall planning similar to later buildings. While the 1902 Chicago Tenement House Ordinance could have been used to produce central corridor type buildings, like those used in New York City, local precedents established the preference for buildings that utilized the vertical stair hall planning strategy.

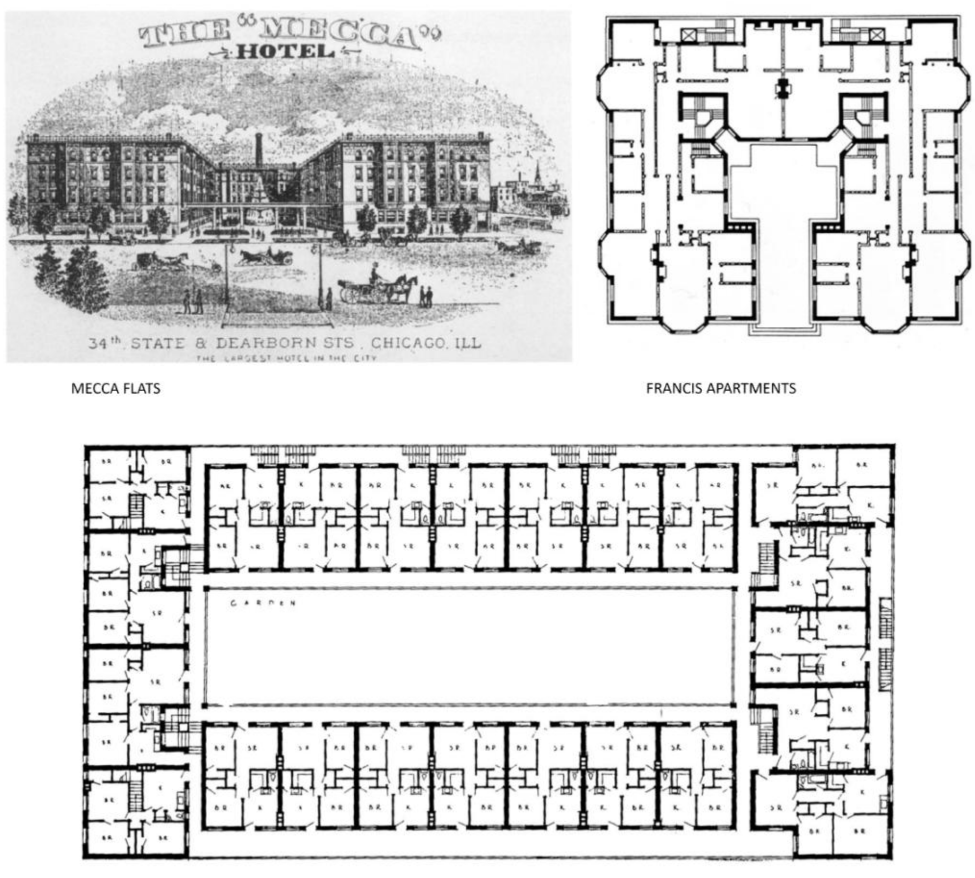


Figure 3. Meccas Flats, Francis Apartments & Francisco Terrace

SIGNIFICANT PLANNING AND CONSTRUCTION REQUIREMENTS FROM THE CHICAGO 1902 TENEMENT HOUSE ORDINANCE

Construction: All multi-family buildings built within the central fire district had to have a perimeter wall of fire-proof construction, usually masonry. Perimeter walls built to the lot line could not have openings but the Ordinance outlined the required setbacks for perimeter walls with openings (doors & windows) (Figure 4). Buildings that were built to a limit of three stories over a high basement could utilize dimensional lumber for framing within the perimeter of the fire-proof walls. Buildings that were 4 to 5 stories over a high basement had to utilize heavy timber framing within the perimeter of the fire-proof walls, as a minimum. Buildings over 6 stories had to utilize fire-proof framing construction within the perimeter of the fire-proof walls. [Adams 1903]

Sec. 21. **Courts—Inner—Sizes of—Lot Line Courts.**—The "inner courts" of all new tenement houses defined in Section 1, Paragraph 4, shall have areas and minimum widths in all parts not less than the widths and areas as follows:

Building.	Square Feet.	Least Width.
2 stories	100	6 ft.
3 stories	120	7 ft.
4 stories	160	8 ft.
5 stories	250	12 ft.
6 stories	400	16 ft.
7 stories	625	20 ft.
8 stories	840	24 ft.

"Lot line courts" shall have areas and minimum widths in all parts not less than one-half of those specified in the above table of "inner courts."

Sec. 22. **Courts—Outer—Sizes of—Width Increased.**—The "outer courts" of all tenement houses defined in Section 1, Paragraph 4, shall have not less than the following widths for their minimum in all parts:

Building.	Least Width.
2 stories	3 ft.
3 stories	3 ft. 6 in.
4 stories	4 ft.
5 stories	6 ft.
6 stories	8 ft.
7 stories	10 ft.
8 stories	12 ft.

If the "outer court" has windows on each side of the same, the least width given in the above table for "outer courts" shall be doubled for the minimum widths, and where the depth of a court shall exceed three (3) rooms the court shall be made at least one (1) foot wider for each additional room over two (2) rooms from outer or lot line end of court.

Figure 4. Court sizes from the Chicago Tenement House Ordinance

Passive Ventilation and Day-Lighting: All Occupied rooms were required to have a window opening directly to a street, yard or court. Occupied rooms included living rooms, dining room, sleeping rooms and kitchens. According to the 1902 Ordinance toilets and pantries were required to have a window opening directly to a street, yard or court but were also allowed to have a window that opened to a ventilation shaft. [Adams 1903] Later revisions of the Chicago Tenement House Ordinance eliminated the use of ventilation shafts so toilets and pantries were required to have operable windows that opened to a street, yard or court only. [Hall 1920]

Stair Halls: Chicago flat type apartment units are planned around a pair of vertical stair halls. The front main stair hall was enclosed and had to have windows or a skylight that allowed for passive ventilation and day-lighting. The rear service stair could be open, but covered, and constructed of wood as long as it was built outside of the buildings perimeter fire-proof walls (Figure 5). [Adams 1903]

Figure 5. Secondary open stair: two flat and reverse corner lot building

Sectional Planning: All of these buildings share a common sectional scheme. The Ordinance made a distinction between a cellar (more in the ground than out) and a basement (more out of the ground than in). According to the Ordinance a basement could have occupied space while a cellar was suitable for storage only. [Adams 1903] When we look at a section we realize that there are two primary advantages to elevating the first floor units over a high basement in an urban context. First, the first floor unit is raised over the sidewalk slightly so the occupant has a higher, and more private, vantage point than someone on the sidewalk (Figure 6). And second, a switchback stair (the most common type of stair configuration used in these buildings) will have a landing at the level of the unit on the side away from the street allowing for a very efficient vertical stair hall in plan and section (Figure 6).

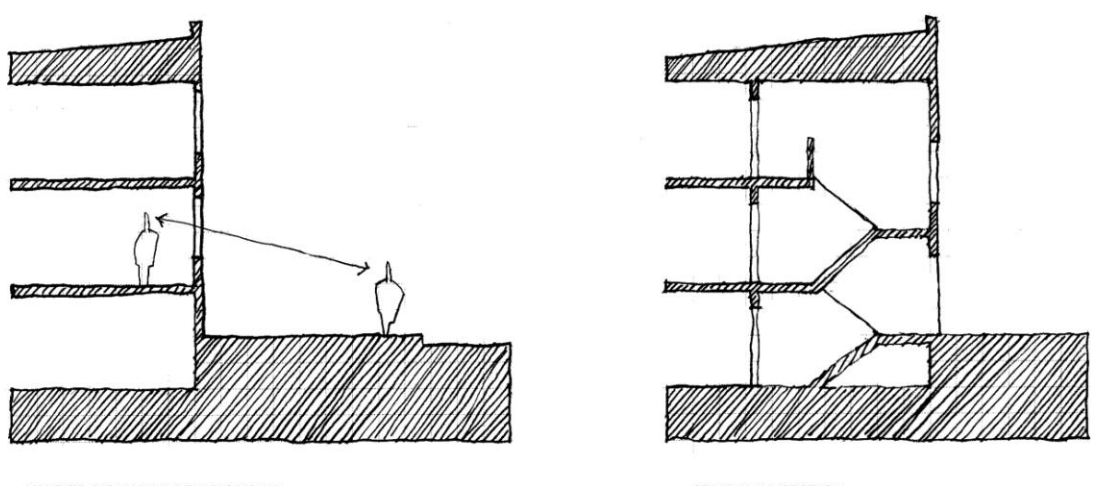
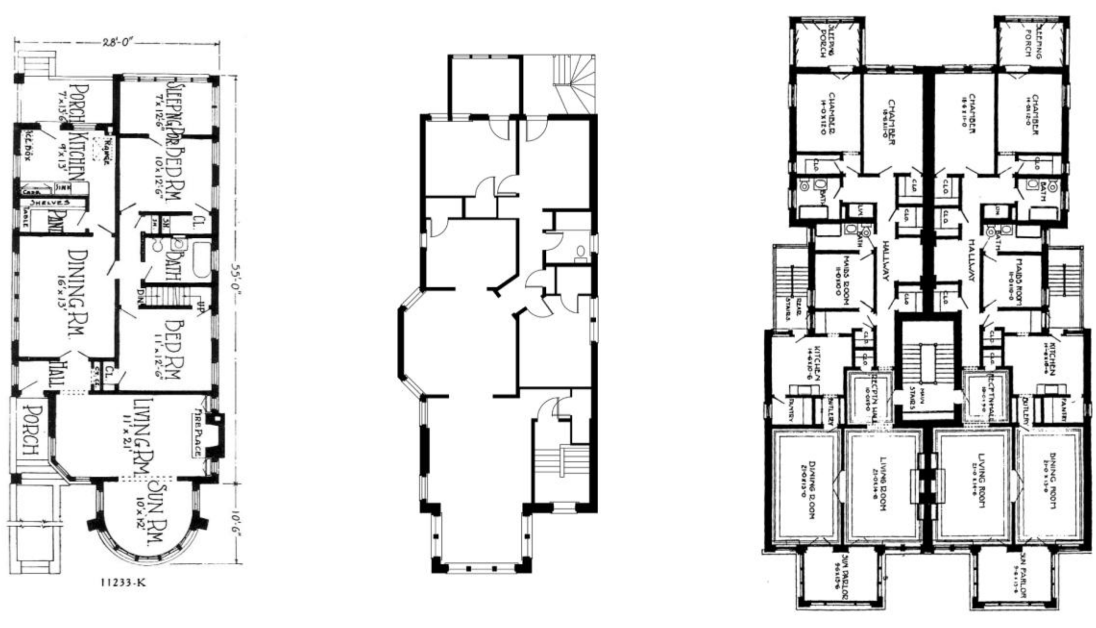


Figure 6. Unit to sidewalk section and stair hall section

FLAT TYPE PLANNING FROM THE BUNGALOW TO THE MID-RISE ELEVATOR BUILDING

I have described how I first became interested in Chicago courtyard apartment buildings and the influences and differences between New York City and Chicago tenement design and regulation. Now I will show how the Chicago flat type planning strategy was applied to a single family bungalow (on a 25’ x 125’ lot) all the way up to a 10 or 20 story mid-rise elevator building. The various types of residential buildings that utilize flat type planning include: bungalows (single unit), two flats (two units), three flats (three units), four flats (four units), six flats (six units), reverse corner lot buildings (usually nine or more units), half court buildings (usually twelve or more units), courtyard buildings (usually eighteen or more units) and mid-rise elevator buildings (usually two or more larger units per floor).

The Single Stack Types: Bungalows, two flats and three flats are all essentially related in that they all have a typical floor plan that is repeated, along with a pair of vertical stair halls, as many times as necessary in order to get the number of units that is required (Figure 7). In 1902, 25’ x 125’ lots were common in Chicago so many of the oldest examples of these buildings were built on 25’ wide lots. In general, a building of this type built on a 25’ wide lot could only have a useable interior width of about 17’ when you set the windows back the required 3’ from the lot line and allowed for the width of the exterior walls. Even when a room could be extended to the lot line the widest useable inside dimension was only 20’ wide which, when you have two rooms across the width, did not generate generous room sizes. The advantages of a 30’ lot for this building type quickly became obvious and by the 1920’s 30’ wide lots were common. By the late 1920’s on the far north side, there were even some “jumbo” flats that were designed for 33’ and 40’ wide lots.



BUNGALOW | TWO & THREE FLAT | SIX FLAT

Figure 7. Bungalow, two, three, and six flat types

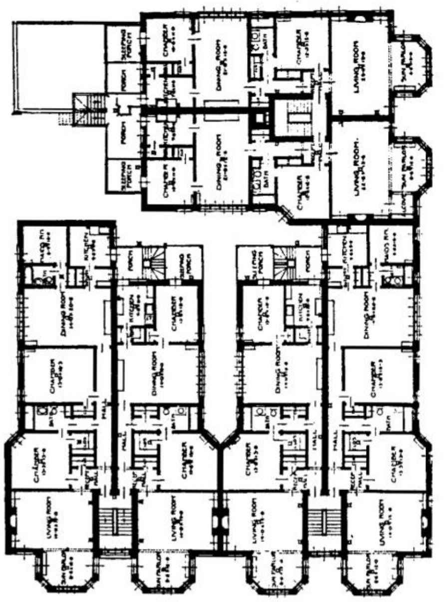
The Mirrored Stack Types: A two flat that is mirrored about the stair halls becomes a four flat and a three flat that is mirrored about the stair halls becomes a six flat (Figure 7). Because these buildings share a common internal wall the lot width was less of an issue since this configuration limited each unit to a plan that was only one room deep at the middle. While examples of four flats exist, they were not common.

Reverse Corner Lot Types: The 1902 Ordinance allowed a higher density on corner lots because the corner location could provide more direct access to light and ventilation than a mid-block site. Reverse corner lots did not require a set back from the sidewalk on the primary or secondary street frontages. This significantly increased the allowable square footage of a corner lot. Reverse corner lot buildings are generally configured in two ways. First, a reverse corner lot building may be configured by combining a series of two, three or six flats that are configured to face the primary and secondary street frontages (Figure 8). This type of building tended to be located on wider corner lots. Second, there was a bar type configuration that was used for two and three story buildings that tended to be located on narrow corner lots.

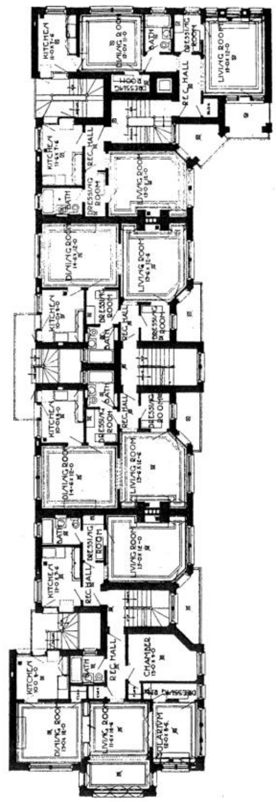
Half Court Type: Half court buildings are a mid-block type since reverse corner lot types generate a higher density on a corner lot than a half court building could and the court would serve no purpose since a corner lot already has ample access to day-lighting. Half court buildings take advantage of lot line walls at the front and rear of the lot (Figure 8). The half court type is planned around two side courts as defined in the Ordinance. [Adams 1903] The front side court will often be wider than the minimum dimension allowed by the Ordinance and it will be open to the street at the front. The front court forms the primary public (formal) access for all of the units through the front court and the front stair halls. The rear stairs are accessed from the rear side court, which was usually built to the minimum width allowed by the Ordinance and was open to the alley at the rear.

Courtyard Building Types: There are many possible configurations for the courtyard type but they all share the same conceptual planning principles. If you take a regular street of six flats and push some back to form a court you have the general idea of how a courtyard building is configured (Figure 8). While this doesn't sound like much of a strategy this approach can produce buildings that can be laid out to accommodate a wide variety of lot sizes and configurations. I have found examples of Chicago courtyard buildings on just about every type of site that one can imagine including: mid-block sites, corner lots, deep lots, shallow lots, lots on residential or commercial streets, irregular lots, and finally courtyard buildings that have been adapted to unique contexts (Figure 1).

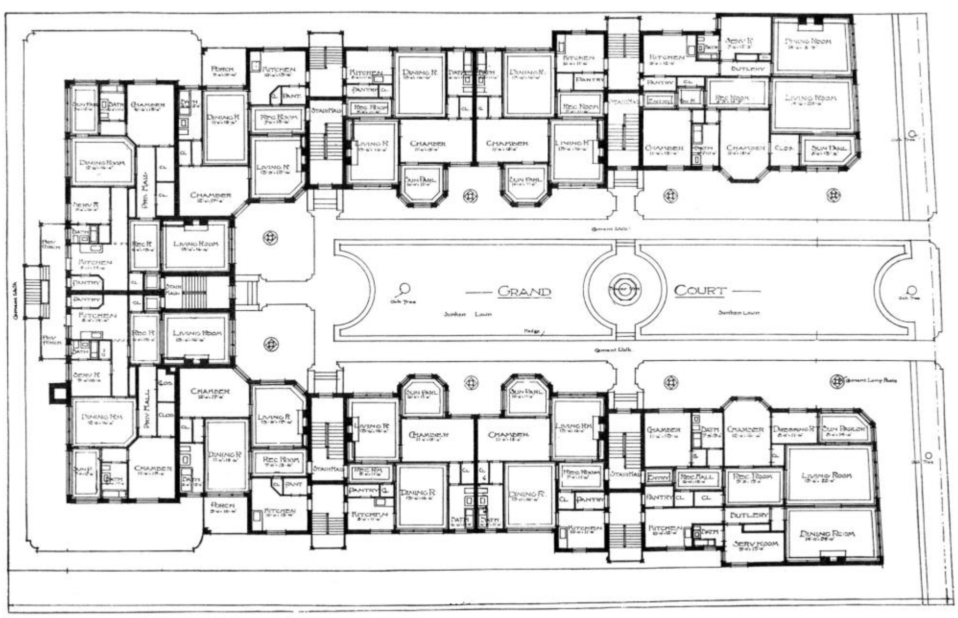
Mid-Rise Elevator Building Types: Mid-rise elevator buildings of 10 to 20 stories tend to have larger units with multiple bedrooms but the same planning principles from the low-rise buildings are still utilized. While the units in these buildings tend to be larger and more luxurious the same planning strategy could be used for a building featuring smaller unit sizes. Some mid-rise buildings have just one unit per floor like a two or three flat and some have two units per floor like a six flat. However, there are buildings with larger footprints that have multiple elevator and stair halls (Figure 9). The Chicago flat planning strategy has even been used on a mid-rise elevator building that features duplex units with double height living rooms (Figure 10).



REVERSE CORNER LOT TYPE

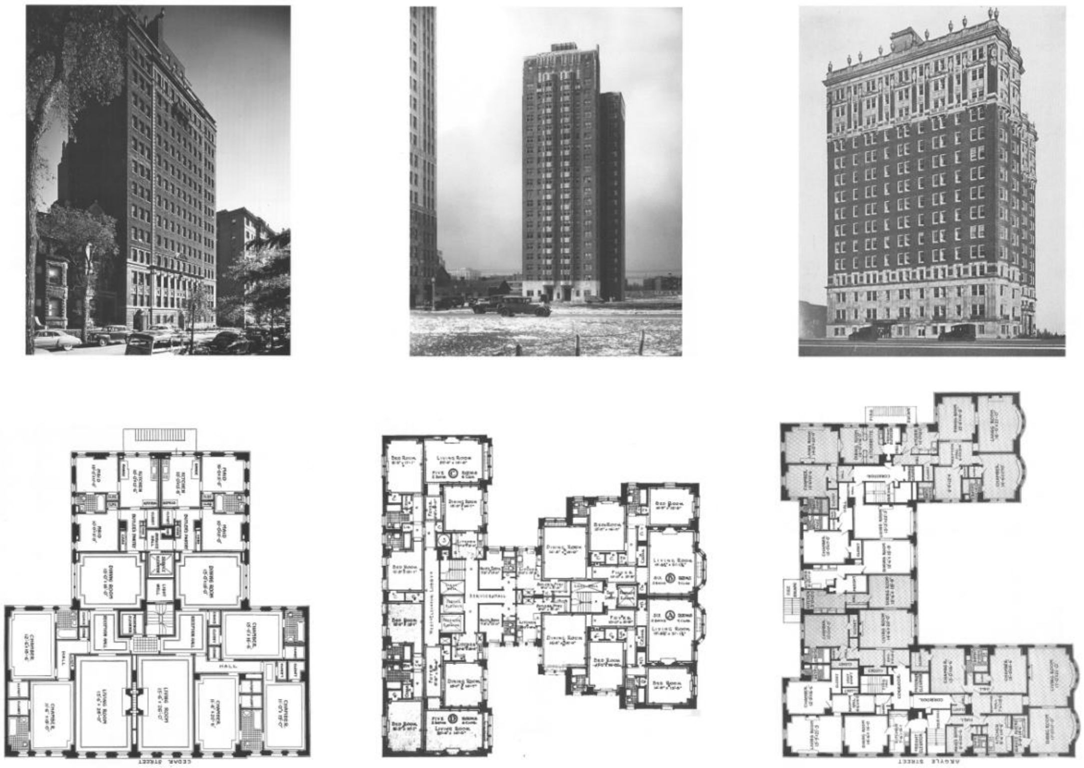


HALF COURT TYPE



COURTYARD TYPE

Figure 8. Reverse corner lot, half court and courtyard types



SIDE / REAR COURT SIDE / FRONT COURT FRONT COURT

Figure 9. Mid-rise elevator flat type apartment buildings

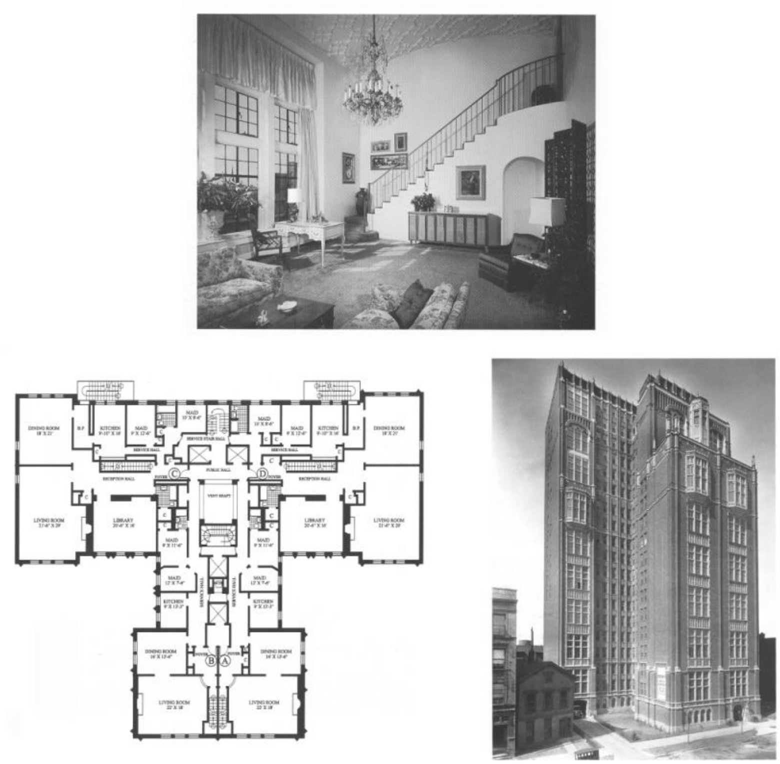


Figure 10. Mid-rise elevator building with duplex (two story) units

CONCLUSION

The period from 1871 (Chicago fire) until 1902 (Chicago's first Tenement House Ordinance) was characterized by the minimally regulated and ultimately temporary rebuilding after the fire but this period did produce a few important local multi-unit housing planning precedents. The period from 1902 until 1929 (stock market crash) was perhaps the most significant period for multi-unit housing development in Chicago's history. In many regards, the apartment buildings built during this period still define the character of many of Chicago's neighborhoods. This was a unique period because home owners and apartment dwellers demanded state of the art housing amenities (the same amenities we still demand today) and the planning and design principles embedded in the 1902 Ordinance guaranteed that every room, in every unit, had access to natural ventilation and day-lighting. In 1902 mechanical ventilation was uncommon and air-conditioning did not exist on a practical scale for residential buildings so these buildings form a type of reference point for the height of passive ventilation and day-lighting design in America. When you think about the design and planning precedents that you might utilize for your sustainable housing projects you should consider utilizing the Chicago flat planning approach.

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Responsive Housing: Potential & Projected Impact

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ABSTRACT:

Currently, the made-to-last building techniques of American housing are incongruent with personal, family, energy, and technology evolution. Why aren't buildings designed to be flexible enough to respond to the fluctuating cadence of human inhabitance? This paper proposes a new design concept: responsive housing.

Responsive housing is a theoretical building system that can be continuously adjusted at the will of the home's occupants to provide the best living conditions possible. By componentizing the major elements of a home a responsive house can be built in stages, disassembled in stages, reconfigured internally and externally, and completely relocated to a different building site. Akin to providing homeowners with a set of life-sized building blocks, this system makes each home easily customizable. Ongoing occupant-executed customization has the potential to revolutionize the current state of residential building. This paper explains how responsive housing would work and the impact it would have socially, economically, and environmentally.

INTRODUCTION:

Structures are a fundamental part of our society; however, the connotation of rigidity that is associated with buildings evolved throughout history. Although shelters were originally ephemeral - moving and changing as our nomadic ancestors needed – longer lasting dwellings were constructed when societies settled and established communities (Friedman 2002; Kronenburg 2007). The buildings that created the legacy for our current inhabitation practices were the rigid, semi-permanent structures of the past starting with government buildings, banks, and religious facilities (Kronenburg 2007). The legacy excludes the flexible, transitory structures that were present at the same time in history. Eventually more and more landlords mimicked the characteristics of prominent buildings leading to the various regional typologies of today (Brand 1994; Kronenburg 2007). Brick and stone were chosen over timber and animal hides; mortar and nails were used instead of pegs and lashings – buildings became more indestructible, but also more static (Brand 1994; Kronenburg 2007). Unfortunately the easy-to-change nature of ephemeral dwellings gave way when permanent structures were required.

Buildings are not required to be and should not be static in order to be lasting (Brand 1994; Friedman 2002; Leupen 2006; Kronenburg 2007). This paper presents an overview of the potential for buildings to be less static, to become the opposite in fact – responsive.

WHAT ARE RESPONSIVE BUILDINGS?

The Merriam-Webster Dictionary (2012) defines the term "responsive" as *quick to respond or react appropriately*. *Response* implies that an initial action or change occurred. Therefore, responsive buildings are those that appropriately react to change.

What constitutes change?

Change as it relates to human nature and inhabitance is expansive. Change, something that is so integrated into our lives that it is often not noticed, is constant, unpredictable and can take many forms. As our buildings are an extension of us, they are subject to every change that we are; in fact, because buildings often serve more than one person, it is very likely that the climate of change surrounding a building is much more volatile than what the average individual experiences throughout their life. We may think that most of our buildings adequately suit our needs. We may believe that the vast amounts of time and money spent on planning and constructing a new building result in a product that will continue to repay us for generations. And of course we hope that our buildings will stand up to the volatility of Mother Nature. Most likely, we are wrong (Brand 1994).

Buildings are subject to two main types of change – internal and external (Brand 1994, Friedman 2002, Kronenburg 2007). Internal changes focus on the occupants of the building and may include anything from the daily turnover or accumulation of things spurred by changing occupant tastes, opinions and cash flow to the slow fluctuation of family composition as couples unite, children grow and the abilities of seniors diminish. Occupant turnover begins this cycle of change all over again. External changes may involve the immediate environment around a building such as the streetscape or the building site (Kronenburg 2007) or larger external forces such as demographics, cultural attitudes, economic climate, and/or environmental resource availability (Brand 1994, Friedman 2002, Kronenburg 2007, 2008, Leupen 2006).

How can buildings change?

When used as an adjective for buildings, the term responsive could take on several meanings. Past authors have focused on both physical and functional responses and have utilized various synonyms of *responsive* including *learning* (Brand 1994), *changing* (Duffy 1998), *adaptable* (Friedman 2002, 2010), *flexible* (Kronenburg 2007; Schneider, Till 2005), *polyvalent* (Leupen 2006), and *open* (Kendall, Teicher 2000). Physical responses can be described in various ways; material replacement (Brand 1994), interior wall reconfiguration (Friedman 2002), building relocation (Kronenburg 2002), or spatial additions and contractions (Brand 1994, Friedman 2002, Leupen 2006) are all examples. While buildings should be able to physically change throughout their life, built-in responsiveness can also be achieved if the design and construction methods incorporate areas that have the ability to change function (Brand 1994, Friedman 2002, Kronenburg 2007, Till, Schneider 2005). Functional changes are characterized as happening automatically or with little monetary or physical effort (Brand 1994, Friedman 2002, Kronenburg 2007, Leupen 2006, Schneider, Till 2005). A change in use constitutes a functional change; for example a bedroom might have the ability to change functions to serve as a den.

When should buildings change?

Although flexibility during the design and construction of a building is desired, responsiveness is most important during the extended period after construction is complete (Brand 1994, Friedman 2002, Kronenburg 2007). The occupancy phase is the longest and most volatile; buildings must withstand the test of time, both in durability of materials and in usability (Brand 1994, Leupen 2006). Throughout this lifespan of continuous change, all buildings have constant requirements they must meet. Most notably they must be well built to keep the outside out and inside in (Brand 1994) and they must provide a spatially and aesthetically pleasant environment for occupants to be able to establish a sense of place (Heidegger 1971, Kronenburg 2007). As a building changes it must not lose these characteristics or else it becomes a wholly unsuccessful building (Brand 1994, Kronenburg 2007).

Goals of a responsive house:

In essence, a responsive building is one that is able to physically change or accommodate changing functions as required throughout the lifespan of the building. For this paper the targeted definition of the responsive house is as follows: *an easily adjustable dwelling that transforms based upon the needs of its occupants*. The overall goal of this exploration was to push design and construction techniques to their limits in hopes of devising an interchangeable housing system where homes can be assembled, disassembled, and re-assembled to enable a myriad of options for additions, divisions, spatial reconfigurations and even complete relocation. Therefore responsive housing should achieve four goals:

1. Able to be easily increased in size.
2. Able to be easily decreased in size.
3. Able to be spatially reconfigured both internally and externally.
4. Able to be completely relocated.

RESPONSIVE HOUSING: AN EXAMPLE

Perhaps the most straightforward way to exhibit the capabilities of a responsive housing system is through an example. The accompanying figures (Fig. 1 - Fig 4) and descriptions explain a theoretical narrative of the life of a typical North American family, the changes they experience and how a responsive house can adjust to be continually accommodating.

First imagine a young couple who has dreams of owning their own home. This couple is quite savvy; although they know that one day they want to have children, they decide to buy a smaller, more affordable home that can expand in the future as their spatial needs and bank accounts grow. They purchase a small kit of responsive house components and assemble them to form a one bedroom, one bath home that has a galley kitchen, a small utility room, and a combination living room/dining room (Fig. 1). Upon the arrival of their first child they reposition their bedroom, install a staircase and assemble two new floor plates and a few wall panels to create a living room downstairs and bedroom upstairs (Fig. 2). With the birth of a second child, the couple purchases a half bath and another bedroom and places both upstairs (Fig. 3). The couple also adds a large master bath and an office downstairs (Fig. 3).

Many years have now passed and the family begins to upgrade some parts of their home, first the kitchen, then the upstairs bathroom, making both larger (Fig. 4). But an interesting opportunity occurs during this upgrading process: because this responsive system can be disassembled, the previous kitchen and bath are not taken to a landfill, in fact they can be stored to be used again someday. Additions are traditionally easy, but the ability for disassembly

Figure 1. Initial House

Figure 2. First Expansion

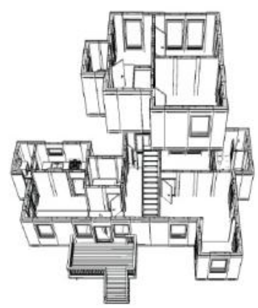

Figure 3. Second Expansion

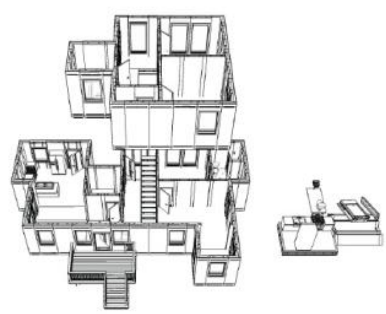

Figure 4. Replacement Phase

and reuse enables the system to achieve the other three goals: division, reconfiguration, and relocation.

Perhaps something monumental happens – a disaster, a population change, or an economic fluctuation creates a housing shortage. Because this family lives in a responsive home, they are able to pare down their dwelling to just what they need – two bedrooms, one bathroom, a kitchen, and a common space (Fig. 5, left). The leftovers include several components – a stair case, a kitchen, three bathrooms, a utility room, and multiple wall and floor panels – that can be reassembled to create a second independent home (Fig. 5, right). The family wants to loan out their extra parts to help satiate the community's need, so they call a trucking company and all of the components are loaded up and taken to help those who don't have homes.

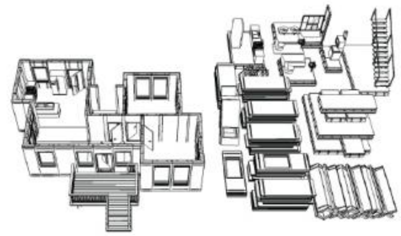

Figure 5. Partially Disassembled

DETAILS OF A RESPONSIVE HOUSING SYSTEM:

How is all of this possible? The four goals are achieved through the use of a 2'-0" design grid, temporary joints, and a separation of building layers. This erector-set mentality allows for initial and continued mass customization. Each house component is explained further below. These components have been grouped utilizing five of Stewart Brand's six shearing layers of change (Brand 1994).

Site:

Helical piers can be installed on gridlines to be used or lie dormant as the home's foot print fluctuates. Helical piers are driven into the ground using a torque motor operated by hand or by a small piece of machinery; small installation equipment allows the opportunity to avoid destroying existing site vegetation for the purpose of creating space for construction activities. If the house is ever to be relocated this foundation type can be completely removed, allowing the site to begin to return to its natural state.

Structure:

Floor plates are designed using light gage steel joists with rigid insulation installed between. These floor plates come in 4'-0" increments ranging from a 4'x4' up to a 16'x16'. The separation of structure from skin allows these components to be used as the first floor, intermediate floors, or the roof of the house. Wall panels are also made from steel studs and rigid insulation. Each panel is 4'-0" wide by 10'-0" tall. Homeowners would be able to mix solid wall panels with panels that incorporate door and window openings to achieve a satisfactory enclosure both in terms of circulation and daylighting. Again, because of the separation of structure from skin, structural wall panels can be used to form exterior or interior walls.

Services:

The incorporation of a raised floor and dropped ceiling throughout the home provides ample flexible space for service lines to be run, rerouted, and replaced. Outlets can be placed where required through the use of baseboard electrical chases. The system incorporates pods for utility laden areas like the kitchen, bathroom, or mechanical room. These pods come as a room unit with the needed utility lines already installed.

Skin:

The interior and exterior skins of the building are provided by separate panels that attach to the walls. Exterior façade panels have two layers; the cladding material is attached to rigid insulation which upon installation forms a continuous layer around the home. The composition of interior façade panels changes with the desired material – some may need a backing material (hardwood floor panels) while some might just be a single material (finish grade plywood for walls). A library of materials would be provided to be easily selected, installed, and replaced at will.

Space Plan:

As explained above the responsive house system can accommodate whole house size changes (i.e. a change in the footprint of the home), in addition internal, non-structural spatial reconfigurations are also possible. Non-structural wall panels are identical to structural wall panels in everything but their height. These panels are designed to be placed between the raised floor and dropped ceiling systems. The difference in size and placement delineates these non-structural panels from the structural wall panels so the two types are not confused. The sole function of a non-structural wall is to delineate spaces; therefore, panel location can be altered at will.

RESPONSIVE HOUSING: EXAMPLE CONTINUED

Returning to the example, the disaster has passed and life is returning to normal. The components that the family donated are given back to them. But life is not the same so this family decides to assemble their panels in a different way and turn their single family house into a duplex (Fig. 6). As their children move away for school the couple is able to send the upstairs apartment along with them (Fig. 7). At some point the children only visit for special occasions; it is during these occasions that the couple decides to rent panels for a larger living space (Fig. 8). Eventually the couple reaches a point where independent living is no longer an option. There is no need to vacate their original home, they simply pare it down to an accessory dwelling unit to be transported and attached to one of their children's homes or incorporated into a senior living community (Fig.9).

Figure 6. Duplex

Figure 8. Special Occasions

Figure 7. Empty Nest

Figure 9. Accessory Dwelling Unit

ENABLED POTENTIAL:

The responsive housing system and the occupant-executed customization that it enables have the potential to revolutionize the current state of residential building. While continued customization might be seen as an attribute that only occupants will value, incorporating responsive houses into our typology enables the housing industry to achieve a more balanced triple bottom line. The triple bottom line, accounting for social, environmental, and economic vitality, can be used to evaluate the potential impact of the responsive house system. The following paragraphs summarize responsive housing's triple bottom line components in three separate scales of analysis: 1, 10, and 100. The 1 scale is singular; it represents a single family or a single house. This section details the relationship between home and occupant in terms of family structure (social), household income (economic), and availability of resources (environmental). The 10 scale represents a neighborhood. This section proposes what social, economic, and environmental opportunities can be achieved by making our neighborhoods more responsive. The 100 scale represents a society. Although societies will vary in size, this section imagines how societies might utilize the increased flexibility that a conglomeration of responsive neighborhoods would provide.

1 Scale:

Many of the social changes that commonly occur in a single household were exhibited in the example above. A responsive house allows families to grow, divide, age and evolve naturally; the home is no longer a hindrance, instead it is a facilitator. One economic advantage of a responsive house stems from the ability for segmented growth. Young families would be able to purchase homes in stages as their funds allow, eventually accumulating the needed or desired number of components to suit their preferences. The opportunity for affordable expansion is a characteristic that could bring buyers into the market earlier. Just as with size, quality of finishes can be procured over time. In conventionally built homes families may choose to replace a linoleum floor with ceramic tile, responsive house occupants have this same option along with the ability to easily upgrade all the other finishes of the house, both interior and exterior, whether the finish is on the floor, wall, ceiling or roof. Unlike a conventionally built home, if household income is ever to wane, responsive house occupants would be able to disassemble parts of their home to sell or trade in for less expensive options. Environmentally, a responsive house would be sensitive to its surroundings from the beginning of construction to the time of complete house disassembly. During construction the manageable sizes of the floor and wall panels require only human power for assembly instead of heavy machinery; without the need for large equipment, building sites would no longer need to be clear cut saving the site's natural vegetation. Throughout the occupation period of a responsive house, less energy is needed because the house can always be sized appropriately. Consuming extra electricity and gas to service a room that is only used one time a year would become a thing of the past. Finally, once there is no longer a need for a house at that location all components, including foundations, can be completely removed to allow the site to begin to return to its natural state.

10 Scale:

For this paper the definition of a responsive neighborhood is a group of homes that contains more than one responsive house. Communities do not need to be made up of only responsive houses to be considered responsive. However, the inclusion of responsive homes in a community would enable ongoing social flexibility. Because of their ability to easily change, responsive homes allow a diversity of people to live in the same area; neighborhoods with multiple responsive houses could easily include an assortment of family compositions, ages, and income levels. Multiple responsive houses assembled in the same area create the opportunity for a new material marketplace to be created. Because house components are interchangeable, this economic venture could provide a medium for neighbors to buy, sell, trade or even share their house components. Responsive neighborhoods would impose less of a burden on our landfills because components can be disassembled and reused instead of demolished and trashed.

100 Scale:

A network of responsive neighborhoods creates a responsive society. Although societies are usually slow to change, responsive societies would have the ability to quickly adjust to unexpected obstacles. Responsive societies would be less devastated when area demographics change; the housing stock could easily be adjusted as populations grow or shrink. When economic swings cause a switch in the job market of an area a responsive society would be poised to offer a medium of exchange as families relocate for work. And if a natural disaster wreaks havoc in an area, a responsive society would be able to rebuild quicker because of the interchangeability of the system.

CONCLUSION:

This paper first explained what *responsive* means as it relates to housing, then outlined the fundamental design and construction details of a proposed responsive system and lastly projected what opportunities would be enabled through the incorporation of responsiveness at three different scales. This paper has shown that responsive housing's potential is vast. Beyond the suggested possibilities outlined in the 1, 10 and 100 sections of this paper, imagine the capabilities if responsiveness is integrated at the 1,000 scale. As a global population, we would be able to react faster to future world problems. Of course globalization has both positive and negative connotations, which is why this paper is not suggesting that all future homes should be built in the manner described. A complete switch of design and construction techniques would lead to the loss of indispensable vernacular building practices. Similarly, a responsive housing system may take different forms, utilizing materials other than what was proposed above. No matter the details of a responsive system, this paper has shown that building technology has advanced to the point that ongoing, occupant-executed customization is possible and has the potential to solve several common social, economic, and environmental problems.

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An Introduction to Steel and Concrete Modular Construction

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ABSTRACT

For many years, wood framed modular construction has been a useful and cost-effective solution in the residential market. While this type of construction has been a good solution for one- and two-family residential construction, it has been limited by factors such as available beam spans, lateral force resisting system requirements, and fire resistance, affecting its use in larger multi-story projects, such as hotels and dormitories. This presentation will explore the benefits of using steel-framed modules to achieve greater exterior opening distances, increased floor plan flexibility, LEED certification, and non-combustible occupancies.

Additionally, we will discuss the concept of the off-site "Build Together" process used by one manufacturer to ensure a precise fit of components, including structural, plumbing, electric, HVAC, and fire protection systems.

INTRODUCTION

History. Modular construction has been used in residential construction for more than a century. For the purposes of this paper, "residential" shall include one- and two-family dwellings and townhouses – as covered by the International Residential Code – and commercial enterprises, including dormitories, apartments, and hotels – as covered by the International Building Code R-1, R-2, R-3, and R-4 occupancies. While the concept of building in modular units is not new, some relatively recent advances in modular technology have made the process very attractive to certain project types and conditions.

It is important to make a distinction between modular construction and manufactured or "mobile" homes. The most significant differences between these types of structures from a construction perspective is that modular construction must be built to the same building codes as conventional stick-built construction and be placed on a permanent foundation, while manufactured homes are built to the less-stringent Housing and Urban Development standard and may not be required to be installed on a permanent foundation. Manufactured homes are limited to one- and two-family residences and would not be appropriate for use with R-1, R-2, R-3, or R-4 occupancies.

Process. The modular construction process involves the construction of modules – three dimensional sections or boxes – off-site and then transported to the permanent building site and lifted into place by crane. The modules are constructed in a controlled environment, often in an assembly line. Constructing within a controlled environment allows the materials to remain dry and protected. The protected environment also promotes worker comfort, which in turn increases productivity.

Figure 1 - Placement by crane, top pick

The traditional building design process by the design team, involving the Owner, Architects and Engineers, is unchanged. However, a benefit to choosing modular early in the design development is that it allows the manufacturer to provide input on the design to ease the modular detailing process.

Modular construction requires specialized detailing to accommodate the connection of the modules and additional ceiling to floor space to allow for framing in the top of the lower module and in the floor of the upper module.

Materials. In the past, wood construction was the obvious choice for residential construction, whether modular or conventionally built. Practically speaking, wood remains the most economical material for one- and two-family housing, as well as for many R occupancies.

Steel modules have come onto the market more recently. These modules are typically constructed with a structural steel frame, steel and concrete floor deck, and cold-formed steel wall panels.

ADVANTAGES OF MODULAR CONSTRUCTION

Quality. The modular manufacturing and approval process requires adherence to all applicable codes. Quality control staff within the manufacturing facilities are responsible for reviewing the work for each trade. While code enforcement rigor can differ by locality, all modular units are required to be inspected by a third party agency prior to being shipped. Several states also require a separate code review and approval process for modular units prior to issuing a permit for construction.

For steel modular structures, additional certifications are often required for welders and concrete finishers.

Speed. Because the superstructure is constructed off-site, the fabrication of the building can begin in conjunction with the site and foundation preparation. This can reduce the time from beginning of construction to occupancy by 30%-50%. The time saved on site can translate into reduced costs for general conditions, for such items as construction trailer rental, Construction Management staff on-site, and utility costs. The ability to occupy the building in a shorter period of time from the start of construction also represents a faster return on investment.

ADVANTAGES OF STEEL CONSTRUCTION

Sustainability. The off-site fabrication process results in less material waste than traditional site-built construction. Steel modular construction is exceptionally sustainable, as structural steel shapes produced in the United States contain approximately 80% recycled content. Because steel is the most widely recycled material, when a steel modular structure reaches the end of its useful life it may be easily dismantled and recycled, thus diverting what would otherwise be construction material headed for a landfill.

Steel modular buildings may be designed to be disassembled and relocated, prolonging the structure's useful life. This concept is currently being explored by developers following the Marcellus Shale development in northern Pennsylvania and the anticipated development in New York. While a steel modular structure could be disassembled with relative ease, the same cannot be said for wood framed modules.

Fire Resistance. Steel and concrete construction is compliant with Type II Construction. The inherent fire resistance of these materials allows for increased building height and footprint. In Europe, steel modular construction has been used in buildings up to 24 stories in height, and a 32 story high rise is currently underway in the Atlantic Yards sports village in Brooklyn, NY.

Structural. Steel modular construction allows for longer opening spans when compared to wood-framed modular construction. The rigidity of the module frame is greater than that of site-built construction and may be considered as part of the lateral force resisting system. Where additional capacity is required, steel cross bracing, knee braces, moment frames, or shearwall panels are all options available to the Engineer. Because of the ease of connection and the higher capacity of steel connections versus the capacity of wood connections, steel frames are more likely to act together when connected across mate lines.

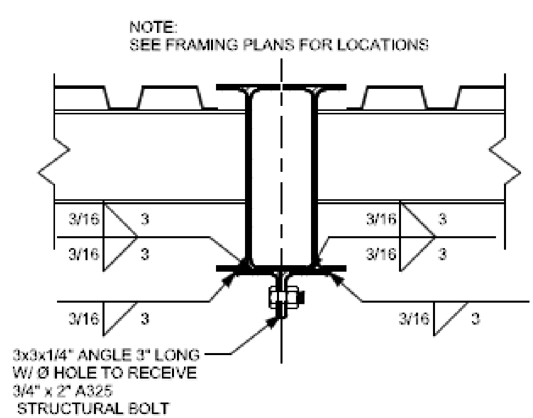

Figure 2 - Mate line connection

The use of steel also offers the advantage of consistent material properties and durable long term behavior. When the building design allows for repetitive module sizes and design, the Engineering analysis and detailing for such a structure also becomes simplified and more efficient.

Design Flexibility. The increased spans and tolerance for concentrated loads or cantilevered conditions allowed by steel construction provides a high degree of design flexibility for Architects. Because steel allows increased spacing between structural members and greater spans can be achieved with shallower members when comparing steel to wood construction, more space is available in the ceiling to floor space to run plumbing, electrical, and HVAC. A typical floor joist spacing with conventional wood or light-gage steel joist construction is 16” on center, while the joist spacing in the structural steel and concrete system is typically four feet for floors and up to five feet for roofs. In addition, the typical structural steel joist depth used can be shallower than wood or cold formed joist options.

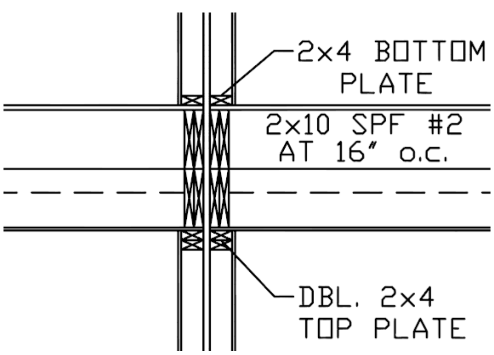

Figure 3 - Wood modular framing @ mate line, 2-story

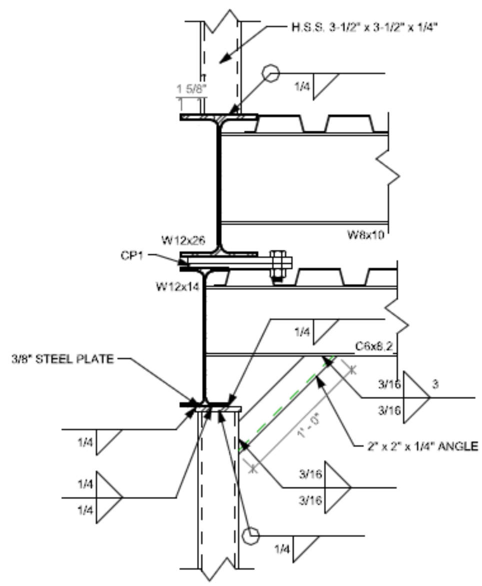

Figure 4 - Steel modular framing, 2-Story

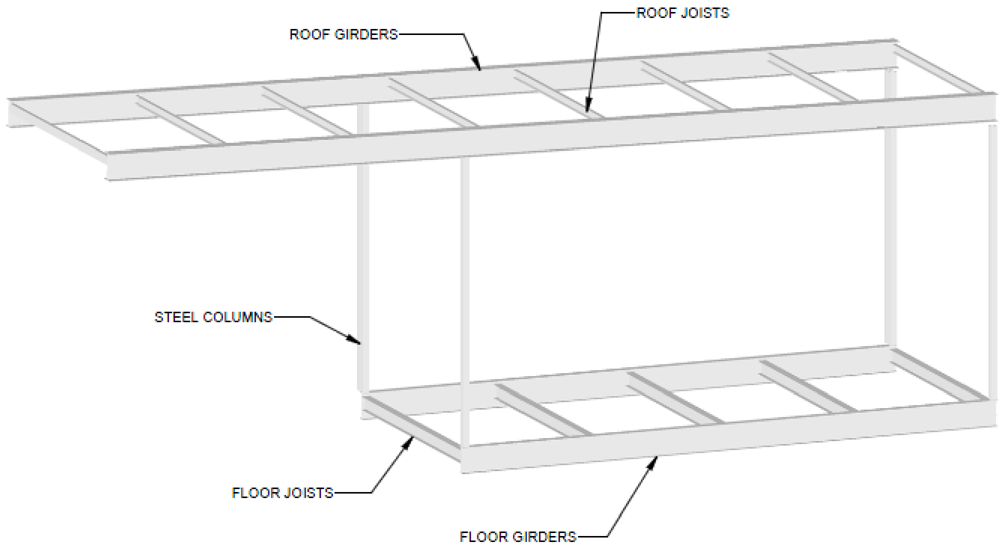

Figure 5 - Typical steel "box"

Figure 6 - Under construction

"BUILD-TOGETHER" TECHNOLOGY

NRB offers off-site construction in a process it has termed *The Build-Together Advantage*. Unlike assembly line manufacturing where individual modules never truly meet each other until they are on the site, NRB puts all the modules together, forming a complete structure at the plant, which means with *The Build Together Advantage* everything is finished and you can be sure the modules all fit together with incomparable precision. Plumbing, mechanical, and electrical components can be tested as a complete building system ahead of time; no surprises on site. NRB buildings are also inspected and certified by a Commercially Licensed Building Inspector, Third Party Inspection Agency (TPIA), and the project Architect or CM team at the facility.

As a direct result of *The Build-Together Advantage* construction process, shipping every NRB modular building is easier and faster; *The Site-to-Site Transfer* is an efficient, pre-planned transition between the factory and the site. Modules are configured to allow a top-pick craning method, allowing for a faster site set, with less site disturbance and no gaps between units.

As a result of the *Build Together* process, the subsequent product provides an easy, fast, and accurate on-site installation.

NRB's "Build-Together" "Off-Site" Method	Assembly Line Construction
1. Design is driven by Customer's or Architect's design	1. Design is driven by plant capabilities.
2. Schedule is driven by completion date.	2. Schedule is driven by the plant's need for volume; either dollars-out-the-door or units-out-the-door capacity.
3. Generally utilizes the Architect's construction drawings supplemented with structural steel drawings from NRB.	3. Requires production drawings to be developed by the manufacturer for each station in production.
4. Fewer restrictions or limitations on custom designs or materials.	4. Custom designs and use of custom materials are very limited. Custom production slows down an assembly line, which adds cost; decreases profit.
5. Generally built outside (same as on-site construction) due to size, complexity. (Very few factories have the capability to build large projects inside, all at one time.)	5. Generally built in a factory.

6. Multiple projects can be built at the same time. Your building does not have a "Line Lead-Time" so your project never waits in queue and therefore is much faster to start than assembly line lead-time methods.	6. Requires a "Line Lead-Time" which is the period of time your project has to wait in queue behind the other projects that are already "booked", or in production. Construction of multiple orders requires a plant to have multiple production lines and more production workers.
7. Uses sub-contracted, skilled or trained labor, so the level of quality is the same or better than site-built construction.	7. Generally uses unskilled, but trained, factory labor.
8. Uses "Just-in-Time" materials for construction; however, non-receipt of material does not create costly or time consuming delays or quality issues.	8. Requires custom materials to arrive "Just-in-Time" for production. Nonreceipt of materials creates costly and time consuming yard and potential delivery delays.
9. Not forced to use factory-stocked or "standardized" materials. Most any type of material can be incorporated in the "off-site" construction method.	9. Generally requires the use of the factory's standardized/stock materials and methods of installation for optimum efficiency.
10. Units have already "met" before arriving on site so the installation process is much faster than assembly line delivery.	10. In most cases, modules don't "meet up" with each other until they get to the customer's site.
11. Mechanical, plumbing, and sprinkler systems are built together at the factory and can be pre-tested.	11. Mechanical, sprinkler, and plumbing are generally not tested and fairly incomplete from the factory.
12. Welding certifications can be provided for all welding.	12. Welding certifications are rarely available.
13. Tour the building while it is under construction, just like a site-built building, even if multiple story.	13. Allows a limited walk-through of the project as units are in varying stages of completion on the assembly line or are already stored in the factory yard.
14. Last minute changes can be accommodated.	14. Last minute changes cannot be easily accommodated.
15. More scope is completed at the factory = faster speed to completion on site.	15. Level of finish when leaving the factory is generally lower, requiring more finish work to be completed on-site.

16. Project is bondable with invoicing by AIA monthly draw, verified to a schedule of values, with release of lien or waiver documents; all notarized, just as if site-built.	16. Most factories are not bondable and project is invoiced as each unit comes off line.
17. Allows proper application and installation of SCIF and fire spray treatments to code and specification.	17. Difficult to install SCIF and/or fire spray treatments. Continuity or integrity of treatments is difficult to maintain on-site.
18. Built to the latest edition of the International Building Codes, inspected and certified by an NRB Licensed Commercial Building Inspector, Third Party Inspection Agency, and project Architect or CM team.	18. Built to the latest edition of the International Building Codes and inspected by plant employees with a Third Party Inspection Agency.
19. Uses top pick craning, faster site set, no gaps between units.	19. Generally requires axles to be removed before set and a sling type set process. Slower process; more site work involved. Gaps between units up to 1”.
20. Installation and completion is handled by experienced riggers and skilled tradespeople.	20. Installation and completion is generally handled by typical modular set crews.

SUMMARY

Where site and schedule constraints are limiting factors, modular construction is an excellent choice. For projects that require fire resistant construction or LEED certification, steel and concrete modular units combine the advantages of the modular process with the advantages of the strength and durability of those materials. And, where projects require a higher level of customization and precise fit, the off-site “Build-Together” method offers an advantage over a traditional assembly-line process.

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Concrete in Residential Construction

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ABSTRACT

Concrete is widely used in residential construction for footings, walls, and slabs on ground. This paper provides a summary of the requirements needed to achieve high quality concrete in residential constructions. Aspects include concrete materials, proportions, mixing, placing, consolidation, finishing and curing. Some of the problems that can occur in concrete discussion are discussed and suggestions for avoiding these problems are mentioned.

INTRODUCTION

Concrete is the most widely used construction material in the world and residential construction represents a major market for concrete in the U.S. The main uses for concrete in residential construction include footings, basement walls, and slabs on ground (floor slabs, driveways, sidewalks, and parking areas), however concrete may also be used above ground for suspended slabs, wall and roof systems. Information on concrete construction is available from organizations such as the American Concrete Institute (ACI), Portland Cement Association (PCA), and National Ready Mix Concrete Association (NRMCA). The purpose of this paper is to provide a summary of the main factors that need to be considered to produce quality concrete for residential construction.

ACI Standard "Residential code requirements for structural concrete and commentary" (ACI 332-10) covers the design and construction of cast-in-place concrete one- and two-family dwellings and multiple single-family dwellings (townhouses). Requirements for multi-story (high-rise) concrete construction are contained in ACI 318-11. ACI 332-10 contains detailed design and construction provisions for footings, foundation walls and slabs-on-ground. ACI 332-10 also provides a report entitled "Guide to Residential Concrete Construction" (ACI 332.1R). The guide provides practical information about the construction of residential concrete. For above-grade concrete construction such as suspended slabs, wall and roof systems, reference should be made to ACI 318. The following provides a summary of factors that need to be considered to produce quality concrete for residential construction.

CONCRETE MATERIALS

Concrete consists of cementitious material (Portland cement, fly ash, slag etc), coarse aggregate (gravel), fine aggregate (sand) and water. Admixtures and additives may also be added to produce desired properties. The strength of the mix depends to a large extent on the proportions of these ingredients. Each material in concrete has its own significance and changing proportions alters the properties of concrete significantly. Concrete is usually supplied to the site by a ready mix concrete supplier. Hence, the concrete mix supplier should be consulted prior to altering the proportion of cement, aggregates or water. The information regarding the constituents of concrete is presented in the following paragraphs.

Aggregates:

Aggregates occupy the major portion of concrete by volume and serve as inexpensive filler. Aggregates should be chemically inert so that they do not react with cement or water which might lead to deterioration of concrete. The size, shape, and surface texture of aggregate also affects the quality of concrete. Aggregates should preferably be cubical or rounded. The aggregates size should not be more than one fifth of the narrowest form dimension or one-third of the cross-sectional dimension of a structural member or three quarters of the minimum clear spacing between reinforcing bars. They should be without impurities and well graded.

Aggregates with high absorption should be avoided as they may lead to high shrinkage. Alkali-silica reaction can occur between certain aggregates and portland cement. This can be controlled by keeping concrete as dry as possible or by using blended cements or using fly ash, slag, silica fume materials or certain admixtures.

Water/Cement ratio

The cementitious pastes consist of cement and water that coats and bonds the aggregates together. This paste also fills the voids between the aggregates. The strength of concrete depends primarily on water cement ratio. If the amount of cement is increased, the strength of the concrete will increase. However, there should be sufficient water present in the mix to hydrate all of the cement. Addition of water more than the specified amount will provide ease of placing the concrete i.e. workability; however, it will decrease the strength of the resulting mix and increase the potential for shrinkage which may further increase development of cracks. Water cement ratio should be preferably less than 0.45. No additional water should be added at the job site to ready mix concrete unless water-cement ratio at the time of batching is lower than the allowable. If the slump is lower than the maximum allowed value, high range water reducing agents may be used. Retarders can be used when the concrete mix truck has to travel a long distance from the concrete plant to the job site so that concrete does not set before it reaches the site. Retarders temporarily stop the action of hydration of cement.

Compressive Strength

The compressive strength of concrete used for residential construction should not be lower than 2500 psi. This range is applicable only where the weathering probability is negligible. For construction of driveways, stairs, curbs, slabs which will be exposed to weather, the minimum compressive strength of concrete should not be less than 4500 psi and slump should not be more than 5".

Concrete has a tendency to shrink when it dries. Cracks may develop when shrinkage is restrained. This restraint may result from support conditions, reinforcing steel, connection between different parts of structure etc. Cracks are generated as a result of shrinkage. Since shrinkage is greater at the surface, it generates surface cracks initially. Concrete has low tensile strength. If the tensile stress on a concrete component is greater than the tensile strength, concrete tends to crack. Joints may be provided to control cracking. Concrete may crack randomly in slabs on ground if control joints are not provided to divide the slab into smaller sections. Hence, control joints are created into concrete so that cracking occurs at predetermined locations. These control joints are created by grooving and sawing the concrete surface.

Figure 1. Grooving of concrete slab

Source: ACI 332.1R-06 Guide to Residential Concrete Construction

Concrete in cold/hot weather

Concrete may be permanently damaged if it is exposed to freezing temperature before reaching a compressive strength of 500 psi. Hence, for cold weather concreting special provisions are needed for maintaining the placement temperature. Insulation products and supplemental heat may be needed to maintain the concrete temperature. Accelerators can be used when casting concrete during cold weather. Accelerators decrease the setting time of concrete to counter the effect of low temperature.

If the ambient temperature is less than 35 °F, concrete temperature should be maintained above 35 °F till the compressive strength reaches 500 psi. Frozen material containing ice should not be used in the mix. Materials coming in contact with concrete like aggregates, reinforcement, form, should be free from frost. ACI 306R provides detailed requirements for cold weather concreting.

Casting concrete in hot weather can also lower the ultimate concrete strength and serviceability of a concrete member. In hot weather, water is evaporated from the mix, slump decreases rapidly and cement sets up rapidly. The water at the surface may dry up quickly and if not cured adequately, it may decrease the ultimate strength. Loss of water may lead to shrinkage and cracking.

Adding more water may compromise the ultimate strength of the mix. Sometimes dry sub grades and formwork can absorb water from the concrete mix aggravating the problem. Thermal differential may set up between two parts of the member which might lead to cracking. Retarders are used in areas where high temperature may decrease the setting time of concrete. ACI 305R should be referred for hot weather concreting.

Workability of concrete:

The concrete mix should be workable during placement and finishing. Properties like consistency, setting time and bleeding also affect the strength of concrete. Some parameters concerning the casting phase of concrete are discussed below.

- *Slump*:

Consistency of concrete defines the flowability of concrete and it is measured through the slump test. During the slump test, a truncated cone is filled with concrete and the amount by which the concrete subsides is measured once the cone is lifted. If the slump value is high (6"-8"), it means that the concrete is more workable. However if the water content is more than the designed water content of the mix, it would result in weak concrete. Low slump (1"-3") means concrete is difficult to consolidate and is stiffer. Concrete with low slump is difficult to place and finish. Slump usually varies from 5" - 6".

Figure 2. Slump test (left: High slump; right: Low slump)

Source: ACI 332.1R-06 Guide to Residential Concrete Construction

The slump value of concrete should not be increased only by adding water as water may make the cement paste thin and reduce the strength of concrete and increase shrinkage. If required, slump can be increased by the use of admixtures.

- *Setting time:*

Setting time is the time concrete takes for initial stiffening once the water has been added to the mix. It can vary from 4 to 8 hrs depending on the mix composition, cement properties and temperature of mix and ambient temperature. The setting time of concrete increases with decrease in temperature.

- *Bleeding*

After the concrete has been placed, solid material settles down whereas excess water rises to the surface. This phenomenon is known as bleeding. During finishing, this water may get mixed with the surface layer leading to creation of weakened zone and fine cracks, and surface defects such as dusting and scaling. Hence, finishing should not be done while bleed water is present.

- *Air entrainment:*

Air entrainment admixtures help entrain tiny air bubbles in the concrete. This improves the workability of concrete. The amount of water required to achieve a certain consistency also decreases with the use of air entrainment admixtures. As the amount of water decreases in the mix, the strength of concrete increases and the problem of bleed water reduces. The bubbles remain as discrete voids after hardening of concrete. These voids help in releasing the pressure during the freeze-thaw cycle. It is required that concrete subjected to freezing and thawing should have between 5%-8% of entrained air by volume. For regions of minimum weathering probability, there is no minimum air entrainment requirement.

- *Placement*:

The normal discharge time for placement of concrete is 1.5 hours after adding water. This discharge time can be exceeded if the temperature of concrete is in the range of 55 to 100 ˚F and the water amount present in the mixture is not more than the specified mixture proportion.

While placing concrete, care should be taken so that consistency and matrix of the concrete mix is maintained and there is no loss of material. The area should be cleared of debris, ice and excess water before concrete is placed over it. Concrete should be consolidated using vibrators. Extra care should be taken while placing concrete around reinforcement bars, corners of forms and other embedded items so that there is no void around them. Removal of forms should be done in such a way that the surface of concrete is not damaged.

- *Concrete cover:*

Concrete cover for concrete cast against earth should be minimum 3 inches, for concrete exposed to weather or earth should be 1.5 inches and for concrete not exposed to weather and earth should be 0.75 inches.

- *Calcium Chloride:*

Calcium chloride should not exceed 2% by weight of cementitious materials for structural plain concrete in dry areas protected from water. For structural work, plain concrete exposed to atmospheric conditions and reinforced concrete , calcium chloride should not exceed 0.3% by weight of cementitious materials.

Curing:

The concrete mix loses moisture once it is placed and loss of moisture may lead to improper hydration of cement. Curing is done to maintain adequate moisture and temperature conditions in a freshly placed concrete mix so that hydration of cement takes place and the desired strength of the concrete mix is developed. It has significant impact on strength, permeability, abrasion resistance, and resistance to freezing and thawing of concrete structures. All concrete structures should be cured for the specified period. ACI 308.1-11 contains specifications for curing concrete. ACI 308R-01 provides a report describing current curing techniques and procedures for curing different types of construction.

The curing period is the time period beginning at placing of concrete and extending until the concrete has attained the desired strength. Curing should be started as early as possible when drying conditions exist. For temperatures above 40 °F, curing should be done till the concrete has achieved 70 percent of specified strength. Curing duration should not be less than 7 days for ASTM C150 Type I mix, 10 days for ASTM C150 Type II mix, 14 days for ASTM C150 Type IV & V mix. Curing duration can be decreased if accelerators are used for development of early strength. For temperatures below 40 °F, the concrete must be protected from the effects of cold weather throughout the process of placing, finishing, and curing. During cold weather, heat should be used to maintain the temperature of the concrete, along with proper curing.

The curing procedure can be described in three stages. Initial curing measures such as fogging and use of evaporation reducers are applied between placement and final finishing of concrete. It is done to reduce the loss of moisture from the surface. Intermediate curing is done using spray applied liquid membrane forming curing compounds and is implemented after finishing and before the final set of concrete. Final curing is implemented when the concrete has reached final set. It is implemented through measures such as applying wet coverings or using liquid membrane-forming curing compounds. A complete and continuous water cover should be available over concrete surface for wet water curing. Alternate wetting and drying of concrete surfaces deteriorate its quality. The water should be free from harmful chemicals and impurities. Potable water is acceptable as curing water.

If wet covers are used for curing, they should not be allowed to dry and absorb water from concrete. Curing period should terminate with uniform, slow drying of concrete surface. To achieve this, cover material should be allowed to dry thoroughly before removing it.

Consolidation:

Consolidation of freshly mixed concrete results in reduction of voids by expelling entrapped air. It leads to a compact mix which has closer arrangement of particles of concrete and has a strong and durable structure. If concrete is not consolidated it may lead to porous, low strength, highly permeable structure. ACI 309R-05 provides information on consolidation mechanism and gives recommendations on available consolidation procedures.

The consolidation requirements are determined by the workability of the mix. While determining the workability, reduction due to loss in slump because of high temperature, premature hardening, etc should be considered. Workability determines the ease with which concrete can be mixed, placed, consolidated and finished. Workability is primarily controlled by water-cement ratio of the mix. When the mix has high ability to flow (contains more water), the mix may segregate during consolidation. Concrete mix with low water-cement ratio requires more effort to achieve proper consolidation. In such cases, admixtures can be added to achieve desired consistence and workability. If stiffer mixes are not consolidated properly, they will contain entrapped air and will be porous resulting in decrease in strength.

Manual and mechanical methods are available for consolidation. Consolidation is usually done by vibration, centrifugation (spinning), spading and tamping. The consolidation method depends on the concrete mix, placing conditions and amount of reinforcement. If the mix has flowing consistency, rodding may to done to consolidate it. Spading is done in the formed concrete surface. If the mix is stiff, hand tamping may be done to consolidate the mix. While applying these methods, a thin layer of concrete is laid and rammed. Consolidation obtained through manual methods is effective but is time and labor intensive.

Mechanical methods consist of the use of equipment that applies static pressure, power tampers, centrifugation, shock tables, and vibrators. Two or more methods can be used together. Vibrators are predominantly used for consolidating concrete. Vibratory impulses induced by vibrators, liquefies the mortar and internal friction between particles results. When internal friction decreases, concrete is not able to support its honeycomb structure and becomes unstable. While in this condition concrete becomes denser eliminating the honeycombs. Once the vibrations are stopped, internal friction is again established. Agitating the mix further forces the entrapped air to rise to the surface. The vibration should be terminated when entrapped air is reduced sufficiently.

Figure 3.Vibration of concrete

Source: ACI 303R-12 Guide to Cast-in-place Architectural Concrete Practice

Figure 4. Honey Combing

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

CONCRETE FORMWORK

Design:

Formwork should be able to support all vertical and lateral loads applied to the structure. Formwork should be constructed to provide the correct dimension, elevations, position, shape and alignment to the structure. Formwork should not be supported on frozen ground. ACI 347-04 provides guidelines regarding design, construction and material of formwork.

Construction

Formwork can fail due to use of substandard materials & equipment, inadequate design and human error. It is important to supervise and inspect formwork throughout its erection till its removal. Safety measures should be followed for safe installation. The details of scaffold, working platforms and guard rails should also be included in the design and drawings.

Construction deficiencies may lead to failure of formwork. Hence, formwork should be continuously inspected for abnormal deflections or behavior. Installation should be done as per the drawing. Sufficient number of nails, bolts welds should be provided. It should be properly braced. Rate of placing concrete should be maintained as per the design documents.

Studs or shores should be properly spliced. Joints and splices should be staggered. The fasteners should be properly tightened. There should be no gap in the form from which loss of mortar may occur. The joints should be provided as per the contract document. For construction of sloping surface with slope more than 1.5 horizontal to 1 vertical, a top form should be provided. Concrete should not be placed on formwork containing dirt, mortar, or any foreign material. Any extraneous material should be cleaned from the surface and a release agent should be applied before using the formwork.

Several practices should be followed before concreting. Formwork should be properly anchored to prevent its movement. Provisions for realignment and readjustment of shores in the case of settlements should be provided. Additional elevation of formwork should be provided to allow for certain irregularities. The elevation, camber and alignment of formwork should be continuously checked during and after concreting. Any corrective measures, if required, should be quickly take to prevent further damage.

Removal of formwork:

The formwork should only be removed when the concrete has attained its minimum strength. The strength can be determined by testing job cured specimens or in place concrete or using procedures like maturity method, penetration resistance, pullout tests etc as specified by ACI 228.1R. The concrete should not have excessive deflection or damage due to removal of formwork. If the forms are removed before the curing requirements are complete, curing should be done as per ACI 308R-01. Proper measures should be taken to protect concrete from the cold weather. The supporting forms for structural members should not be removed till the time they are able to carry their own load and superimposed load. In some cases permanent forms can be used which do not require removal and become a permanent feature of the structure. Permanent forms can be rigid or flexible. Rigid forms consists of wood, plastic, metal deck, fiberboard, precast concrete. The flexible form consists of reinforced, water-repellent, corrugated paper, or wire mesh with waterproof paper backing.

Figure 5. Metal framework with plywood sheathing faces

Figure 6. Aluminum forms

Source: ACI 332.1R-06 Guide to Residential Concrete Construction

Economy:

In the United States the cost of formwork can be as high as 60% of the total cost of the completed concrete structure. The cost of formwork can be reduced by proper planning and design of structure. When the dimensions of footings, columns, and beams are in standard multiples, formwork can be reused increasing economy. The number of sizes in a structure should therefore be minimized. If the design of the structure is based on one standard depth, the cost of formwork will be reduced. Using readymade formwork and keeping sizes of joist constant will lead to speedy construction and thus reducing labor cost.

CONCRETE ELEMENTS

Typical elements in residential building construction include footings, foundation walls and slabs on ground. Detailed information on design and construction of these types of elements is provided in ACI 332.1R-06.

Footings are provided to distribute loads to the soil and to provide a platform for construction of foundation walls and support posts. In addition to distributing the loads to the soils and minimizing differential settlement that can cause cracking in walls above the footing, the footings can bridge isolated areas of settled soil under the footing. Footings should be placed below the frost line and concrete should not be cast in standing water or mud. During cold weather the soil should be protected from freezing before and after concrete placement. A footing drainage system is usually required to minimize lateral loads on foundation walls.

Formwork for concrete walls is supported on the footings. Forms may be re-usable or stay in place. Reusable forms may be made of wood, aluminum, or a wood-steel combination. Stay in place forms are usually made from polystyrene foam forms connected by plastic ties. Horizontal and vertical reinforcement is usually placed in concrete walls to resist applied loads and control cracking due to shrinkage and temperature effects.

Concrete slabs are used as the floor in basement areas, or as the main floor in buildings without basements in residential construction. Elevated slabs spanning between walls or column supports are sometimes, used particularly in multi-occupancy residential construction with several floors above the ground level (Bondy, 2005). Slabs are also used outdoors for sidewalks, driveways, carports, and parking areas. Slabs on ground can be structural plain concrete without reinforcement although reinforcement is often used to control cracking due to settlement, shrinkage and temperature effects.

TROUBLESHOOTING

To achieve quality concrete in residential construction, careful planning and attention to detail is required at each step of the process. Typical problems encountered in concrete construction include cracking, scaling, blisters, popouts, dusting and discoloration. Troubleshooting concrete problems should usually be left to an experienced concrete professional, however understanding the causes of these defects can help in planning to avoid them.

Because concrete is relatively weak in tension, some cracking can be expected in most concrete construction. The most common cause of cracking in residential concrete is drying shrinkage and temperature effects. Drying shrinkage is caused by loss of moisture during the hydration process. To minimize cracking potential, concrete should be placed with the lowest possible water content and properly cured. Contraction joints using saw cuts need to be sawn early enough, deep enough and not spaced too far apart. Plastic shrinkage cracks near the surface can occur before finishing due to rapid loss of moisture from the top surface. Use of wind breaks, sunshades and other means to prevent rapid drying can minimize plastic shrinkage cracking. Other causes of cracking include soil settlement and structural overloading.

Dusting is the development of a fine powdery material due to a thin layer of weak concrete called laitance at the surface. This is often caused by floating bleed water back into the surface. It may also be caused by overly wet mixtures, inadequate curing, and freezing at the surface.

Scaling is caused by the loss of surface mortar surrounding coarse aggregate particles, leaving the coarse aggregate exposed. It is usually caused by water freezing in the concrete and lack of air entrainment to relieve the internal pressure due to freezing.

Popouts at the surface are usually caused by internal pressure developing due to expansion of unstable materials or chemical reaction between cement and some types of aggregates.

Blisters can appear on the surface during finishing due to bubbles of entrapped air forming under an airtight surface layer. This can be prevented by using proper finishing procedures and good quality concrete.

Figure 7. Plastic shrinkage cracking

Figure 8. Dusting

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

Figure 9. Scaling of concrete

Figure 10. Popouts

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

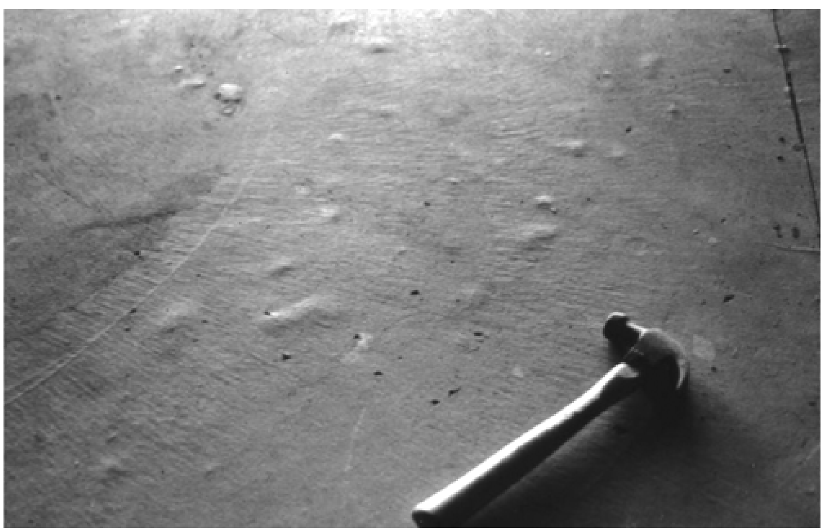

Figure 11. Blisters

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

PBOBLEMS FACED IN RESIDENTIAL CONCRETE CONSTRUCTION

The residential sector is the least regulated of all segments of the concrete industry and this leads to several defects in the construction as described in the paper. According to Nasvik (2003), the problem with residential sector is that the guidelines specified by ACI are rarely read and enforced. The decisions at the construction site are taken by the individual contractors and the requirements of air entrainment, slump, curing water-cement ratio, admixtures, control joints etc are ignored leading to the inferior quality of construction.

Jaffe (1988) describes the issues faced during residential construction. The main problem arises due to slow pour of concrete. The concrete from ready mix trucks may not be used within 90 min and water may be added to prevent loss of slump. The added water may not be mixed sufficiently further deteriorating the quality of concrete. To avoid this situation, forms must be in place with sufficient workers to place the concrete when the ready mix truck arrives.

Problems arise due to rapid drying of the surface. Finishers may rewet and then trowel the surface which weakens it. Such surfaces have poor wear resistance and are prone to scaling. To avoid this, surface should be kept wet by covering it with plastic film or by spraying evaporation retardant. By no means, should added water be forced back in to concrete.

Sometimes, the mindset of contractors is that curing is not required in cold temperature because it harms the concrete surface. During cold weather, curing must be done by taking precautions to avoid freezing.

Joint errors are prevalent in residential concrete. The contractors may provide joints that are too far apart or may not be sufficiently deep. This causes cracking of concrete. Joints should be properly placed with sufficient depth. Joints re-entrant corners should be jointed.

A study was carried out when problems like scaling, cracks, pop-outs, discoloration were noticed in concrete houses after the winter of 2000/2001 in Illinois (IRMCA 2002). A task force was formed and recommendations were given for the use of ready mixed concrete for residential sector. IRMCA (2002) specifies that the residential flatwork is unacceptable when it displays major cracking, major scaling of major spalling for the period of one year. These problems may arise due to either defective material or workmanship or may be both.

IRMCA (2002) defines a major crack as "an uncontrolled crack with a width of 1/8” or more that covers more than 10% of the total length of all the joints and edges of the slab and the total length is no more than 20% of the perimeter length of any one panel". Similarly, major scaling and spalling occurs when it covers more than 15% of the total slab or 20% of any one panel. To maintain the quality, the contractors should warrant the work for a certain period of time against failures due to construction procedures, material and workmanship.

With the advent of modern technology, quality can also be maintained by using precast members or insulating concrete forms (ICF). Because of its several advantages, ICF is becoming very popular in residential construction. According to Portland Cement Association, about 70% of utilization of ICF is in the single family residential construction with remaining 30% for commercial and multifamily purposes.

CONCLUSION

Concrete construction has been and will continue to play a major role in residential construction. High quality concrete construction requires careful planning and attention to detail at phases of the process. This paper provides an overview of aspects that need to be considered to ensure a high quality product. Efforts should be made to make available to the housing industry, training programs to ensure that recent advances in concrete technology can be implemented in the construction of housing.

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Investigation for the Removal of Steel Tie Rods in a Historic Segmental Arch Floor

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ABSTRACT

Gilsanz Murray Steficek, LLP investigated the removal of the tie rods in the floors of the landmarked Metropolitan Life Tower in New York City when the tower was converted for residential use. The typical floor is constructed of segmental concrete arches supported on steel beams with tie rods perpendicular to the beams below the arches. GMS evaluated the removal of the rods by performing linear and nonlinear 3D finite element analysis of the floor system. Load tests were also performed at 5 locations in the building in order to confirm that the floor would perform satisfactorily. Both the analysis and the load test confirmed that the tie-rods could be removed safely.

INTRODUCTION

The Leviev Clock Tower is a 50-story steel frame tower in New York City. Originally built as an office tower for the Metropolitan Life Insurance Company Tower, it was the tallest building in the world when it first opened in 1909. The landmark tower is being converted into a luxury condominium under the direction of new ownership. The building's typical floor system consists of segmental concrete floor arches tied with steel rods. At the request of the owner, Gilsanz Murray Steficek, LLP (GMS) investigated the possibility of removing the tie rods to accommodate the proposed architectural design. As part of the structural system, the tie rods would require fireproofing, which would reduce the ceiling height at every floor and increase the cost of the project. Through the use of finite element analysis and the code required load tests, GMS was able to confirm the safe performance of the floors under the new loadings.

DESCRIPTION OF STRUCTURAL SYSTEM

The typical floor consists of tied segmental cinder concrete arches spanning to beams spaced at 4' to 5'. The arches are 4" thick at mid-span, and at least 8" at the face of the beam. At the bottom of the arch is a perforated metal mesh form with metal strips. ¾" diameter tie rods are installed in the framing bay at approximately 6 feet to 7 feet on center perpendicular to the beams. The steel framing of the floors consists 10" to 20" beams and 15" to 24" girders. The framing is supported by built up column, laid out in a rectangular grid spaced at 14' to 25'. Two inches on cement finish is on top of all the floors as a wearing surface. Figure 1 provides an illustration of the floor system.

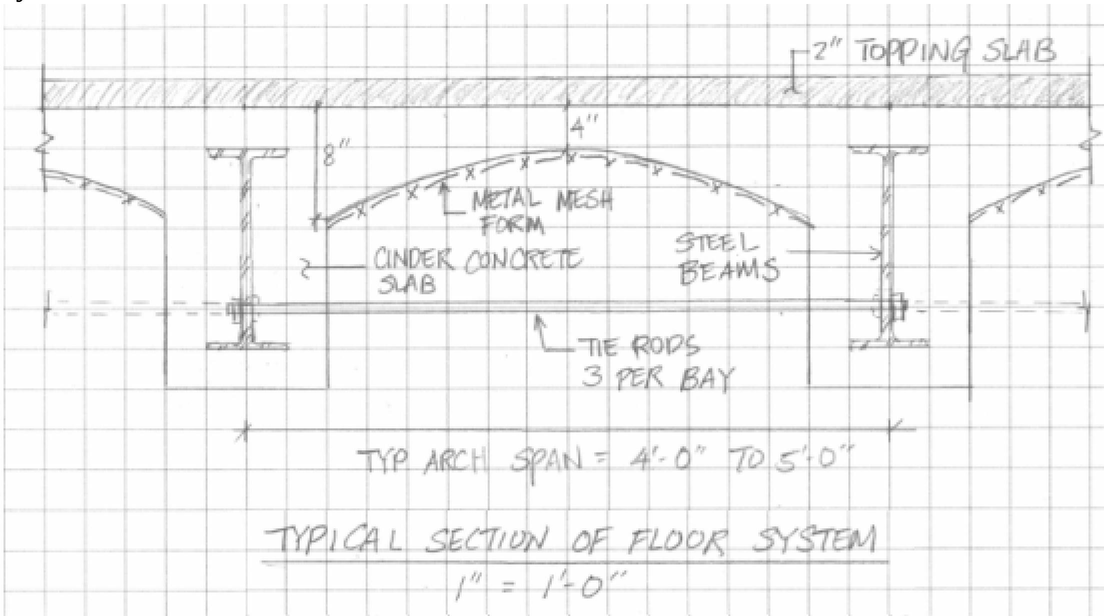

Figure 1: Typical Section of the Floor System

In a tied arch system, the tie rods served two purposes: to provide stability to the steel framing during construction while concrete is poured, and to resist the lateral thrust of the concrete arch. While the tie rods are necessary in the classical tied arch model, GMS observed that the rods are slack or have been cut at several locations in the building due to their interference with existing risers. At these locations, no visible distress is observed in the floor system, suggesting that the tie rods may not be required.

The lateral system of the building consists of a perimeter knee brace frame with 24” to 36” built up girders. At the lower portion of the building, twin plate girders are used to resist the higher cumulative lateral loadings. All steel framing is encased in cinder concrete for fireproofing.

The concrete and steel properties are shown in Table 1.

Table 1: Material Properties

			Design Stress (psi)		
Material	Weight (lb/ft^3)	E (ksi)	f'c	fr	fys
Cinder Concrete	108	860	600	110	
A9 Steel	490	29000			30000

THE LOAD TEST

The test was performed under a two stage loading criteria in accordance with the New York City Building Code (NYCBC) section 27-599 b “Load tests for completed construction,” which specifies both a strength requirement and a deflection requirement. The strength requirement consists of two testing stages.

For the first stage loading, the applied load shall equal 100% of the superimposed dead load (35psf) and 100% of the live load (40psf). At this stage, the deflection is not to "exceed that permitted deflection in the applicable reference standard." For the typical floor framing, the industry accepted deflection standard is L/240 in the gravity direction and, for masonry construction, L/600 in the lateral direction.

For the second stage loading, the load is increased to 150% of the total dead load (100psf self-weight and 35psf superimposed dead load) plus 180% of the live load (40psf). The equivalent superimposed load for this stage is 175psf. This load was maintained on the floor for a minimum of 24 hour to ensure safety under a factored overload condition. In this stage, the residual deflection after removal of load "shall not exceed 25% of the calculated elastic deflection under the superimposed test load." After each stage of the loading, the test areas are inspected for signs of serious distress indicative of a potential failure.

Photo 1 shows the typical test set up.

Photo 1: Typical Test Set Up

THE TEST AREAS

Five representative test areas were selected. All the tested areas were located at the exterior bays of the building, where impact of removing the tie rods would be the most pronounced. As the thrust in the arch would be resisted by the edge framing once the tie rod is removed, the test areas included each of the three different edge conditions in the building. Each test area consisted of a floor bay bounded by column grid lines and the three floor arches. When choosing the test areas, the bays with the smallest girders were typically chosen since they would have the least reserve capacity. A characteristic of each test area is shown in Table 2.

Table 2: Characteristics of the Test Areas

Floor	Side	Bay location	Bay Span	Rows of Rods	Edge condition
7th	West	Corner (N)	25'-1"	3	Twin Girder
9th	West	Side	20'-4"	2	Twin Girder
25th	East	Side	20'-4"	2	Beam + Girder
28th	East	Corner (N)	25'-1"	3	Beam + Girder
37th	West	Side	20'-4"	2	Single Girder

ANALYSIS

A 3-D model of the 28th floor test area was created in SAP2000 to simulate the behavior of the floor during the load test. The bay is framed by a steel wind girder on the exterior edge, and steel edge beams on north and south sides. The typical floor beams span from north to south and are modeled with pins and rollers to represent their simple span condition without the transmission of residual axial forces. The beams are restrained at the web to represent a riveted connection which ties the beam ends to the girders. As shown in Figure 2, the coordinate is defined such that the x-axis is perpendicular to the steel beams and the y-axis is parallel to the beams. Figure 3 is a diagram of the test bay floor plan.

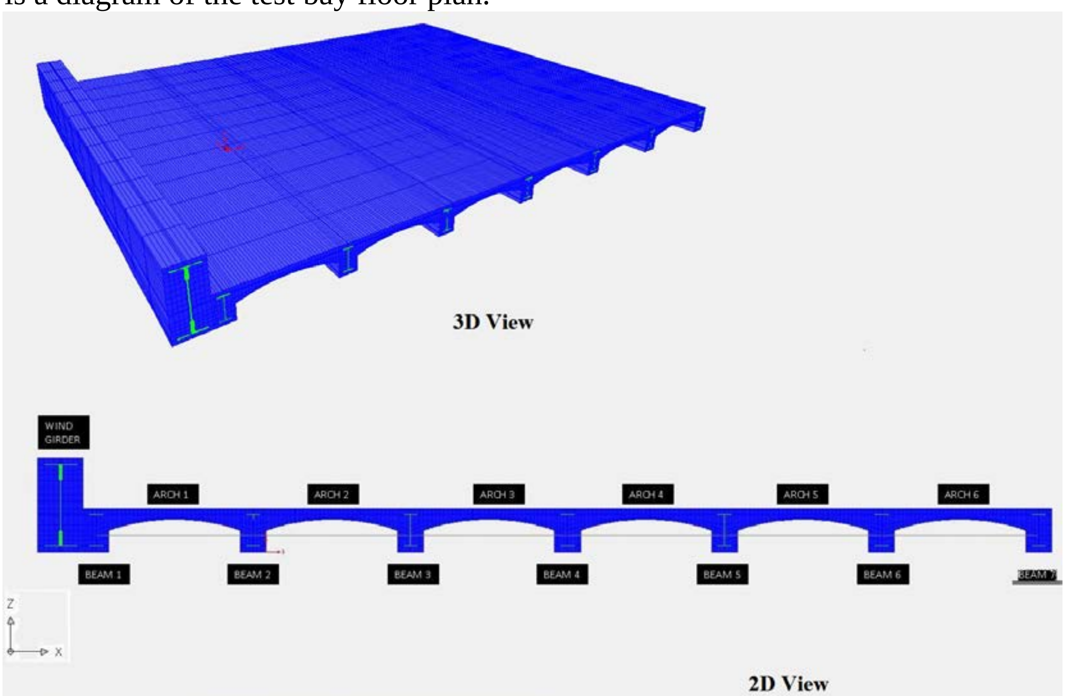

Figure 2: Analysis Model of the 28th floor test area

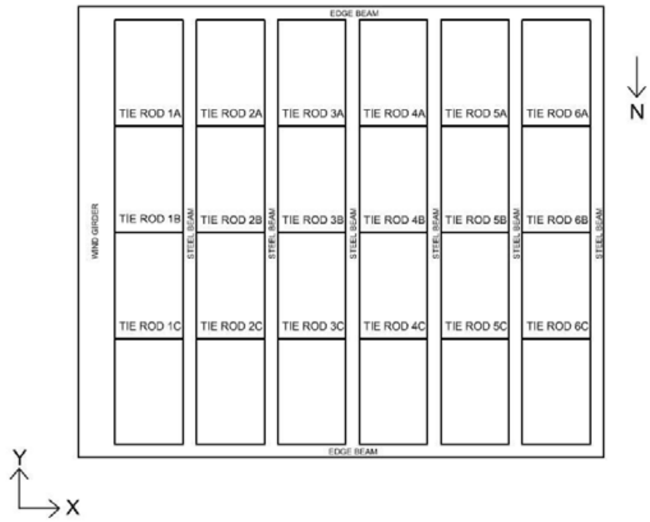

Figure 3: Plan of test bay at the 28th Floor

The cinder concrete arches and steel beams are represented by 3d solid elements. The cross-sectional area of each element is approximately 1.5" by 1.5". The tie-rods are modeled using frame elements and are pinned at both ends. The metal strips and wire mesh on the underside of the arches are modeled as membrane elements. The 2" cement topping is not considered. The mesh sizes were fine-tuned to minimize analysis time while maintaining the accuracy of the results.

The analysis is divided into 3 steps using separate models to represent the different states of the floor system. The results are then superimposed to obtain the final stresses and deflections.

1. Concrete Hardening. This step calculates the stresses in the tie-rods and metal strips induced by the dead weight of the wet concrete. As the concrete is not yet self-supporting, its weight is carried completely by the wire mesh form and the rods. At the end of this step, the concrete is unstressed, the tie rods are in tension, and the metal form, which is in the shape of an arch, is in compression. The tie-rod forces in this stage are tabulated in Table 3.

Table 3: Tie-Rod Forces

Tie Rod	Tension Force (kip)	Tie Rod	Tension Force (kip)	Tie Rod	Tension Force (kip)
1A	1.36	1B	1.77	1C	1.35
2A	1.38	2B	1.91	2C	1.37
3A	.82	3B	1.13	3C	.81
4A	.67	4B	.89	4C	.66
5A	.86	5B	1.12	5C	.85
6A	1.12	6B	1.26	6C	1.11

2. Removal of Tie-rods. This step captures the change in stresses in the floor as a result of removing the tie-rods. First, the tie-rods are removed from the model, and the forces in the rods are added back to the model as point loads. The model is checked to ensure no stress change occurred. The point loads are

then removed from the model. The measured change in stress in the concrete and the steel is less than 0.01 ksi, which is negligible on the overall result.

3. Superimposed Loading. This step simulates the behavior of the floor under stage 1 and 2 load test after the tie-rods are removed. The deflections calculated in this step represent the expected deflections measured during the load test. The stresses from this step, when superimposed with the stresses found in steps 1 and 2, represent the final stresses in the floor. Both linear and nonlinear analyses are performed to account for cracking in the unreinforced cinder concrete. The results are presented below.

Linear analysis. In the linear-elastic model, cracking is modeled by reducing the EI of cinder concrete, incrementally from 100%EI to 20%EI. The deflections obtained are shown in Figure 4. The increase in deflection is not linearly proportional to the reduction of EI, as shown in Figure 5, since the strength of the steel elements are constant.

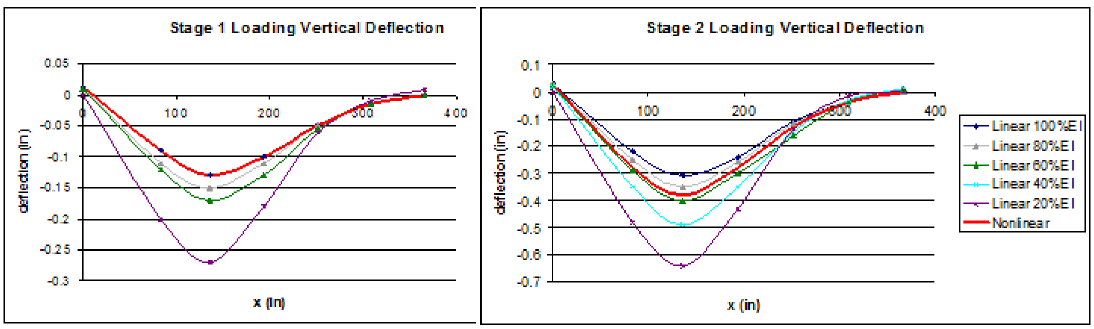

Figure 4: Predicted Deflection under Stage 1 and Stage 2 Loading

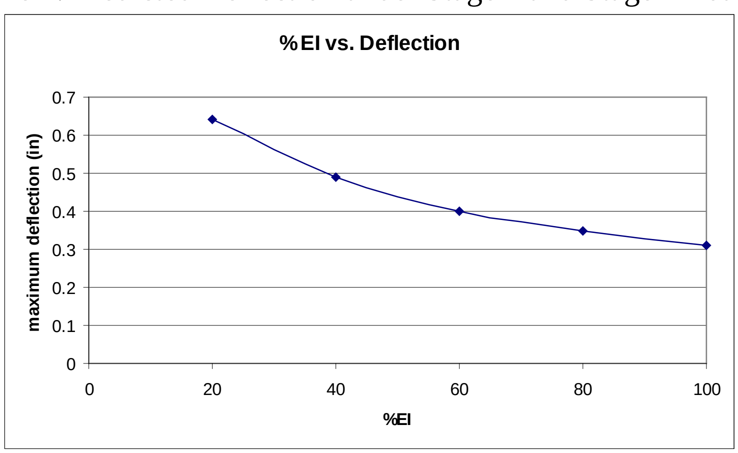

Figure 5: Relationship between Deflection and EI of Cinder Concrete

The lateral displacement of the wind girder is 0.01" under stage loads and 0.03" under stage 2 loads.

Nonlinear analysis. A nonlinear analysis was done to better approximate the effect of cracking. The linear model (with 100% EI) was used as a starting point, and in regions where the concrete stress exceeded the cracking stress of 110 psi, the concrete elements are considered "cracked," and their elastic modulus was reduced to 5% of the uncracked modulus. The analysis was then performed again on the cracked model. The stresses and deflections typically converge after 5 iterations.

Under Stage 1 loading, cracking is observed only at the bottom face of Beam 3 at mid-span, and results from the cracked analysis are within 1% of those from the elastic analysis. (See Figure 1 for the numbering of the beams and arches.) Under Stage 2 loading, cracking is observed at the bottom face of three beams and at the three arches closest to the wind girder. Figure 6 illustrates the degree of cracking observed. The cracked vertical deflection is 123% of the elastic deflection, and the cracked lateral deflection at the wind girder is 133% of the elastic deflection. Interpolating from the linear analysis results, these deflections correspond to using 68% effective EI. The maximum lateral deflection, which occurs at the mid-span of the wind girder, is 0.01” under Stage 1 loads and 0.04” under Stage 2 loads. Figures 7 and 8 show the deflections under stage 2 loads.

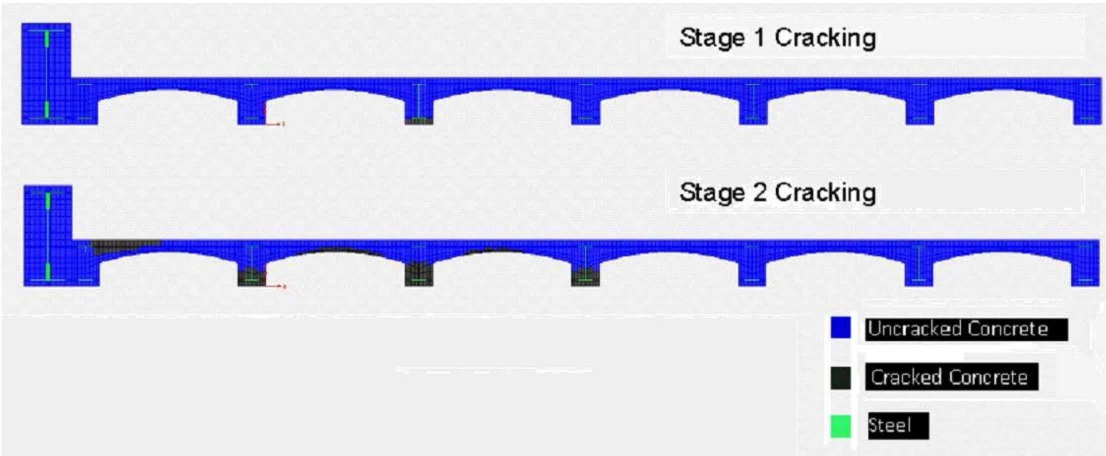

Figure 6: Cracking Observed at Stage 1 and Stage 2

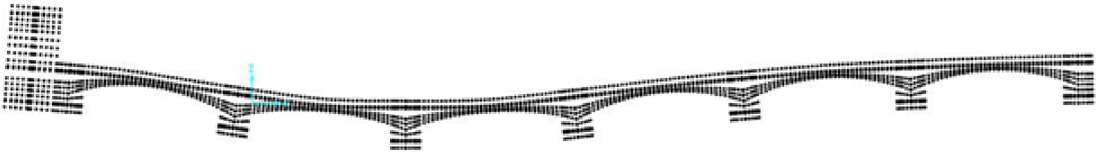

Figure 7: Deflected Shape in X-direction at Stage 2, magnified 50x for illustration

Figure 8: Deflected Shape in Y-direction at Stage 2, magnified 50x for illustration

The deflected shape shows that the floor system is acting with two way action, similar to the behavior as a two-way slab. The moment is largest at the mid-span of Beam 3, which is where the first crack occurs. Under both loading conditions, the concrete does not fail in compression and the steel stresses are always below the maximum allowable stress. The maximum stresses are tabulated in Table 4.

Table 4: Maximum stress in structural elements under stage 1 and stage 2 loads

Member	Max. Stress under Stage 1 Loading		Max. Stress under Stage 2 Loading	
	Tension	Compression	Tension	Compression
Concrete	0.11 ksi	-0.12 ksi	0.11 ksi	-0.35 ksi
Steel Beam	8.1 ksi	-4.4 ksi	14 ksi	-7.0 ksi
Wind Girder	2.4 ksi	-2.8 ksi	3.6 ksi	-3.6 ksi
Metal Strip	4.6 ksi	-3.9 ksi	12 ksi	-7.0 ksi

To assess the difference in behavior with and without tie rods, the behavior of the floor with tie rods was also analyzed. The difference in maximum deflections, both vertical and lateral, is within 5% of each other for both Stage 1 and 2 loads, which shows that removing the tie rods will not significantly change the behavior of the floor slab. Under Stage 1 loading, the maximum tension in the tie rod is 3.7 kips. Under Stage 2, the maximum tension is 7.3 kips.

LOAD TEST PROCEDURES

The test areas were prepared by installing shoring frames underneath test areas and screw jacks under the floor below to engage an additional floor level in case of any serious structural distress. Dial gages with a precision of .001" were installed to measure the horizontal and vertical displacements of the floor under the loaded condition. The gages were placed to measure the vertical deflection of the floor at mid-span of the beams and arches and the horizontal deflection at each of the tie rod locations.

Gages and rods were epoxied to the underside the concrete encasement. After the gages were installed and zeroed, the tension rods were loosened by pulling the beam flanges until the rod is slack. The transferred tension could be measured in a dynamometer attached to the pulling rig. Once the rod was slack, the nuts at the end of the rods were loosened to allow a deflection of at least a half inch. This would allow the beams and the floors deflect without the influence of the rod up to a certain limit. If this limit was exceeded, the rod would engage to prevent excessive deflections.

The loading was applied using an equivalent weight in concrete masonry units. The CMU was placed in layers on the floor area with the stage 1 loading applied in two layers of CMU and the stage 2 loading applied in up to 4 layers. The weight of the masonry was first determined using information from the material supplier, and we verified the weight by field sampling the units that were delivered. The verified weight was used to determine the number of layers of masonry to be placed. Each layer of masonry was a uniform loading of 48 lbs per square foot. The last layer of masonry was a partial layer to match the target weight as close as possible. With the unloaded condition set to zero, measurements were taken at the addition of each layer of CMU. The repeated measurement allowed us to monitor the floor as it was progressively loaded and to ensure that the floor was deflecting in a stable manner and within the specified limits.

LOAD TEST DATA SUMMARY

The floor system was able to support the stage one and stage two loadings without the tie rods in all five of the tested areas. The maximum measured deflections are shown in Tables 5 through 10.

Table 5: Maximum vertical deflections observed during Stage 1 Load Test

Floor	Deflection	Span to deflection ratio	Maximum Allowable deflection (L/360)	Results
7th	.082”	L/3600	.825”	Pass
9th	.066”	L/3700	.678”	Pass
25th	.054”	L/4500	.678”	Pass
28th	.110”	L/2700	.825”	Pass
37th	.067”	L/3600	.678”	Pass

Table 6: Maximum lateral deflections observed during Stage 1 Load Test

Floor	Deflection	Span to deflection ratio	Maximum Allowable deflection
7th	.025”	L/11900	.3”
9th	.014”	L/17400	.3”
25th	.023”	L/10600	.3”
28th	.050”	L/5900	.3”
37th	.014’	L/17400	.3”

Table 7: Maximum vertical deflections observed during Stage 2 Load Test

Floor	Deflection	Span to deflection ratio
7th	.174”	L/1700
9th	.116”	L/2100
25th	.114”	L/2100
28th	.190”	L/1600
37th	.116”	L/2100

Table 8: Maximum lateral deflections observed during Stage 2 Load Test

Floor	Deflection	Span to deflection ratio	Maximum Allowable deflection
7th	.041”	L/7200	.3”
9th	.034”	L/7200	.3”
25th	.039”	L/6300	.3”
28th	.067”	L/4400	.3”
37th	.024”	L/8400	.3”

Table 9: Maximum vertical deflections observed after removal of the load

Floor	Set	Calculated elastic deflection	Max. Allow Set.	
7th	.010”	.902”	.226”	Pass
9th	.019”	.512”	.128”	Pass
25th	.021”	.512”	.128”	Pass
28th	.009”	.902	.226”	Pass
37th	.011”	.512”	.128”	Pass

Table 10: Maximum lateral deflections observed after removal of the load

Floor	Set	Elastic deflection	Max. Set.	
7th	.014”	.495”	.124”	Pass
9th	.009”	.407”	.102”	Pass
25th	.021”	.407”	.102”	Pass
28th	.020”	.495”	.124”	Pass
37th	.011”	.402”	.102”	Pass

It should be noted that the maximum deflection of approximately 1/50” is negligible relative to the span.

No signs of severe distress were observed in the floor system after load removal. The load test showed that the requirements set by the New York City Building Code were met.

COMPARISON OF ANALYSIS PREDICATION AND LOAD TEST RESULTS

The floor deflections were less than those predicted by the analysis in the vertical direction. At stage 1, the load test vertical deflection is approximately 85% of the deflection predicted by the analysis model, and at stage 2, the deflection is roughly 50% of the deflection predicated by analysis. The load test results suggested that an additional effect is at work to increase the stiffness of the floor. In the finite element analysis, we noted that the floor system is showing stress both in the direction of the arch span and in the direction parallel to the arches, which suggested that the floor system is acting as a two way slab instead of a one-way arch system. It is also possible that the cement finish on the floor may have some bond with the underlying concrete, and thus contributed to the stiffness of the floor. However, the exact contribution cannot be quantified as the topping slab was most likely poured after the concrete is set, and the bond strength between the topping and the structural slab is not known. The topping slab was not considered in the of the computer analysis.

The lateral deflections observed in the load test were larger than those predicted by the analysis model. However, both the predicted and the observed deflections were insignificant compared to the allowable deflections and the span.

CONCLUSION

The finite element models showed that the behavior of the floor slab is similar regardless of the presence of the tie rods. The load tests showed that without the tie rods, the floor system was able to meet the strength and deflection requirements of the New York City Building Code. The lateral movement of the slab was monitored during the load test to ensure that the façade would not be damaged due to the lateral movement after the tie rods were removed, and the movement was found to be minimal. Based on these results, we concluded that the ties rods were required only during construction to support the wet concrete, and that it was acceptable to remove the rods after the concrete has set.

REFERENCES

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Sierra Bonita: Innovative Use of Long Span Metal Deck Slabs and Shored Construction

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INTRODUCTION

Sierra Bonita is a mixed use building providing affordable housing for people living with disabilities. The five story building is located in West Hollywood, CA and was completed in 2010. A 6 inch reinforced metal deck slab system spans 20 feet between supporting steel framing. The supporting framing consists of 43 foot long beams and 60 foot long girders supported by columns at the building perimeter and at the four corners of the central building atrium.

Occupant induced floor vibrations as well as service and creep deflections were taken into account in the design process. Finite element modeling using SAP2000 was used to predict the response of the structure from walking induced vibrations. Testing was later performed during construction in conjunction with The Pennsylvania State University to confirm the acceptability of the structural response. Service and creep deflections were mitigated using slab reinforcement, camber, wood joist shores and loose steel shores. This paper presents our approach to the design of this system, including modeling techniques; use of construction sequencing and shoring; and a comparison of in service vs. design results.

STRUCTURAL SYSTEM SELECTION

In pursuit of the project goals, a structural system with a shallow floor depth and a minimal wall thickness or column size would be required. The system would also need to accommodate the retail and parking occupancies on the lower level. In residential buildings, these goals are typically achieved with a concrete flat plate. A flat plate system, however, would likely have required a transfer level at the second floor and the additional weight would also increase the seismic base shear of the building and thus the cost.

In California, low rise residential buildings typically consist of wood framing supported by bearing walls. While this system provides a fairly shallow floor depth at low cost and weight, it would also require a transfer podium structure to accommodate the lower level occupancy. A hybrid steel frame/wood joist solution combined the benefits of the wood bearing wall system with the flexibility of a steel system. This system, however, provided a modest 7’-8” ceiling height and would not have ideal fire performance characteristics.

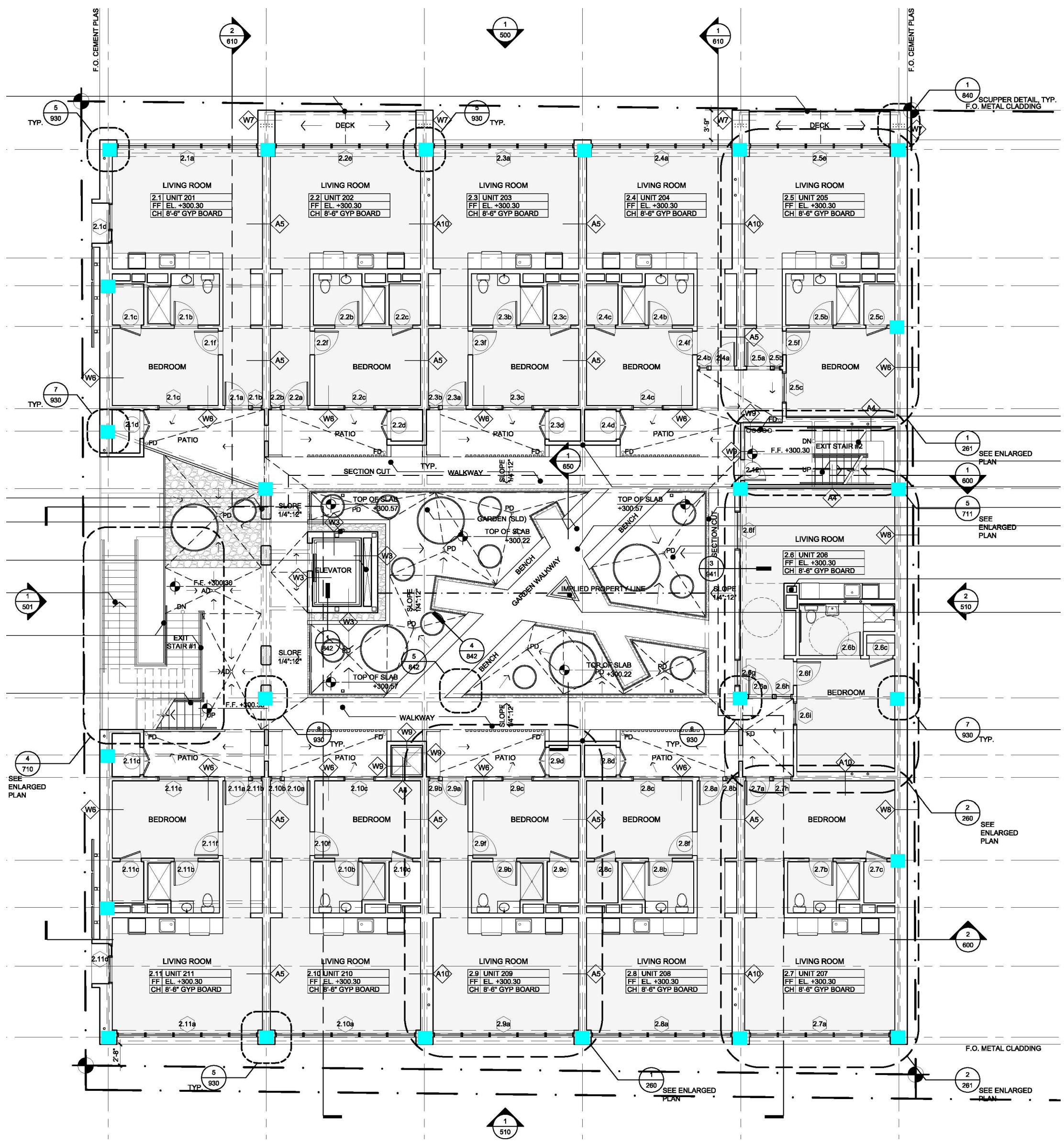

Figure 1
Typical Residential Floor Layout

An ideal solution, combing the flexibility and light weight of steel framing with the shallow floor depth of a concrete flat plate was decided upon. Steel beams were located in line with the demising partitions between adjacent apartments. The beams span between the building perimeter and the girders around the central atrium. Four corner columns define the central atrium space resulting in a structural system with 20 foot slab spans, 43 foot beam spans and 60 foot girder spans. This system required particularly special attention to deflection and vibration performance.

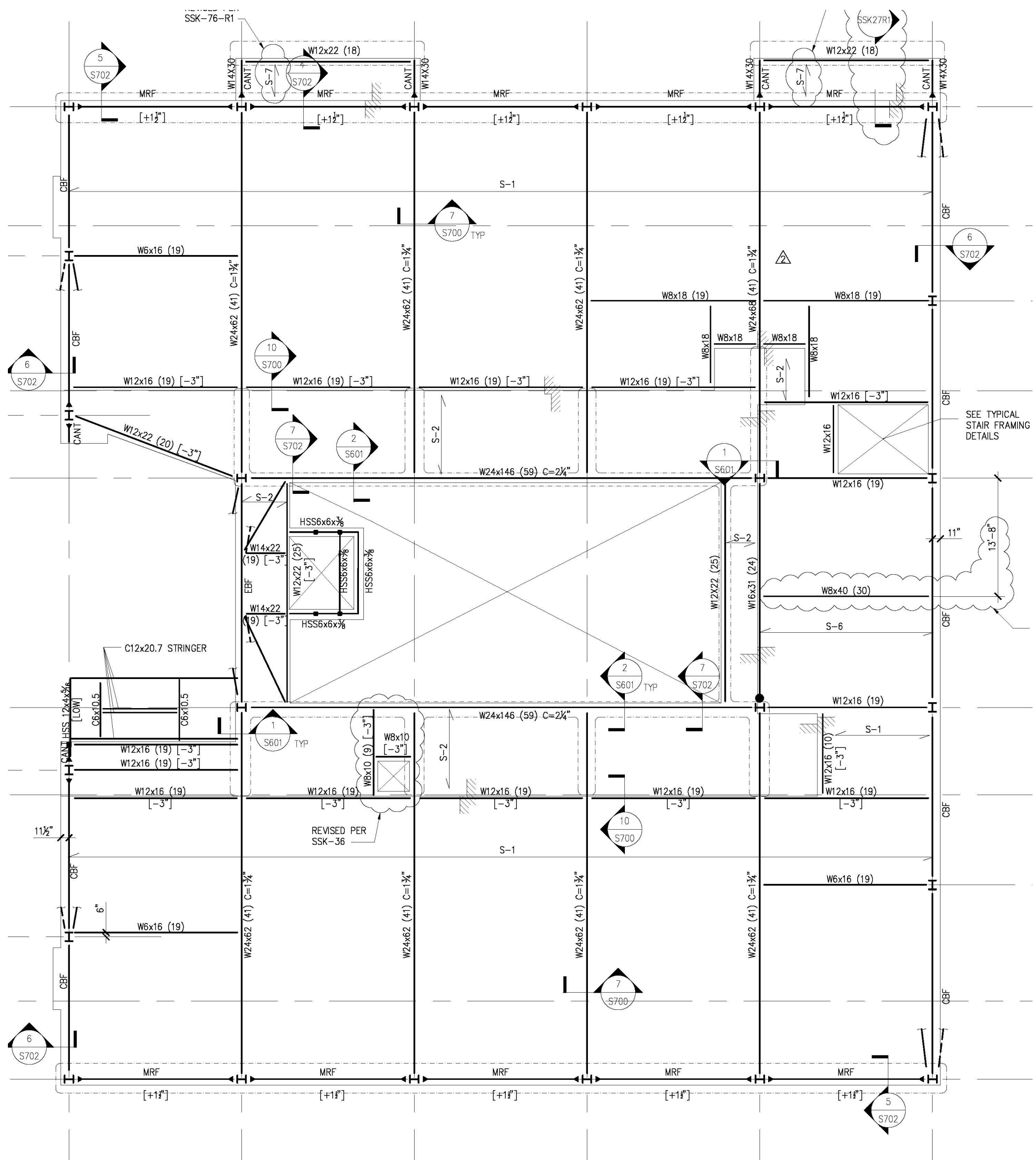

Figure 2
Typical Residential Floor Structural Framing Plan

LONG SPAN SLABS

As a result of the apartment layout, the typical one way slab span of the structure is 20 feet. This is beyond the limits in use for conventional metal deck slabs and required a different design approach. Following ACI 318 guidelines would have required a maximum slab thickness of 10". In previous projects it was found that the performance of reinforced metal deck slabs outperformed this empirical guide line. Performance of metal deck slabs were found to be satisfactory up to a span to depth ratio of L/43. Building on this experience, we selected a span ratio of L/40 for the Sierra Bonita Project.

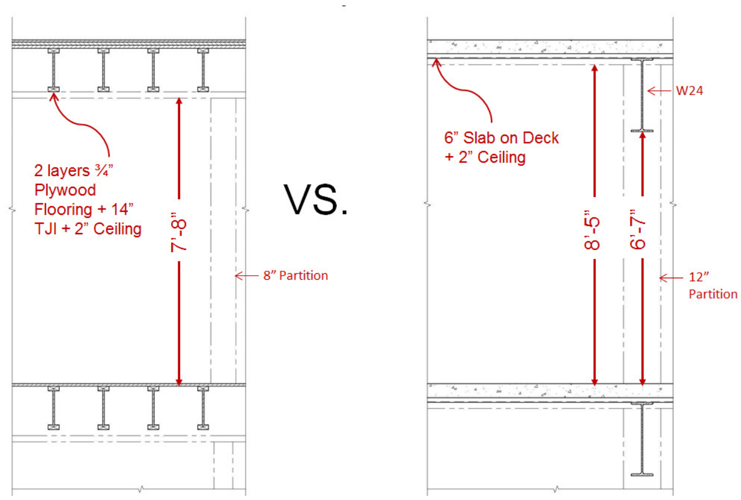

Figure 3
Comparison of Steel/Wood Hybrid System vs. Long Span Slab System

To determine the deflection characteristics of the slab, two methods were used. Initial hand calculations were performed using the effective moment of inertia method in ACI 318. Long term creep deflections were accounted for with a standard multiplier of 2 on the long term dead load. Modulus of rupture of the concrete was assumed to be $7.5\sqrt{(f'c)}$. Using this method, long term dead load deflection plus live load deflection was found to be L/339 and total deflection including long term dead load deflection was found to be L/226. Although these results exceed the recommended deflection limitation of L/360 and L/240, the findings were preliminary and were used for input into a more accurate finite element model that would include the contribution of the framing members and steel reinforcement.

Following the completion of the hand calculations, a SAFE finite element model was constructed that would accurately capture the stiffness contribution of the other structural elements. Several iterations were performed, adjusting the top and bottom steel and concrete strength until the predicted total deflections were within the long term live and total load deflection limits of L/360 and L/240 respectively. The contribution of the metal deck was modeled as an equivalent layer of reinforcing steel at the mid depth of the metal deck.

Once deflections were found to be in accordance with the above limitations the slab reinforcing was checked for strength. Using 6000psi concrete, the 1 ½" 20 gauge metal deck was found to have sufficient strength to function as the bottom reinforcement of the slab. A nominal amount of top reinforcing consisting of #5@12" was required for the negative moment over the beams. End spans required additional reinforcing of #6@6". Because UL fire tests only cover metal deck spans up to 17 feet, bottom reinforcement was added to supplement the metal deck.

SHORING AND ADDITIONAL DEFLECTION CONSIDERATIONS

Typically, concrete flat plate construction requires significant amounts of form work and shoring. Additional time and man power is also required to strip form work and re-shore the slabs as work progresses up the building. In lieu of continuous vertical shoring, a method of "self-shoring" and loose shores provided a procedure that would minimize the deflection of the slab under the wet weight of concrete, increase the levelness of the slab pour and maintain a constant thickness of concrete in the slab. By eliminating the majority of posts and/or screw jacks, work men were able to proceed with further trades on the floor immediately below a concrete pour.

Shoring of the slab consisted of two layers of wood framing spanning between the bottom flanges of the beams. Shims of varying thickness were installed between the top layer of framing and the metal deck to provide a slight slab camber. The bottom layer of framing consisted of off the shelf LVL lumber. Loose Shores at beams and girders were also used in combination with camber to control the deflection of the framing. The gap between the shore and the framing member was set equivalent to the non-composite deflection from the weight of the wet concrete. This allowed the contractor to achieve a level floor with minimal post-composite dead load deflections.

Figure 4: Self Shoring System In Place

VIBRATION DESIGN AND FIELD RESULTS

Due to the long span of the beams, girders and slabs, vibration response of the structure was an important consideration. To determine the vibration response of the structure two methods were used. The first method follows the recommendations in

AISC Design Guide 11 Chapter 4 and the second method estimates the vibration response using a finite element model.

Design Guide 11 estimates the natural frequency and peak acceleration of the floor system by combining a weighted average response of the different "panel" modes of a structure. Typically, the participating panels used in this analysis are

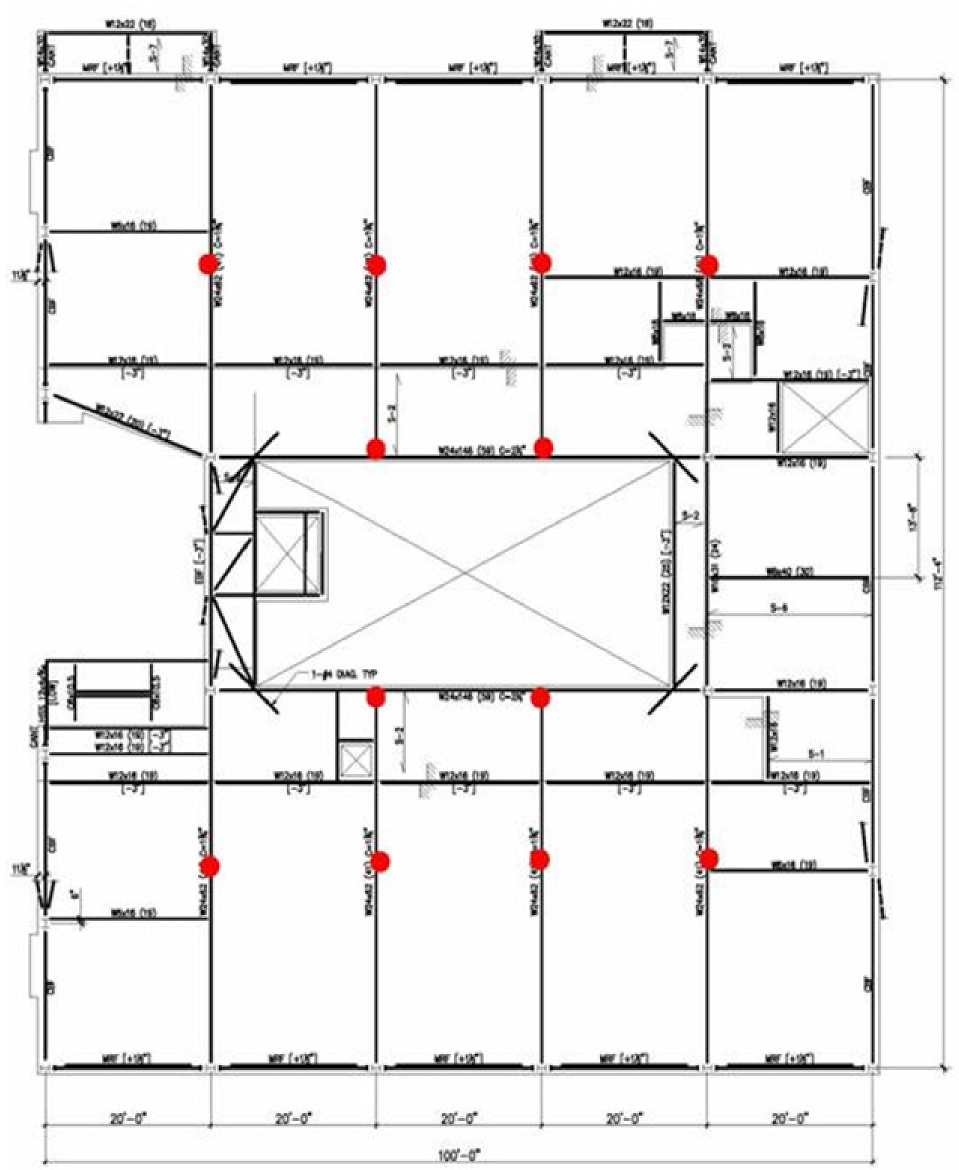

Figure 5: Loose Shore Locations

limited to the beams and girders. In this case, however, due to the long span of the slab, the contribution of the slab panel mode to the overall system response was included. The slab mode is calculated in the same manner as the joist panel mode presented in design guide 11. The results indicated a fairly low frequency for the typical floor at approximately 2.5Hz. A low frequency response was anticipated due to the long spans of the structural system. The acceleration response was within the maximum recommended acceleration limit of 0.5%g for residential occupancy. It was 0.43%g.

Finite element modeling using SAP was also conducted to verify the results derived from DG 11 hand calculations. The typical floor plate of the entire building with columns was modeled in SAP. Slab stiffness parameters were modified to reflect the stiffness contributions of the steel reinforcing and cracked concrete. To determine the floor vibration response, a forcing function for a single 160 pound person was used. A forcing function with 15 foot fall pulses was used to approximate the input of a person walking across the length of the apartment. For simplicity, the input force was located in the middle of the typical apartment in the middle of the framing bay. This would be the most flexible area of the floor plate. A time history analysis was conducted on all force inputs and the acceleration response spectrums were plotted. The resulting peak acceleration of the time history analysis was 0.34%g with 5% damping. This was deemed to be an acceptable level of vibration response and was within the ISO curve in Design Guide 11. Additional areas were analyzed in a similar manner to confirm these results.

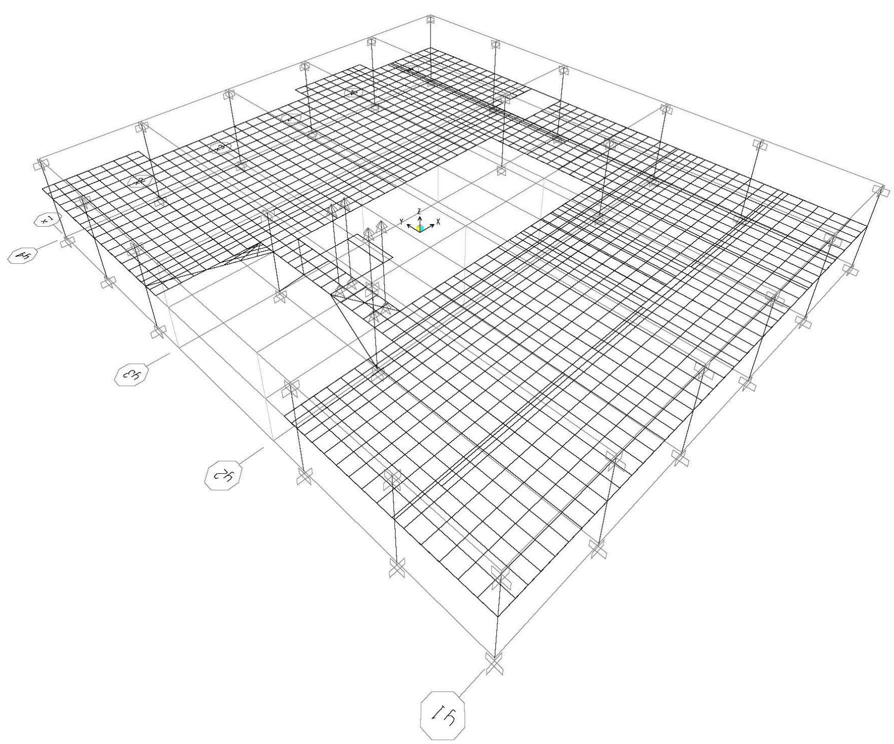

Figure 6
SAP Finite Element Model

During construction, in conjunction with The Pennsylvania State University, we visited the site to conduct vibration testing of the in place floor system. Testing was conducted at an end bay and an interior bay as well as on different floors within the building. An array of accelerometers was located within the framing bay being tested and heel-drop and walking tests were performed. The field measurements indicated a floor system that would not be expected to have objectionable levels of floor vibration due to walking. The damping affect of the partition walls were found to be larger than what was used for the finite element model. The findings of this testing is being presented in a separate paper.

CONCLUSIONS

Residential construction requires that special attention be paid to deflection and the vibration response of structures. For this building an innovative structural system consisting of long span reinforced concrete slabs and beams was used. Occupant induced floor vibrations as well as service and creep deflections were taken into account in the design process. Finite element modeling using SAP and SAFE was used to predict the response of the structure from walking induced vibrations and long term deflections. Testing was later performed during construction in conjunction with Penn State to confirm the acceptability of the structural vibration response. Service and creep deflections were found to be acceptable, because of the added stiffness contribution of the reinforcing steel. A combination of camber, wood joist “self” shores and loose steel shores to achieve a level finished floor with minimal post composite dead load deflection.

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MoneyHousing

Sam Rashkin

1st Residential Building Design and Construction Conference

February 20, 2013

Retooling THE U.S. Housing Industry

MoneyHousing

Story

- Star Players Lost
- The Right Question
- Innovation Challenge
- Innovation Opportunity
- Innovation Business Case
- Innovation Application
- Innovation Example: Quality Construction
- Innovation Benchmarking

Retooling THE U.S. Housing Industry

Star Players Lost

Retooling THE U.S. Housing Industry

Star Players Lost

Background

1997: The Warning Shot No One Heard

2007: History Repeats Itself

Result: A Housing Crisis of Historical Proportions

Retooling THE U.S. Housing Industry

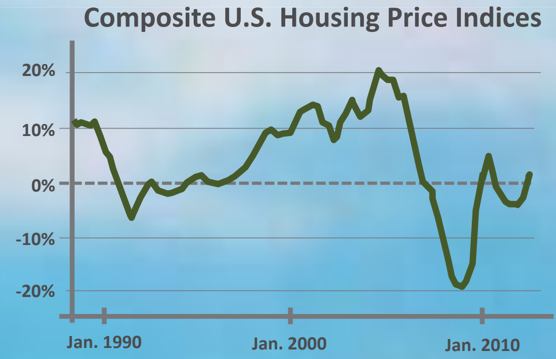
Star Players Lost

Smaller Universe of Homebuyers

Retooling THE U.S. Housing Industry

Star Players Lost

Home Ownership Less Compelling



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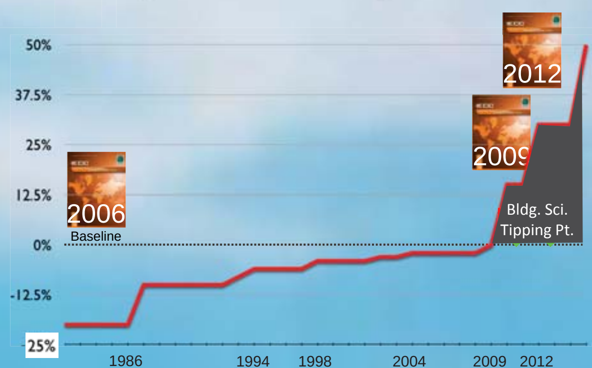
Star Players Lost

Can't Compete on Price

Retooling THE U.S. Housing Industry

Star Players Lost

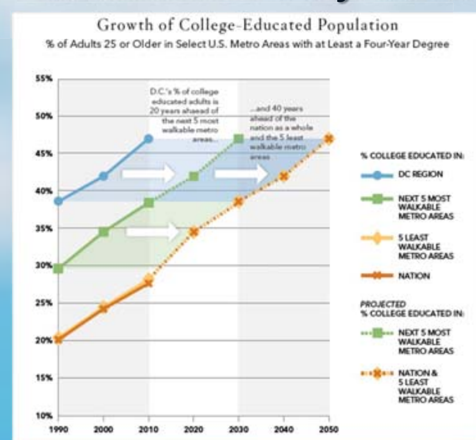
High-Performance Left the Station



Retooling THE U.S. Housing Industry

Star Players Lost

Urban Center Preference



Retooling THE U.S. Housing Industry

Star Players Lost

The New Reality

Smaller Universe of Buyers
Home Ownership Less Compelling
Can't Compete on Price
High-Performance Has Left the Station
Right-Sized, Urban Center Preference

Retooling THE U.S. Housing Industry

Star Players Lost

Result: Housing Lost Star Players

- Price Competitiveness
- Size Advantage
- Assured Appreciation
- Minimum Code is Good Enough
- Remote Location Acceptance

Retooling THE U.S. Housing Industry

The Right Question

Retooling THE U.S. Housing Industry

'Wrong' Question:

How to Minimize Cost?

NAHB estimates for every **$1,000 increase** in sales price, nearly **250,000 households** fail to qualify for a mortgage on a typical new home.

[http://www.nahb.org/fileUpload_details.aspx?contentTypeID=3&contentID=40372&subContentID=112293]

Retooling THE U.S. Housing Industry

'Right' Question:

How can Proven Innovations be Leveraged to Maximize Value?

so homebuyers are compelled to want new housing again.

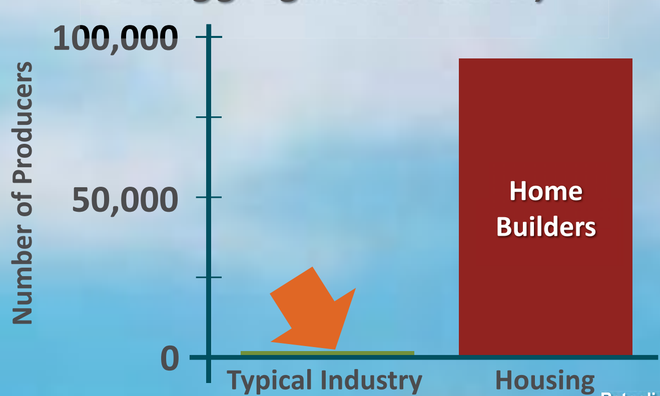
Retooling THE U.S. Housing Industry

Innovation Challenge

Retooling THE U.S. Housing Industry

Innovation Challenge

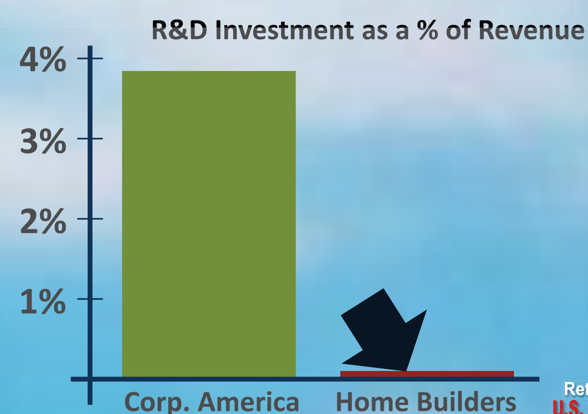
Disaggregated Industry



Retooling THE U.S. Housing Industry

Innovation Challenge

Lack of Investment in Innovation



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Innovation Opportunity

Retooling THE U.S. Housing Industry

Question:

What Innovations?

Retooling THE U.S. Housing Industry

"We build products people never knew they wanted, but have to have once they try them."

Tim Cook, Apple CEO

Retooling THE U.S. Housing Industry

Question:
What innovations?

Answer Part 1:
Innovations homebuyers have to have once they try them?

Retooling THE U.S. Housing Industry

New Homes Competition

- 4/5 Existing Home Sales Prior to Soft Market
- 12/13 Existing Home Sales in Soft Market

95%+ of Competition Existing Homes

Retooling THE U.S. Housing Industry

Question:
What Innovations?

Answer Part 2:
Innovations that make existing home competition obsolete.

Retooling THE U.S. Housing Industry

"If I had asked my customers what they wanted, they would have said a faster horse."

Quote attributed to Henry Ford on the first car he ever built

Retooling THE U.S. Housing Industry

Innovation Question:
What innovations?

Answer:
Innovations homebuyers have to have once they try them?

Tip:

Don't look to customers for innovation opportunities.

Retooling THE U.S. Housing Industry

Innovation Opportunity Example:

Clutter-Free System in My Car

- CDs
- Change
- Maps
- Owners Manual
- Pens
- Sun Glasses
- Drink Cops
- Tools
- Garage Door Opener
- Tissues
- Clothes (hooks)
- Arm Rests (front/rear)
- Long Items (e.g. skis)
- Dry Cleaning
- Safety Kit
- Spare Fuses
- Spare Key
- Spare Tire

Retooling THE U.S. Housing Industry

Innovation Opportunity Example:

Clutter-Free System Not in My Home

- Reasonable Amt. Shoes
- Reasonable Amt. Clothes
- Ironing Board
- Vacuum Cleaner
- Brooms/Dust Pans
- Umbrellas
- Keys
- Owners Manuals
- Important Papers
- Mail/Bills
- Gift Wrap/Supplies
- Cleaning Supplies
- Winter Blankets
- Winter Clothes
- Shoes
- Belts/Ties
- Handbags
- Books
- Tools
- Entertainment Stuff
- Office Stuff
- Garage stuff

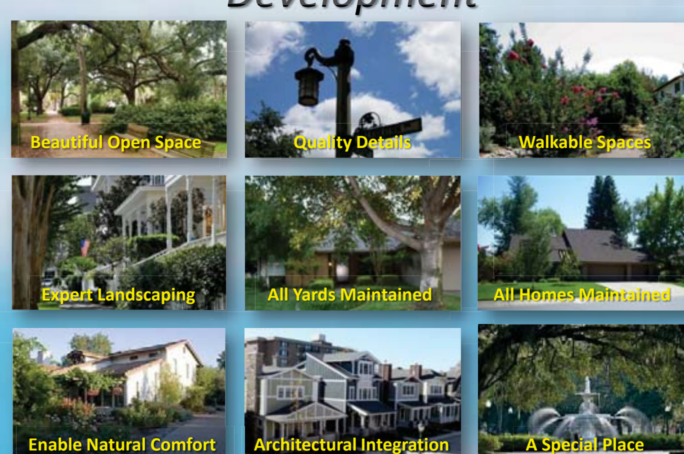
Retooling THE U.S. Housing Industry

Innovation Home
Tour

Retooling THE U.S. Housing Industry

Innovation Home Tour:

Development



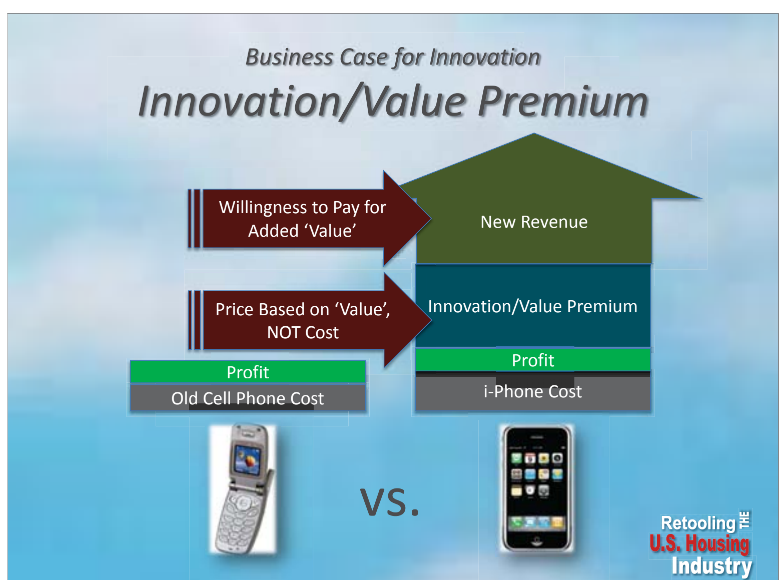

Innovation Home Tour:
Design
Natural Comfort
Floor Plan for Living
Open Layouts
Sense of Community
Exterior Spaces
No Clutter System
Rich Trim/Color
Lighting Design
Quality vs. Size

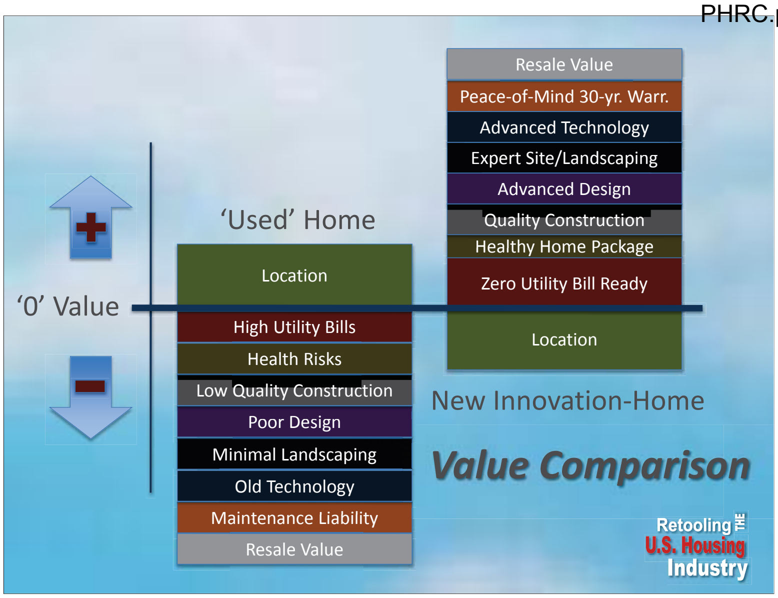

Innovation Home Tour:
High-Performance
The Future
NEXT EXIT
Forward-Looking
Ultra Low/No Utility Bills
Luxurious Comfort
Assured Fresh Air
USDA ORGANIC
Chemical-Free Materials
No Moisture Problems
Minimal Pests/Dust
Disaster Resistance
Enduring Value

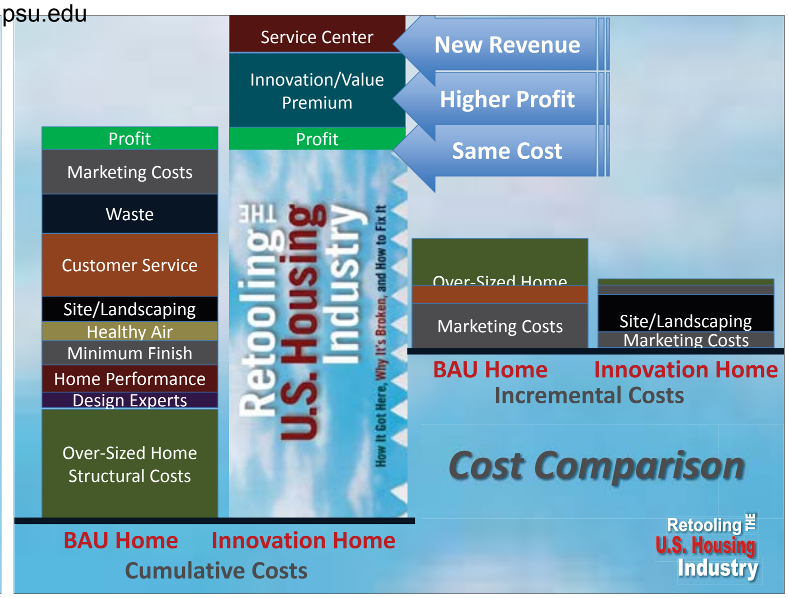

Innovation Home Tour:
Quality Construction
Minimal Defects
Minimal Waste
Instant Hot Water
Lower Level vs. Basement
Advanced Walls
Advanced HVAC
Home Automation
Quality Components
Quality Finishes


Innovation Home Tour:
Buying Experience
Meaningful Brand
Expert Sales Agents
Learning Experience
Value Demonstrations
Compare and Contrast
Third-Party Labels
PITI&E&M
Ownership Cost vs. Price
WARRANTY
30-Year Warranty
Builder Service Center

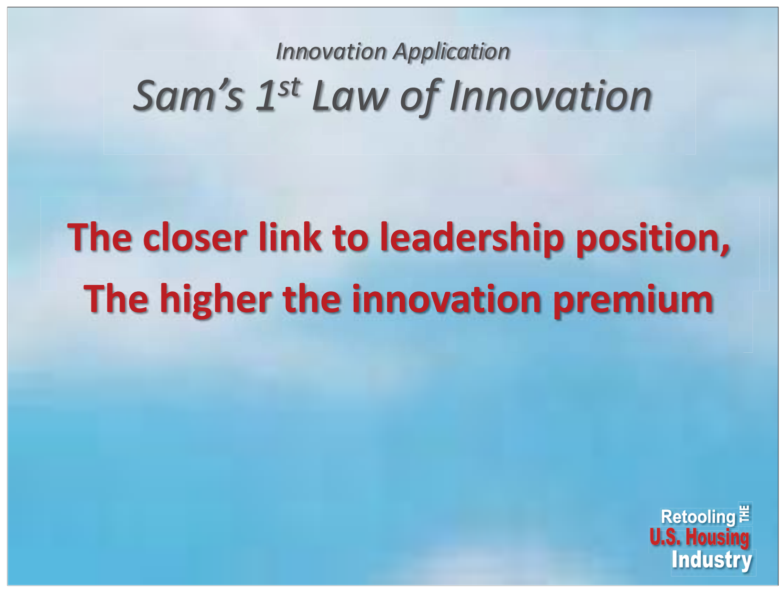

Innovation
Business Case
Retooling THE
U.S. Housing
Industry


Business Case for Innovation
Innovation/Value Premium
Willingness to Pay for Added 'Value'
New Revenue
Price Based on 'Value', NOT Cost
Innovation/Value Premium
Profit
Old Cell Phone Cost
Profit
i-Phone Cost
VS.
Retooling THE
U.S. Housing
Industry


Value Comparison
'0' Value
'Used' Home
Location
High Utility Bills
Health Risks
Low Quality Construction
Poor Design
Minimal Landscaping
Old Technology
Maintenance Liability
Resale Value
New Innovation-Home
Resale Value
Peace-of-Mind 30-yr. Warr.
Advanced Technology
Expert Site/Landscaping
Advanced Design
Quality Construction
Healthy Home Package
Zero Utility Bill Ready
Location
Retooling THE U.S. Housing Industry


Cost Comparison
Profit
Marketing Costs
Waste
Customer Service
Site/Landscaping
Healthy Air
Minimum Finish
Home Performance
Design Experts
Over-Sized Home Structural Costs
Service Center
Innovation/Value Premium
Profit
New Revenue
Higher Profit
Same Cost
BAU Home
Innovation Home
Cumulative Costs
Over-Sized Home
Marketing Costs
Site/Landscaping
Marketing Costs
BAU Home
Innovation Home
Incremental Costs
Retooling THE U.S. Housing Industry


Innovation Application
Retooling THE U.S. Housing Industry


Innovation Application
Sam's 1st Law of Innovation
The closer link to leadership position,
The higher the innovation premium
Retooling THE U.S. Housing Industry


Innovation Application
Sam's 1st Law of Innovation
Retooling THE U.S. Housing Industry


Innovation Application
Sam's 2nd Law of Innovation
Innovation can't look the same
as standard options.
Retooling THE U.S. Housing Industry

Innovation Application

Sam's 2nd Law of Innovation


2001 Toyota Corolla


2001 Toyota Prius

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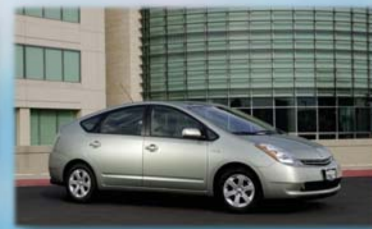
Innovation Application

Sam's 2nd Law of Innovation


2005 Toyota Corolla


2005 Toyota Prius

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Innovation Application

Sam's 3rd Law of Innovation

Investment in innovation is wasted if you don't evaluate business metrics.

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Innovation Application

Sam's 3rd Law of Innovation

Sample Business Metrics:

- True Credit/Debit Construction Costs
- Homebuyer Visits
- Time of Sale
- Profit Margins
- Call-Back Expenses
- Marketing Exposure
- Customer Satisfaction
- Referrals
- Actual Billing Data

Retooling THE U.S. Housing Industry

Innovation Application

Housing Industry Components

Housing Industry: Key Components

- Land Development — Chapter 2
- Housing Design — Chapter 3
- Home Performance — Chapter 4
- Home Construction — Chapter 5
- Home Sales — Chapter 6

Retooling THE U.S. Housing Industry

Innovation Application

The Learning Moment

Observation: All Components Off Target

Retooling THE U.S. Housing Industry

Innovation Application

Chapter Format

- Process, **Goals**, and How Goals Achieved
- What is the Component
- How Component Got Here
- Why Component is Broken
- How to Fix Component
- ‘What is the Story’ Summary

Innovation Example: Advanced Technologies

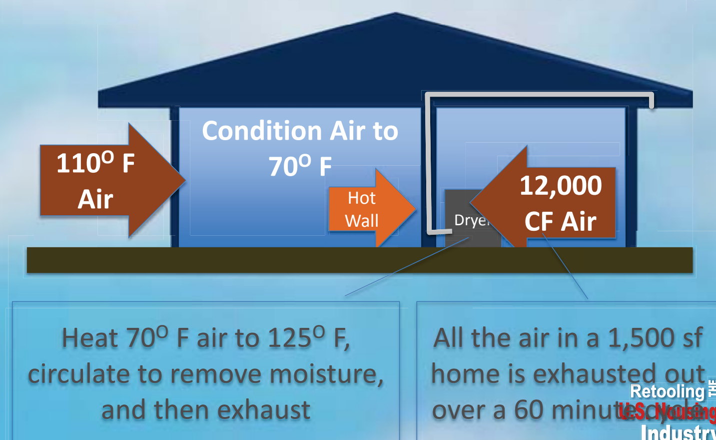
Innovation Example: Advanced Technologies

Advanced Technologies Underutilized

- Foundations
- Framing
- Insulation
- Windows
- Space Conditioning
- Materials
- Plumbing
- Electricity

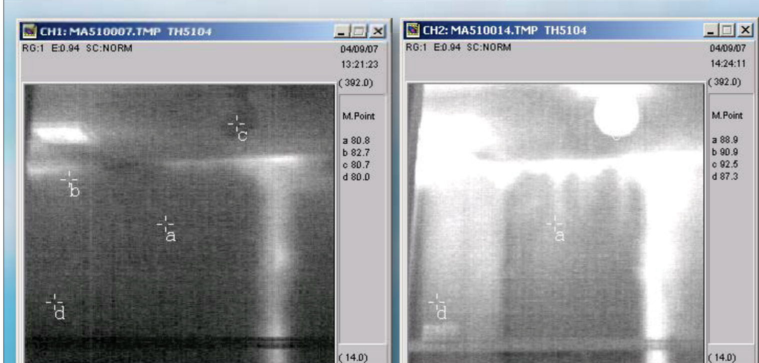
Innovation Example: Advanced Technologies

Conventional Clothes Dryer Inefficiency



Innovation Example: Advanced Technologies

Conventional Clothes Dryer Hot Wall

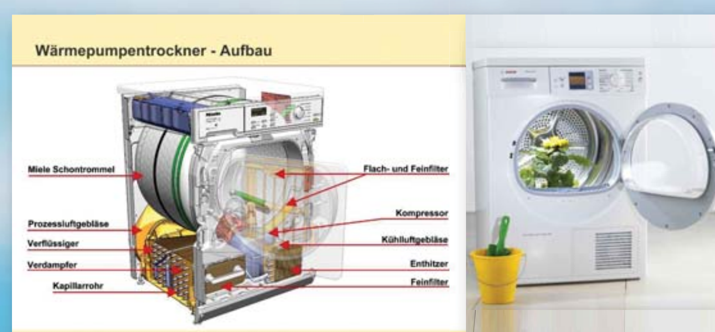


Dryer Not Operating

After 40 Minutes Dryer Operation

Innovation Example: Advanced Technologies

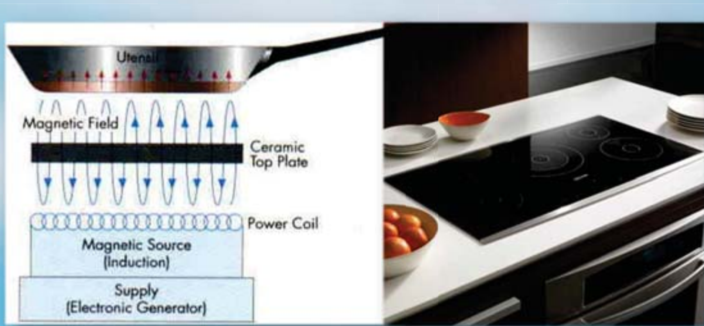
Heat Pump Clothes Dryers



4.5 vs. 12,000 CF Air
Plus No Exhaust Vent

Innovation Example: Advanced Technologies

Induction Cooktop



Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

Precast Concrete Foundations

Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

Fabric Filter Wrapped Drainage

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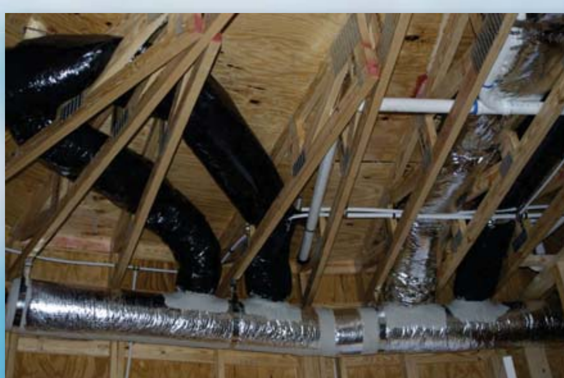
Innovation Example: Advanced Technologies

Liquid Membrane Weather Barrier

Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

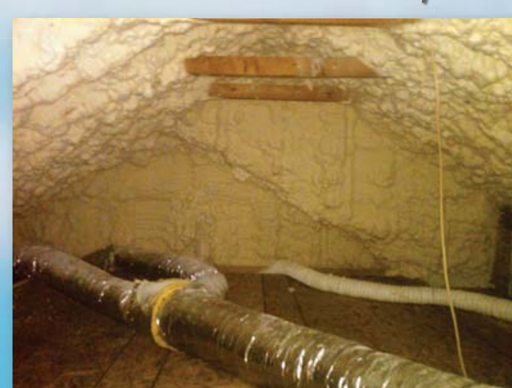
Ducts in Unconditioned Attic Problem



Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

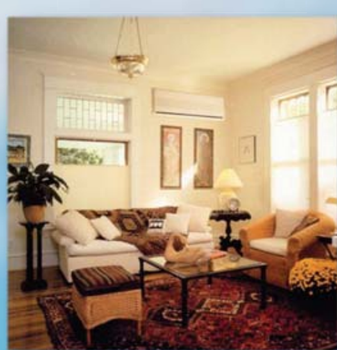
Ducts in Conditioned Space



Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

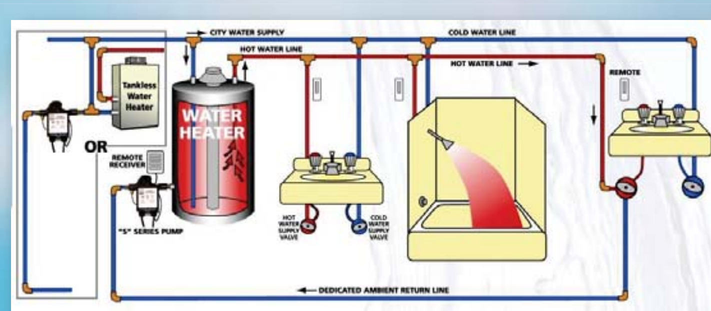
Ductless Mini-Split Heat Pump



Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

Structured Plumbing



Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

Simple Thru-Wall Ventilation

- Virtually Silent
- 90+% Eff. Heat Recovery
- 20-30% Humidity Recovery
- .09 Wh/m^3
- Power: 1.4 – 2.8 W
- 10/18/22 CFM
- Washable Filter
- No Ducts

Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

Transfer Grill Built Into Door

Retooling THE U.S. Housing Industry

Innovation Example: Advanced Technologies

How to Fix Quality Construction

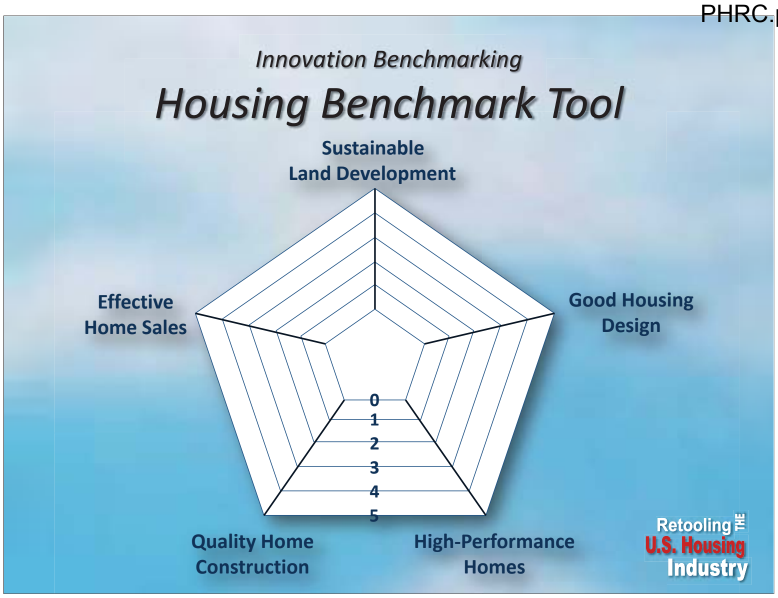
Invest in:

- Comprehensive Construction Documents
- 'Building Science Manager'
- Quality Assurance Processes
- Lean Production Practices
- **New Technologies and Practices**

Retooling THE U.S. Housing Industry

Innovation Benchmarking

Retooling THE U.S. Housing Industry


Innovation Benchmarking
Housing Benchmark Tool
Sustainable Land Development
Good Housing Design
High-Performance Homes
Quality Home Construction
Effective Home Sales
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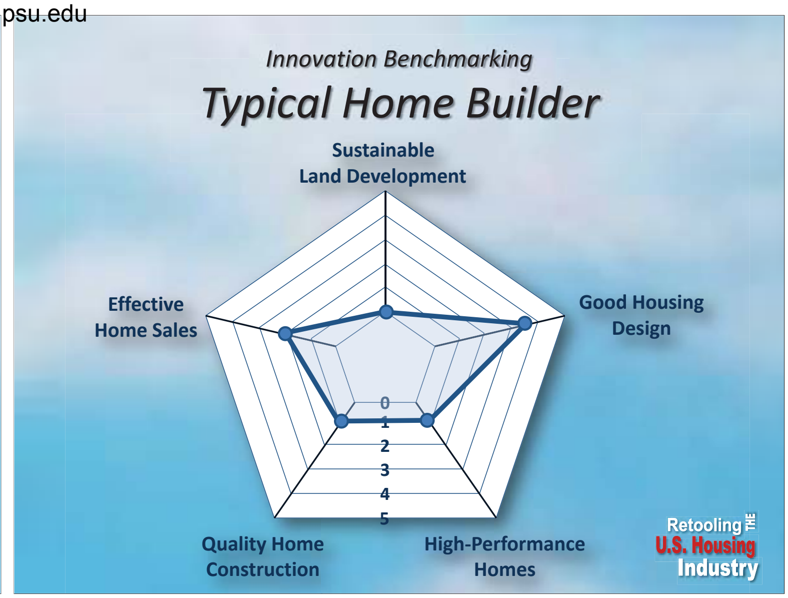
Retooling THE U.S. Housing Industry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Typical Home Builder
Sustainable Land Development
Good Housing Design
High-Performance Homes
Quality Home Construction
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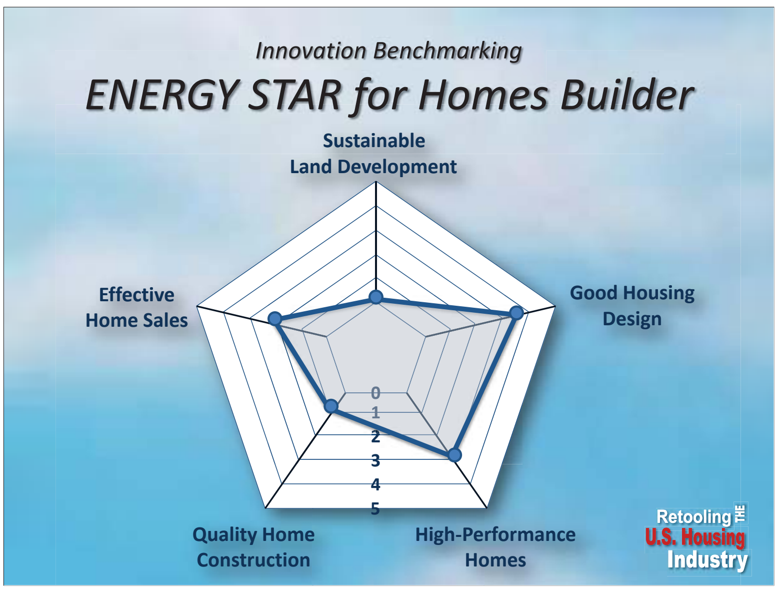
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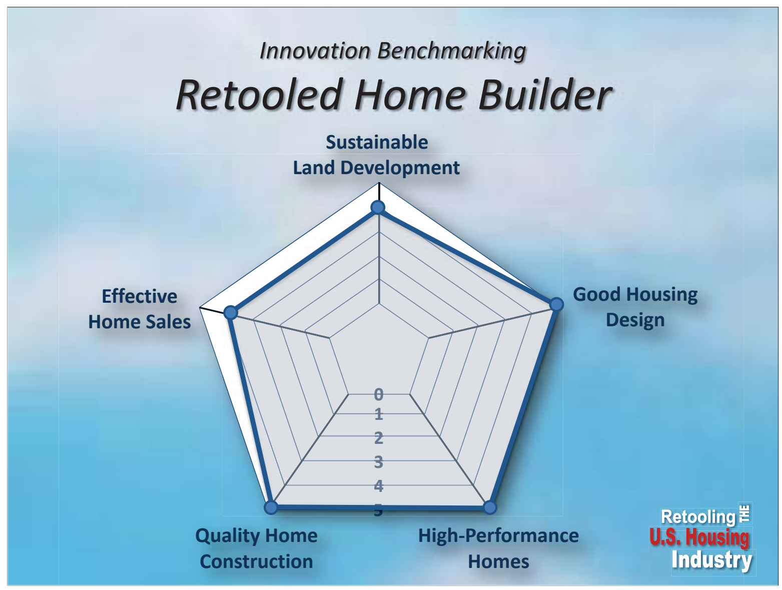
Retooling THE U.S. Housing Industry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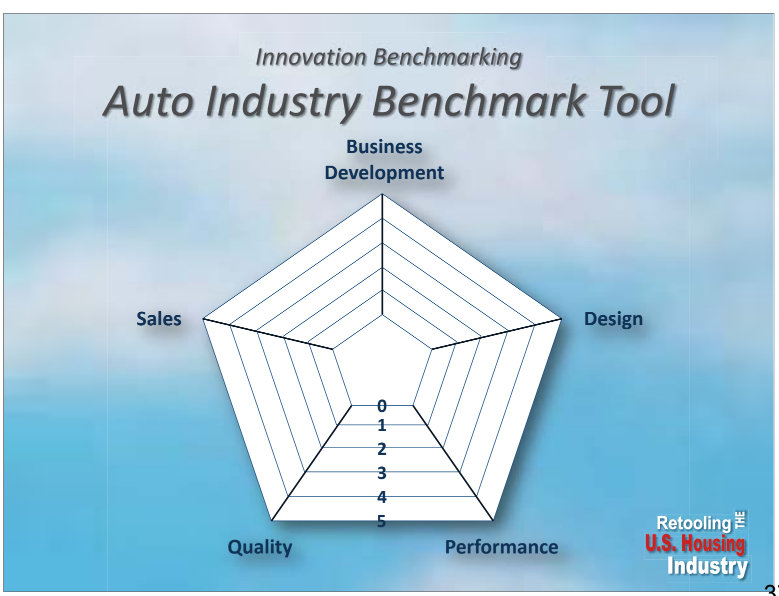
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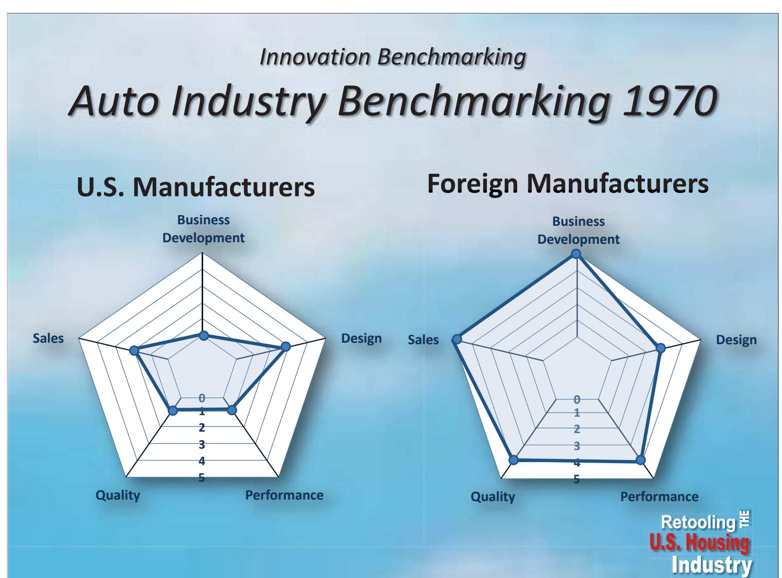
Retooling THE U.S. Housing Industry


Innovation Benchmarking
Auto Industry Benchmarking 1970
U.S. Manufacturers
Foreign Manufacturers
Business Development
Design
Performance
Quality
Sales
Retooling THE U.S. Housing Industry

Innovation Benchmarking

Housing Benchmark Tool

Homework:

Benchmark your homes, or your clients' homes.

Final Word

Why is it a great time to sell homes:

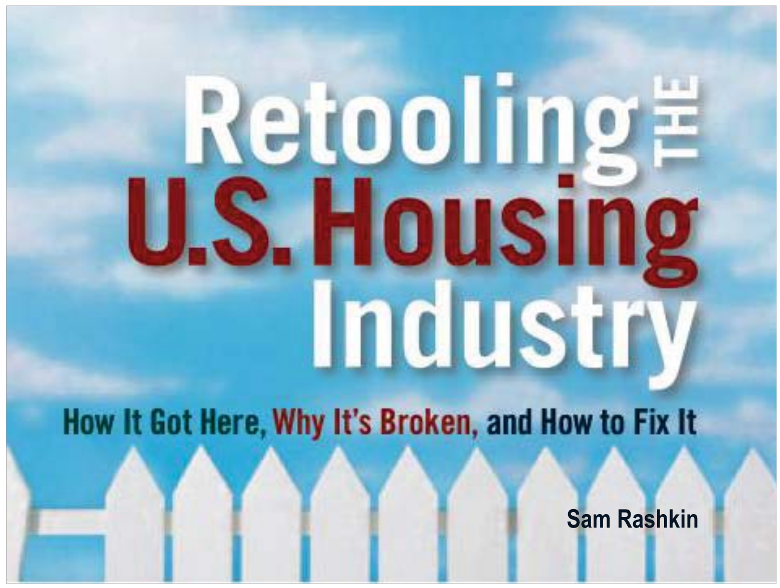
- **Low Cost** of Money
- **Low Price** of Homes
- **$200+ Trillion** National Debt

Final Word

Why it's a great time to sell NEW homes:

- **Low Cost** of Money
- **Low Price** of Homes
- **$200+ Trillion** National Debt
- **Obsolete** competition (used homes)…

if proven innovations applied!



‘To prevent the worst of climate change, high-performance buildings are now a necessity, and this book is a great resource to make such buildings a reality. It clearly recognizes that high performance is not just a technical challenge, but also requires an understanding of people’s behaviors and the complexity of social arrangements.’

NORBERT LECHNER
Architect and Professor Emeritus,
Auburn University, USA

‘From design and analysis, to project construction and delivery, to new materials and techniques, the book carefully collects top authors, content, and case studies to help explicate what the editor describes as “energy-free architectural design”. As well illustrated as it is written, this book convincingly merges the range of historical, technical, theoretical, and architectural obligations that presuppose our understanding of higher-performance buildings.’

KIEL MOE
Assistant Professor,
Harvard Graduate School of Design, USA

‘This book insightfully spans some difficult gaps that have hindered our ecological aspirations in residential design: between the warm sense of home and the cold hard benchmarks of performance; from aesthetic to ethical considerations, between the hardware and the integrated systems; between available technology and material construction; and between simulation models and real-world cases.’

LEONARD BACHMAN
Associate Professor,
Gerald D. Hines College of Architecture,
University of Houston, USA

ARCHITECTURE

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Edited by Franca Trubiano
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DESIGN AND CONSTRUCTION OF HIGH-PERFORMANCE HOMES

Building Envelopes, Renewable Energies and Integrated Practice

Edited by
Franca Trubiano

A Framework for the Process to Identify Dominant Housing Archetypes in a Cold Climate Region:
Matching Energy Retrofit Research to Important Archetypes

1st Residential Design and Construction Conference
February 2013

Presenter Tim Mrozowski, AIA, LEED AP, Professor

Suk-Kyung Kim, Ph.D., Assistant Professor
Tim Mrozowski, AIA, LEED AP, Professor
Amanda Harrell-Seyburn, M Arch, Specialist
School of Planning, Design, & Construction, Michigan State University

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Building America U.S. Department of Energy

Introduction

Building America U.S. Department of Energy

Building America Program of the U.S. Department of Energy

An industry-led research program that aims to accelerate the development and adoption of advanced building-energy technologies and practices in new and existing homes (Department of Energy, 2011). As a part of its program, Building America emphasizes energy-efficient retrofitting for existing homes.

I. Introduction
II. Research Context
III. Research Purpose
IV. Methods
V. Findings
VI. Conclusion

3

Introduction

Cost Effective Energy Retrofit Team and Roles

Dow Building Solutions
(consumer research & product development)

Michigan State University
(market characterization, testing, & on-site implementation)

Ferris State University
(testing & on-site implementation)

Habitat for Humanity International
Habitat for Humanity of Kent County
Habitat for Humanity of Michigan
(testing & construction)

Dow Building Solutions | Michigan State University | Ferris State University | Habitat for Humanity of Kent County

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Introduction

Opportunity to match research with archetypes

Effective energy-retrofit solutions can vary greatly by housing characteristics (such as style, construction type, materials, existing construction details, building form, number of stories, and duct systems) (Hendron & Engebrecht, 2010).

These characteristics can influence the effectiveness of various retrofit solutions.

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Introduction

CEER Research

Four concurrent projects include:

- 6.1 Market Characterization Project
- 6.2 Market Realities and Change Management to Accelerate Adoption of Cost Effective Energy Efficiency Retrofits
- 6.3 Information Framework for Retrofit Technology Implementation
- 7.1 Evaluation and Testing of Individual Retrofit Measures

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Research Context

Need of Market Characterization

This research project is based on the belief that energy retrofit solutions can be matched to the various archetypes and their unique characteristics.

- Currently there is little research that identifies both the range of archetypes' characteristics and the prevalence of these within the existing housing stock of the region.
- This data gap is addressed as part of the four-year Building America project.

Research Context

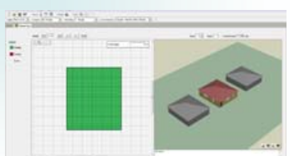
Example factors impacting energy use which can be matched to vintage and archetype

- Construction technology by vintage (Balloon Frame/Platform Frame)
- Construction materials by vintage
- Energy code in existence? (after 1999 in Michigan)
- Insulation patterns by vintage (Walls not insulated until mid 1970's
- Complexity of building form
- Number of stories
- Basement -insulated/un-insulated (after 2005 in Michigan)

Research Context

Example factors impacting energy use which can be matched to vintage and archetype





Research Purpose

- To identify dominant housing archetypes in a local market through general housing data analysis and intensive two case studies.
- To propose a systematic process (or framework) for other researchers or stakeholders for future implementation in other local markets.

Understanding the characteristics of housing groups referred to as archetypes by vintage, style, and construction characteristics can allow research teams to focus their retrofit research and develop prescriptive solutions for those structure types which are prevalent and offer high potential uptake within a region.

Research Methods

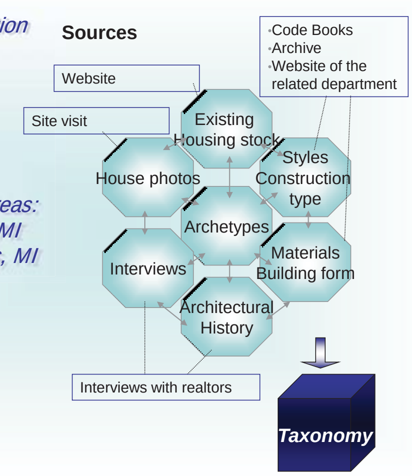
Data Collection Process Descriptions

- Literature review.
- Analyzed 2009 American Housing Survey data, 2000 and 2009 American Community Survey data to identify housing stock characteristics in this region.
- Housing taxonomy.
- Two case studies cities. Ann Arbor and Grand Rapids, Michigan.
- Data collection methods to identify dominant housing archetypes included: site visits, informational meetings with housing experts and staff members of local governments, and analyses of local housing markets and archival documents.
- Analysis focuses on the dominant archetypes in these local markets.
- Developed framework of the process that can be implemented in other local markets to identify dominant archetypes for energy retrofit research.

Research Methods

Data Collection

Case Study Areas:
Ann Arbor, MI
Grand Rapids, MI



Findings 1) Existing Housing Stock

- American Housing Survey
- U.S. Census Bureau analyzed using cross tabulations, multiple regression models, and logistic regression to characterize the housing stock and determine dominant house types using 21 variables.
- Identified 36 categories by date range, size and number of stories.
- Analysis of monthly energy bill data from American Housing Survey (AHS) housing characteristic variables were conducted.
- From this analysis housing sets with high potential for retrofit based on prevalence and monthly energy bill were identified.

Findings 1) Existing Housing Stock

- American Housing Survey

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Table 1. Profile of Single-Family housing Types Overall, by Regions

Housing Characteristics				Single-Family housing Types				Monthly Energy Bill	
				US		Midwest		US	Midwest
	Built	Stories	Size (sq.ft)	Number	%	Number	%	Monthly Energy Bill	Monthly Energy Bill
1	< =1929	1	< =900	433,187	0.56	155,327	0.83	$157.76	$189.00
2	< =1929	1	900-2500	1,251,496	1.61	254,190	1.36	$180.40	$193.11
3	< =1929	1	>2500	74,142	0.10	9,597	0.05	$194.75	$134.47
4	< =1929	2	< =900	258,514	0.33	131,713	0.70	$198.59	$185.98
5	< =1929	2	900-2500	1,657,069	2.13	700,506	3.73	$214.41	$206.09
6	< =1929	2	>2500	295,942	0.38	94,139	0.50	$272.97	$251.62
7	< =1929	>= 3	< =900	165,394	0.21	62,675	0.33	$288.97	$274.21
8	< =1929	>= 3	900-2500	2,901,527	3.74	1,369,578	7.30	$258.95	$226.80
9	< =1929	>= 3	>2500	1,308,959	1.69	476,601	2.54	$308.87	$260.67
10	1930-1940	1	< =900	1,133,601	1.46	218,743	1.17	$154.76	$201.46
11	1930-1940	1	900-2500	3,103,709	4.00	331,482	1.77	$185.62	$188.86
12	1930-1940	1	>2500	172,623	0.22	13,682	0.07	$237.27	$246.20
13	1930-1940	2	< =900	286,362	0.37	117,344	0.63	$186.00	$162.21
14	1930-1940	2	900-2500	1,686,570	2.17	640,187	3.41	$210.16	$205.93
15	1930-1940	2	>2500	316,849	0.41	90,829	0.48	$265.33	$230.58

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Findings 1) Existing Housing Stock

Based on the American Community Survey 2005-2009:

- A total of 4,522,600 homes exist in the State of Michigan in 2009.
- Energy retrofit needs can be diagnosed initially by the age of homes and heating-related equipment.
- Only 8.7% of Michigan homes are less than 11 years old (built after the year 2000).
- Approximately 5.4% of existing homes were built after 2000 in Ann Arbor.
- A majority of existing homes are older than 11 years and shows a higher possibility of their retrofitting needs.
- 25.3% of currently existing Michigan homes were built before 1950.

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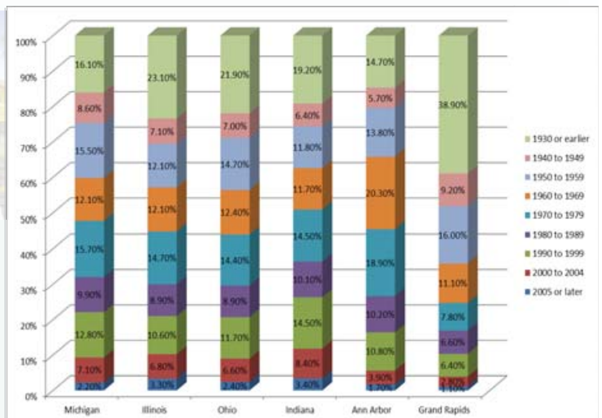
Findings 1) Existing Housing Stock



Existing Home Housing Stock

(Source: U.S. Census Bureau (2010). Selected housing characteristics 2006-2010 American Community Survey 5-Year Estimates)

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Findings 1) Existing Housing Stock

Existing Housing Market in Michigan

Items		U.S.	Great Lakes Sub-Regions				Target Cities	
			Michigan	Illinois	Ohio	Indiana	Ann Arbor	Grand Rapids
Year Structure Built	Total	130,038,080 (100.0%)	4,529,680 (100%)	5,267,614 (100%)	5,107,273 (100%)	2,778,459 (100%)	49,871 (100%)	81,595 (100%)
	2005 or later	5,273,880 (4.1%)	100,312 (2.2%)	171,655 (3.3%)	123,675 (2.4%)	93,250 (3.4%)	826 (1.7%)	927 (1.1%)
	2000 to 2004	11,282,610 (8.7%)	321,086 (7.1%)	358,774 (6.8%)	335,468 (6.6%)	233,108 (8.4%)	1,958 (3.9%)	2,253 (2.8%)
	1990 to 1999	18,316,301 (14.1%)	580,582 (12.8%)	560.625 (10.6%)	595,302 (11.7%)	403,999 (14.5%)	5,381 (10.8%)	5,250 (6.4%)
	1980 to 1989	18,473,041 (14.2%)	450,633 (9.9%)	468,049 (8.9%)	456,878 (8.9%)	281,875 (10.1%)	5,096 (10.2%)	5,418 (6.6%)
	1970 to 1979	21,353,306 (16.4%)	709,303 (15.7%)	775,239 (14.7%)	734,288 (14.4%)	402,219 (14.5%)	9,402 (18.9%)	6,390 (7.8%)
	1960 to 1969	14,808,721 (11.4%)	549,176 (12.1%)	635,128 (12.1%)	633,665 (12.4%)	324,800 (11.7%)	10,142 (20.3%)	9,045 (11.1%)
	1950 to 1959	14,654,704 (11.3%)	700,319 (15.5%)	707,982 (12.1%)	753,012 (14.7%)	327,141 (11.8%)	6,879 (13.8%)	13,038 (16.0%)
	1940 to 1949	7,526,519 (5.8%)	388,636 (8.6%)	372,084 (7.1%)	358,691 (7.0%)	178,238 (6.4%)	2,832 (5.7%)	7,523 (9.2%)
	1939 or earlier	18,348,998 (14.1%)	729,633 (16.1%)	1,218,078 (23.1%)	1,16,294 (21.9%)	533,829 (19.2%)	7,333 (14.7%)	31,751 (38.9%)

Source: All data sets are from http://factfinder2.census.gov - U.S. Census Bureau (2010). Selected housing characteristics 2006-2010 American Community Survey 5-Year Estimates

Findings 3) Understanding Local Context

- **Meetings with Local Housing Experts**

Meetings were held with Grand Rapids Housing Officials to identify available information, identify city boundaries, to gain an understanding of city growth patterns and housing stock and to determine characteristic neighborhoods for site visits. During these meetings five target neighborhoods were identified as candidate site visit neighborhoods.

- **Review of Public Information**

The CEER team reviewed public information for Grand Rapids including census documents, and a development plan report furnished by the City of Grand Rapids. Additional sources reviewed were Sanborn Fire Maps and Google Earth images which were used to gain a perspective on growth patterns and the organization of neighborhoods.

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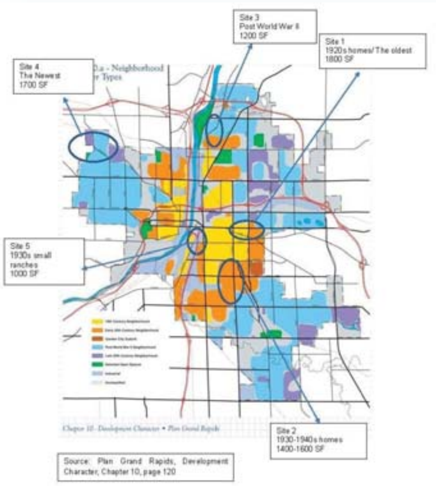
Findings 4) Site Visits



Note
Yellow – 19th century neighborhood
Light orange – Early 20th century neighborhood
Dark orange – Garden City suburb
Light blue- Post World War II neighborhood
Purple- Late 20th century neighborhood
Green- Selected open space
Medium gray- Industrial
Light gray- unclassified

City of Grand Rapids and Neighborhoods for CEER Site Visits in Grand Rapids (Source: City of Grand Rapids (2012). Plan Grand Rapids, p. 120)

Findings 4) Site Visits – Dominant Archetypes

1.5 story homes in the period of the 1930 through the 50's and early 60's:

- Including finished bedroom spaces and other living spaces above the first floor.
- Common examples are Cape Cod style homes with typically two to three bedrooms and possibly one or one a half bathroom located within the roof form and above the first floor.
- Frequently dormers were prevalent.
- Presenting some unique energy retrofit challenges because they frequently have contact ceilings installed on sloping roof structure as well as knee walls. These conditions make the addition of insulation within the attic space somewhat more difficult to accommodate.

Two-story homes: Commonly of Greek Revival, Craftsman (American Four Square) or vernacular styles

- More prevalent than other styles having similar roof, siding, and foundation materials.
- Many of these homes were ballooned framed, had block building forms and steep roofs.

Ranch Built in the 1950s (left) Ranch Built after the 1960s (middle) Ranch Built after the 1960s (right)

Photo credits by Authors

Findings 4) Site Visits – Dominant Archetypes

Ranch style homes were mainly built after 1950.

- Common materials: Asphalt shingled roofs; brick, aluminum or combinations of siding were common for exterior walls, most homes had concrete block basements.
- Ranch style homes built in the 50's typically were built with un-insulated walls, minimal roof insulation, single glazed windows and un-insulated basements. Home from this period closely align with the benchmark home used in a recent NREL study entitled Energy Savings Measure Packages: Existing Homes (Casey and Booten, 2011).

Ranch Built in the 1950s (left) Ranch Built after the 1960s (middle) Ranch Built after the 1960s (right)

Photo credits by Authors

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Findings 5) Real Estate Data Analysis

The CEER team searched www.zillow.com to examine properties which are currently for sale, recently sold and for rent and again reviewed individual property listings and photo sets to apply the housing taxonomy.

Zillow listed close to 11,000 properties for Grand Rapids, representing about 13% of the entire housing stock. The Zillow search yielded 9,308 "recently sold", 1307 "for sale" and 369 "rental" homes for Grand Rapids homes in June 2012 (see Table 12).

CEER team again matched the distribution of housing stock identified by Zillow.com by decade to the Census Bureau data and found there was an approximate match between the Zillow filtered searches and distribution of homes by decade built from the census data.

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Findings 5) Real Estate Data Analysis

Distribution of Recently Sold Homes Grand Rapids

Similar distributions of homes by decades

Construction Eras	Zillow Data		Zillow Data Sub-Totals	Census Grand Rapids	
1800-1899	556	7.6%	43.9%	Before 1939	38.9%
1900-1910	936	12.7%			
1911-1920	256	3.5%			
1920-1929	1303	17.8%			
1930-1939	172	2.3%			
1940-1949	630	8.6%	42.1%	1940-1969	36.4%
1950-1959	1959	26.8%			
1960-1969	482	6.7%			
1970-1979	298	4%	9.9%	1970-1999	20.8%
1980-1989	196	2.7%			
1990-1999	231	3.2%			
2000-2012	279	3.8%	3.8%	2000-2012	3.9%
Total	7298*	100%	100%	Total	100.0%

(Source: http://www.zillow.com)
*Not all homes had dates so the total of searches by decade is less than the total number of homes 9308 in the entire data listing set

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Summary

This table shows characteristics of homes and their criteria for classification into archetypes.
Criteria for selection of archetypes for energy retrofit research include vintage, which correlates with construction systems and materials; prevalence; monthly energy bills; and building form.

ID	Date	Frame		Form		Story		Orientation		Base	Roof		Code	Style Remark
	Date Range	Balloon Frame	Platform Frame	Block Form	Complex From	Multiple Stories	Single Story	Vertical Orientation	Horizontal Orientation	Basement	Steep Roof Slope + Attic	Shallow roof pitch	Energy Code in Place	
1	Before 1930	●			●	●		●		●	●			Vernacular Queen Anne Gothic Revival Stick Queen Anne Folk Victorian
2	Before 1930	●		●		●		●		●		●		Greek Revival Italianate Four Square
3	1930-1949		●	●		●		●		●		●		Colonial Revival Neoclassical Vernacular
4	1930-1949		●	●		●		●		●		●		1 ½ Stories Cape Cod Bungalow Craftsman Neoclassical
5	1930-1949		●		●	●		●		●	●			Tudor Tudor Revival Craftsman Other
6	1930-1949		●	●			●		●					Ranch
7	1950-1969		●	●		●		●		●				Neoclassical Neocolonial Modern

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Summary

ID	Date	Frame		Form		Story		Orientation		Base	Roof		Code	Style Remark
	Date Range	Balloon Frame	Platform Frame	Block Form	Complex From	Multiple Stories	Single Story	Vertical Orientation	Horizontal Orientation	Basement	Steep Roof Slope +	Shallow roof pitch	Energy Code in Place	
8	1950-1969		•		•	•		•	•	•				Split-Level 1 ½ Story Cape Cod
9	1950-1969		•	•			•		•	•				Ranch
10	1970-1979		•	•		•			•	•				Traditional references
11	1970-1979		•		•	•			•	•				Traditional references
12	1970-1979		•	•			•		•	•				Traditional references
13	1980-1999		•			•				•				Traditional references
14	1980-1999		•			•				•				Traditional references
15	1980-1999		•				•			•				Traditional references
16	2000-2012		•	•			•		•	•			•	1 story
17	2000-2012		•	•		•			•	•			•	2 Story
18	2000-2012		•		•	•			•	•			•	2 Story

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Summary

Recommendations for energy retrofit research in Grand Rapids

- Ranch style homes of 1,000 to 1,200 square feet and two-story homes of 1,400 to 1,600 square feet are more prevalent than other housing types. Built after 1950's
- Two-story block form houses in Grand Rapids can be categorized into two groups depending on construction era: prior to 1910s and 1930s to 1940s.
- 1.5 story homes (Cape Cod form began to emerge in the early 1930's in the Grand Rapids market and continued into the 50's.

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Conclusion

Process Framework

Objectives	Data Collection Methods	Data Sources
To explore literature on energy retrofit research and on housing taxonomies and demographics	Literature review	BA Research resources and reports, general research literature, and data from the U.S. Census Bureau
To identify housing styles in the United States and Michigan	Literature review	Literature: A Field Guide to American Houses by Virginia & Lee McAlester. 1984.
To identify housing styles available in Michigan and the Great Lake sub-region	Expert meetings	Two architectural historians in the State Historic Preservation Office
To identify the general characteristics of the housing market in the nation and the targeted areas	Housing data review and analysis	American Community Survey American Housing Survey
To estimate the total number of houses falling on the dominant archetypes	Statistical analysis	The number of entire houses in the city
To understand geographical and socioeconomic growth of the city	Map review	Google Earth maps, Sanborn maps
To investigate local housing market and dominant housing (arche)types for energy-efficient retrofit	Information al meeting	Meeting contents
To quantify the number of houses in the dominant archetypes in the targeted area	Observation s with a local map and a checklist	Actual number of housing reflecting the physical characteristics of the dominant archetype
To confirm major housing archetypes for the targeted city	Descriptive analysis	Intensive Housing Survey Report by the State Historic Preservation Office

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Conclusion

- A framework for characterizing local markets developed.
- Applying the framework allowed us to characterize high priority homes for energy retrofit research in Grand Rapid, but also can serve as a guide approach for other BA teams or for local energy retrofit program managers or retrofit contractors.

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Deep Energy Retrofits with Retrofit Insulated Panels

Ted L. Clifton
Zero Energy Plans
Structural Insulated Panel Association (SIPA)

Learning objectives:

- How (and why) to use Energy Modeling Software before starting any retrofit
- How to use contemporary building products to improve the thermal efficiency of an existing home beyond current energy codes
- How to complete the project through careful selection of appliances and equipment to achieve up to 90% total reduction in energy costs
- How to calculate the correct amount of alternative energy required to get to net-zero-energy

Who am I, and why am I delivering this presentation?

- I am a hands-on builder with more than 45 years in the building industry
- I am an Instructor for the NAHB Green Building family of classes, and a Master Certified Green Professional
- Our company has increased our construction volume by 50% over the last four years by adding the deep energy retrofit to our offerings

Who are you, and why are you taking this class?

- How many Builders?
- Remodelers?
- Design professionals?
- Code Professionals?
- Municipal Administrators?
- Others?

Goals of this class:

This presentation is about Our Future:

- To weather the current economic conditions
- To mitigate concerns about future fuel costs
- To move our country towards energy independence!
- To save fossil fuels as a portable fuel source for future generations

What is a Deep Energy Retrofit

- A deep energy retrofit (DER) is about applying the whole house approach to our existing housing stock
- Homes and buildings use about 39% of the total energy used in this country each year
- Homes use about half of that total, or around 20% of our total energy budget
- About 75% of our existing housing stock was built in the years between WWII and 1985

The typical 1960s house

- 2x4 walls, R-11 insulation, maybe no insulation!
- R-19 ceiling insulation, R-19 floor insulation, if any!
- Aluminum single-pane windows!

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The typical pre-WW-II house:

- 2x4 walls
- R-11 insulation, maybe no insulation!
- R-19 ceiling insulation
- R-19 floor insulation, if any!
- Wood-sash single-pane windows!

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Why are we doing this?

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What is a Deep Energy Retrofit?

- Average homes from this era use between two and three times the energy of today's code built home
- These homes account for about 90% of the energy our country uses for homes
- Using the simple, relatively inexpensive, and very cost-effective measures outlined in this presentation, you can reduce the energy consumption by these homes by about 90%. This would represent a reduction in total energy use in the U.S. of about 17%!

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How good does it get?

Once you have completed the steps outlined in this class, you could add a relatively small amount of PV to the roofs of these homes, and in many cases, you can turn these formerly energy guzzling homes into true net-zero-energy homes!

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Step One: if you don't measure it, you can't manage it!

- Always perform an energy audit of the home before you begin
- Use energy modeling software to analyze the home from an energy use perspective as it currently exists
- Several programs are available to you, some of them are even free, such as the WSU Component Performance Analysis
- I do not recommend ResCheck, it is too basic
- Commercially available programs include Rem-Rate, used by most HERS Raters

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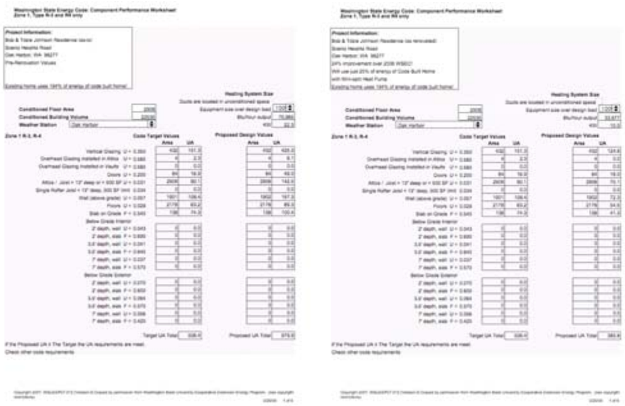
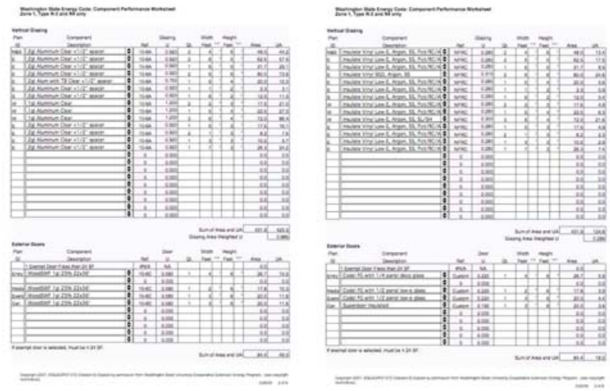
The WSU Component Performance Worksheet



Lets you compare before & after side-by-side

Collect the data:



Compare the possibilities!

Measure it well!

- Have blower door test run on the home BEFORE YOU START to determine where some of the worst energy leaks are occurring
- Have another blower door test run on the home when you have finished to prove your results
- Reduction in air leakage is a major goal of the Deep Energy Retrofit!

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Use the data you have collected to develop deep energy retrofit plan

- Use energy modeling software to experiment with different levels of insulation for:
  - Windows
  - Walls
  - Ceiling or roof
  - Floors, and/or crawlspace
  - Doors, skylights, and other openings

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Determine the cost-effectiveness of each building envelope component and strategy

- Compare insulation levels in different areas, and their effect on overall energy performance of the home
- Compare vented vs. closed crawlspace designs. If a ducted heating system is to be used, closing the crawl space can offer significant advantages over and above those shown in the ZEP Closed Crawl Space Calculator!
- http://www.zero-energyplans.com/press.php

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Determine the cost-effectiveness of each building envelope component and strategy

- Explore the option of moving attic envelope to top of attic, instead of ceiling below
- Again, if ducted heating or cooling equipment is to be used, moving the envelope can offer significant advantages by keeping ducts in a more moderate environment

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Determine the cost-effectiveness of each building envelope component and strategy

- Price each option, give your clients a choice. Not six choices, maybe two or three choices, good, better, best.
- Keep it simple, stupid! (the KISS principle)
- Run the three options through a spreadsheet that takes into account inflation on energy costs, interest rates, and your customers federal income tax status

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Cash-Flow Spreadsheet

High Performance Home Energy Remodel

	Good	Better	Best
Cost of Remodel	$ 15,000	$ 43,000	$ 66,000
Rebates and incentives	1,000	1,000	2,500
Tax Credits	1500	1500	1500
Energy cost/year prior to remodel	$ 3,600	$ 3,600	$ 3,600
Reduction in Energy use	10.00%	35.00%	77.00%
Tax Rate	15.00%	15.00%	15.00%
Rise in energy costs/year	7.80%	7.80%	7.80%
Loan Interest Rate	6.50%	6.50%	6.50%
Loan Terms (in months)	360.00	360.00	360.00
Loan amount	$ 15,000	$ 43,000	$ 66,000
Amount of Rebates and Incentives subtracted from Loan amount	$ -	$ -	$ -
Returns and Cash Flow based on Energy Savings without Loan			
1st year Return	19.07%	8.74%	10.26%
1st year Cash in Pocket	$ 2,860	$ 3,760	$ 6,772
2nd year Return	2.59%	3.16%	4.53%
2nd Year Cash in Pocket	$ 388	$ 1,358	$ 2,988
10 year compounded return	51.11%	47.86%	66.33%
10 year Cumulative Cash in Pocket	$ 7,666	$ 20,581	$ 43,777
20 year compounded return	124.09%	136.97%	194.06%
20 year Cumulative Cash in Pocket	$ 18,614	$ 58,898	$ 128,077
30 year compounded return	278.77%	325.82%	464.74%
30 year Cumulative Cash in Pocket	$ 41,816	$ 140,105	$ 306,730
Cash Flow Based on Energy Savings with Loan			
1st year Cash Flow	$ 1,868	$ 916	$ 2,406
5 year cumulative Cash Flow	$ (376)	$ (4,411)	$ (1,710)
10 year cumulative Cash Flow	$ (2,347)	$ (8,124)	$ (281)
20 year cumulative cash flow	$ (1,725)	$ 594	$ 38,586
30 Year cumaltive cash flow	$ 10,554	$ 50,487	$ 169,177

Determine the cost-effectiveness of each building envelope component and strategy

Show value over time of each option. Do not forget to include:

- Energy bills are not tax deductible, but mortgage interest is
- An energy-efficient home will sell for more, usually at a premium compared to the cost of making those improvements
- Energy costs per unit will rise over time. The mortgage payment will remain the same, and may provide some cash-out financing in the future when you need it most, like sending a child to college.

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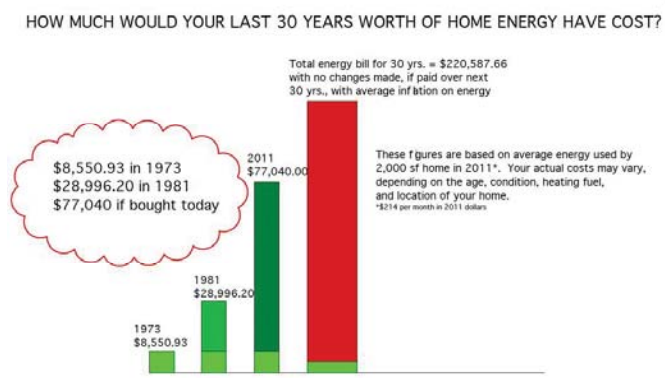
Average Energy-Inflation = 6.05% for last 38 years!



Step Two: begin work

- Start with the exterior walls
- What are retrofit insulated panels and how do you use them?
- Can you use an inch or two of foam sheeting instead?
  - It may depend on your climate zone, and on what type of siding you are planning on using
  - With either choice, you must use vapor-permeable products on the inside of your walls, because drying will only be able to occur to the inside!

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What is a retrofit insulated panel

- I call it "half a SIPS" panel
- It has OSB on one side, laminated to 3 1/2" (or more) of EPS foam insulation on the other
- It has an R-value of about 4 per inch, or 14.1 for a 3 1/2" panel

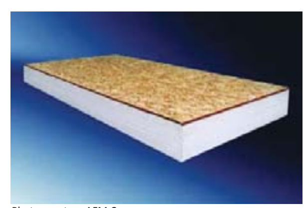

Photo courtesy AFM Corp.

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What is the insulation value of a retrofit insulated panel?

Table 3. Expanded Polystyrene (EPS) Retro-fit Insulated Panel R-values

Total panel thickness, EPS Type VIII	R-value per ASTM C 578[A]
2"	6.5
4"	14.1
6"	21.7
7 ¾"	28.4
9 ¾"	36
11 ¾"	43.6

[A] Stated R-value includes EPS at thickness plus 7/16" OSB R-value from ASHRAE Fundamentals

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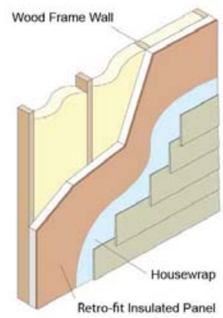
How is a retrofit insulated panel applied?



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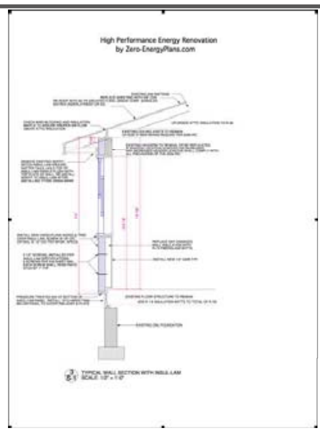
How is a retrofit insulated panel applied?

Standard details are available for most applications



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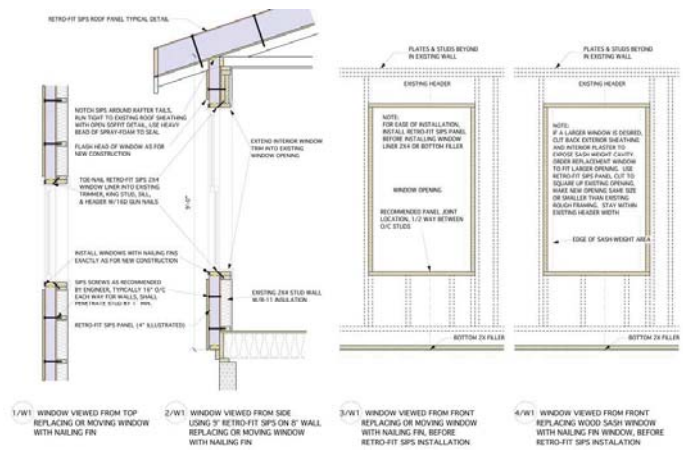
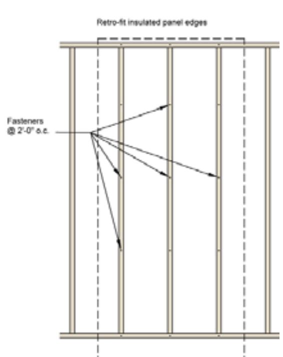
Window installation



Wall panel installation



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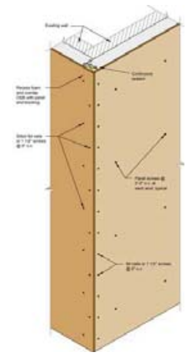
Corner detail



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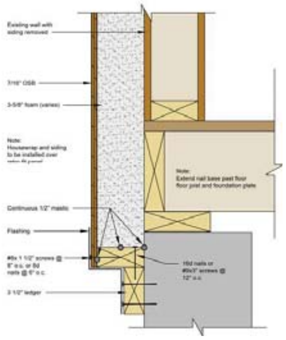
Rim joist detail



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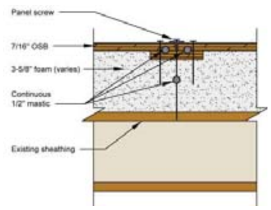
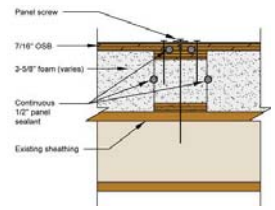
Spline details

Surface Spline



Block Spline



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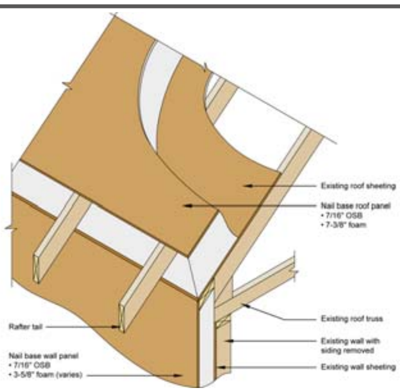
Wall and roof panel overview



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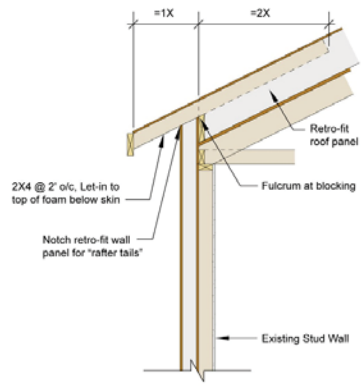
Wall-to-roof connection



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Specialty tools

Foam Scoop

Hot Wire

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Retro-fit panels offer a solution for both air infiltration and insulation value

- Air leakage accounts for about 30% of energy loss in the average home. In some of the homes you will be testing, it will be even more.
- You can more than double the R-values of the walls you are affecting, cutting conductive heat loss from walls in half or better
- You will explore the retrofit panels vs. foam sheeting panel option above in the "measure it" phase

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Need I say more?

Plan your Attack!

- You can remove the existing windows, install the retrofit insulated panels, and re-install new, energy-efficient windows, one wall at a time. You do not need to leave a wall open overnight!

- If there is no insulation in the stud cavities, you can blow in insulation from the outside before installing Retro-fit SIPS

Pretty cool, huh!

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Removing windows

Caulked and prep'd

Panel installation

Panel installation

Installation tips:

- Be sure to use liberal amounts of spray-foam to seal between panels, and to seal gaps between panels and existing siding if it is not removed first (it doesn't have to be). T-1-11 is a perfect medium to cover, it is relatively flat, but be certain to seal up the grooves in the panels at the top and bottom of each sheet, to prevent bugs from entering the wall, and to prevent air leakage.

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Installation tips:

- Apply a suitable building paper for your climate zone, preferably with a rain-screen type feature for wetter climates
- Properly flash all window and door openings as you would for new construction
- Install new siding and trim products, providing proper flashing and drainage at all protruding trims
- Siding application is typically exactly as for new homes

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New house? Looks like it!

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New House? Looks like it!

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Thoroughly air-seal all penetrations under the floor:

- Look for big holes, like around masonry fireplace bases, seal them with spray-foam.
- Under the tub or shower is often the biggest air leak, seal it!
- Now look for small holes, like plumbing and wiring penetrations, fill them all with spray foam.
- While you are there, INSULATE ALL HOT WATER PIPES!

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Now we add up to R-38 under the floor or develop a conditioned crawl space:

- Consider a closed crawl-space, especially if heat ducts are still located there!
- Include climate considerations in your calculations!
- Insulate the walls and floor of the crawl space, as well as the floor between the house and the crawl space.
- Include radon mitigation in your closed crawl space plans

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Now seal up the ceiling and attic:

- Caulk all penetrations in ceiling, such as around recessed can lights, all other lighting boxes, and other penetrations
- If including attic space in the building envelope, use spray-foam insulation on the under-surface of the roof deck
- If re-roofing the house is in the plan, consider using retrofit panels on top of roof-deck as an alternative to the spray-foam on the inside of the attic. This can help make up for the lack of raised heel trusses on most of these homes, and usually costs less!

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Step Three: finish the job right!

- At this point, using building envelope technologies alone, you will have reduced the heating and cooling energy use of the home by more than half, down to about 75-80 percent of the energy of today's code-built home.
- This is where the proper equipment can finish the job:

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Finish the job right!

- The heating and cooling system will usually be by far the largest user of energy in the home. It now needs to be down-sized, and could be completely replaced
- Use high-efficiency heat pump if existing ductwork can be sealed to less than 5% air leakage, and if ducts are located in conditioned spaces. Typical Coefficient of Performance (COP) is usually around 2.5 to 2.9 (HSPF 8.5 to 9.9)

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Finish the job right!

- Consider mini-split (ductless heat pump) if ducts are in poor condition, and especially if closed crawlspace and attic are not economically feasible. Typical COP is often around 2.7 to 3.2!
- Consider Ground Source Heat Pump depending on climate zone, and availability of space for horizontal system, or cost of deep-bored system. Typical COP is usually above 3.8 to 4.6 for heating, even higher for cooling!
- Air-to-water heat pumps are becoming available for hydronic system replacement, COP up to 4.2!

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Ductless mini-split heat pump

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Ductless mini-split heat pump, interior unit

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Ductless mini-split heat pump, interior unit

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How good does it get?

- If you select the GSHP, you can achieve spectacular net efficiencies for the whole house. When you include the building envelope changes made above, you will be able to get the total energy use from heating and cooling down to about 20% of the energy use of today's code-built home.

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Step Three: don't stop until you are really finished!

- Domestic hot water heating accounts for about 15-20% of the energy use of an average home. A combination of solar hot water heater and GSHP with desuperheater can reduce net cost per year of producing domestic hot water by about 87%.
- Lighting and appliances account for the remaining 30% of energy loads, and can be the easiest to address.
- Expect to achieve 75% savings on lighting by replacing all incandescent bulbs with compact fluorescent or LEDs.
- Expect to achieve up to 30% reduction in appliance energy (other than cooking) with careful attention to the EnergyStar stickers!

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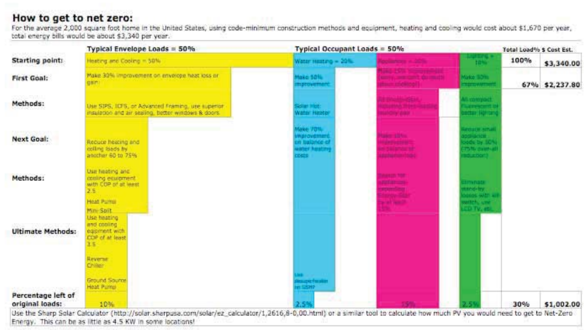
Road-map to net-zero-energy:



Remember this view? HERS 67! (without PV, could go net-zero!)

Measure the results!

Minneapolis House:

2,686 sf. (Cold Climate)

Reduction in Envelope Btu/yr: 37.65%

Reduction in Heating Btu/yr: 57.22%

Total Reduction in Energy: 49.12%

Savings in $$$/yr: $1,371

Gas Cost: .905/therm

Elect. Cost: .09/Kwh

Blower door: 3.97 ACH50 (was 8.26)

Oak Harbor House:

2,908 sf. (Moderate Climate*)

Reduction in Envelope Btu/yr: 60.3%

Reduction in Heating Btu/yr: 83.57%

Total Reduction in Energy: 64.45%

Savings in $$$/yr: $3,060

Gas Cost: N/A

Elect. Cost: .10/Kwh

Blower door: 5.25 ACH50 (was 15.3!)

Now go buy yourself a really good, organic micro-brew, you have earned it! (Better yet, buy me one!)

Questions????

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Zero-EnergyPlans.com

DOE Challenge Home:
Taking Homes to the Next Level

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Zero Net-Energy Ready Home Training

SAM RASHKIN
Chief Architect
Building Technologies Program

Outline

Zero Net-Energy Ready:

- Home of the Future
- Made Simple
- Business Case
- Value Proposition
- Technical Specifications

Zero Net-Energy Ready
Home of the Future

Not This!

This…

- Ultra-Low/No Utility Bills
- Advanced Home Management
- Built-in Black-out Power Supply
- Luxurious Comfort & Quiet
- Much Lower Insurance Cost
- Healthier Living
- Lower Mortgage Rate
- Quality Components
- Long-Term Warranty
- Low Maintenance
- Minimal Wasted Water
- Disaster Resistance

Cost Comparison

	Home of the Future:	Typical Existing Home:
First Cost:	$350,000	$300,000
Monthly Mortgage:	$1,500	$1,400
Monthly Energy:	$ 30	$ 150
Monthly Water:	$ 20	$ 50
Monthly Insurance:	$ 50	$ 100
Total Monthly Cost:	**$1,600**	**$1,700**
Monthly Savings:	**$ 100**	N.A.
7-yr. Savings:	**~$8,500**	
Warranty Coverage:	**30 yrs.**	**1 yr.**
7-yr. Resale Value:	**$400,000**	**$325,000**

Cost Comparison Summary

~$100/month less ownership cost

~$8,500 less ownership cost over 7 years

30-year vs. 1-year warranty

~$75,000 more value

7

Why Build House of the Future?

- Consumers want it, (they just don't know it yet) and
- It's readily achievable today

Question:
Is it time for you lead?

8

Zero Net-Energy Ready
Made Simple

Step #1:

Ensure Comprehensive Building Science
by making ENERGY STAR v3 a prerequisite.

Step #2:

Add proven technologies and practices
from Building America which, along with complete building science, lock in Zero Net-Energy capability.

Step #3:

Include energy efficient components
throughout the home
to complement high-performance enclosure.

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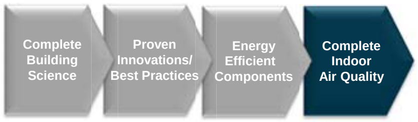
Step #4:

Provide comprehensive pollutant control

critical in homes this tight and well-insulated (specify EPA Indoor airPLUS requirements).



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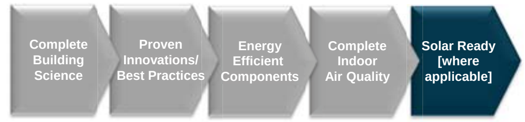
Step #5:

Ensure low-cost details that can save $1,000's downstream to install solar

since homes are ready for zero net-energy performance.



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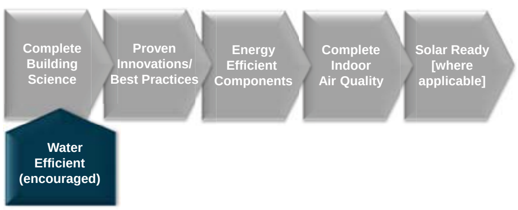
Step #6:

Start addressing related water efficiency issues

in homes this environmentally responsive (recommend EPA WaterSense specifications).



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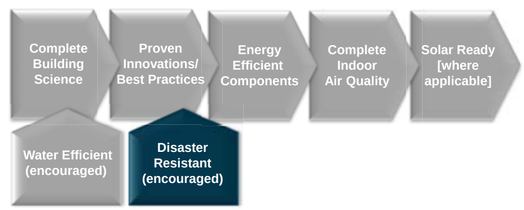
Step #7:

Don't ignore disaster resistance

since homes built this well should last 100's of years (recommend IBHS Fortified Homes specifications).



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Step #8:

Encourage QA/QC practices

to help ensure the success of builder partners.

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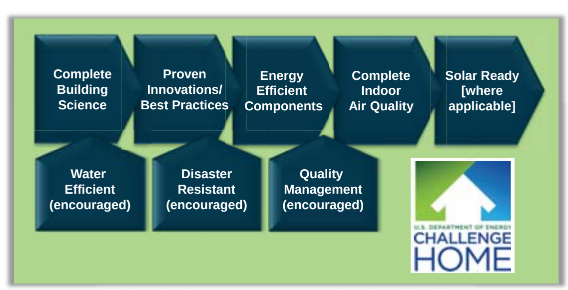
Summary:

All the pieces add up to DOE Challenge Home...



Summary:

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…and now home is ready for renewable power. This is a Zero Net-Energy Ready Home.

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Zero Net-Energy Ready
Business Case

Old Business Solution:

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Minimize Cost

NAHB estimates for every **$1,000 increase** in sales price, nearly **250,000 households** fail to qualify for a mortgage on a typical new home.

[http://www.nahb.org/fileUpload_details.aspx?contentTypeID=3&contentID=40372&subContentID=112293]

New Business Solution:

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Maximize Value

so homebuyers are compelled to want new housing again.

Innovation/Value Premium

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Price Based on 'Value', NOT Cost

Innovation/Value Premium

Profit | Profit

Old Cell Phone Cost | i-Phone Cost

VS.

Home Innovation Real Cost

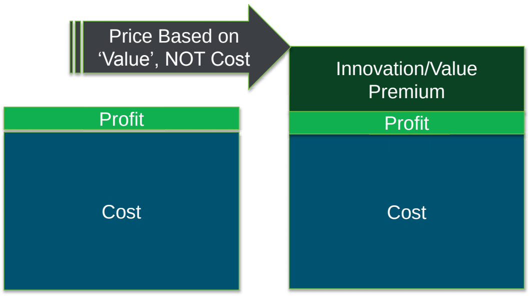
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Standard Home	DOE Challenge Home
Marketing Cost	Marketing Cost
Call-Back Cost	Call-Back Cost
Hard Cost	Hard Cost

Standard Home VS. DOE Challenge Home

Home Innovation/Value Premium

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Standard Home vs. DOE Challenge Home

1st Law of Innovation

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The closer link to leadership,
the higher the innovation/value premium.

Innovation Leadership Example

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2nd Law of Innovation

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Innovation option
shouldn't look the same
as the standard option.
[owners want 'badge of honor']

Innovation Looks Different

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

2012 Toyota Highlander

2012 Lexus RX400

Personal Experience

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Existing Home:
Low Performance

Retrofitted Home:
High-Performance

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Innovation 'Brand' Recognition

U.S. DEPARTMENT OF ENERGY
CHALLENGE HOME

Independent Voice of Authority vs. "Trust me."

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Pent-up Consumer Demand

The Washington Post

Model home shows off its green side

"They didn't have this [model] when we purchased our home" three doors down the street in October, said Nickiea Youmans, who along with her husband, Linzy, walked into the back yard to check out the house. "We would have been very interested in this," she added.

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Zero Net-Energy Ready

Value Proposition

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THE
U.S. DEPARTMENT OF ENERGY
CHALLENGE HOME
STORY

Provided by:
ACME Homes™

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ACME Homes

U.S. Department of Energy

U.S. DEPARTMENT OF ENERGY
CHALLENGE HOME

Exclusive

Only the top builders in the country
meet extraordinary levels of excellence
specified by U.S. Department of Energy (DOE) guidelines.

Feel great knowing you selected a 'best-in-class' home.

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ACME Homes

U.S. Department of Energy

ENERGY STAR + Building AMERICA U.S. Department of Energy

Tech-Savvy

Starting with a solid foundation of building science
specified by ENERGY STAR for Homes,
every DOE Challenge Home adds advanced technology features
from DOE's world-class research program, Building America.

Look for the proven innovations that work better.

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ACME Homes

U.S. Department of Energy

Visionary

Every DOE Challenge Home embraces a unique opportunity during design and construction to meet and exceed forthcoming codes. Additional details can save $1,000s installing a solar system down the road.

Rest assured your largest investment will meet future expectations.

ACME Homes

U.S. Department of Energy

Ultra-Efficient

Every DOE Challenge Home is so energy efficient, a small solar system can often offset most, or all, of your utility bills. We call this ***Zero Net-Energy Ready***.

Never worry about rapidly increasing utility costs.

ACME Homes

U.S. Department of Energy

Comfort Plus

Extraordinary attention to detail and better equipment included in every DOE Challenge Home surround you with even temperatures, low humidity, and quiet in every room on every floor.

Enjoy outstanding performance.

ACME Homes

U.S. Department of Energy

Healthful

The same way we want nutritious food on our plates, we want healthy air in our homes. Every DOE Challenge Home has a comprehensive package of measures that minimize dangerous pollutants, provide continuous fresh air, and effectively filter the air you breathe.

Experience a healthier home for your family.

ACME Homes

U.S. Department of Energy

Quality-Built

Advanced construction practices and technologies are specified for every DOE Challenge Home, but that is not enough. Independent verifiers rigorously inspect and test each home with detailed checklists diagnostics.

Hold your home to a higher standard.

ACME Homes

U.S. Department of Energy

Enduring

The advanced levels of energy savings, comfort, health, durability, quality, and future performance in every DOE Challenge Home deliver exceptional value. Value that will stand the test of time.

Live life in a home built to last.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

U.S. DEPARTMENT OF ENERGY CHALLENGE HOME

ACME Homes™

123 Main St., Any Town, US 12345
123-456-7890
acme@acmehomes.com
www.acmehomes.com

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

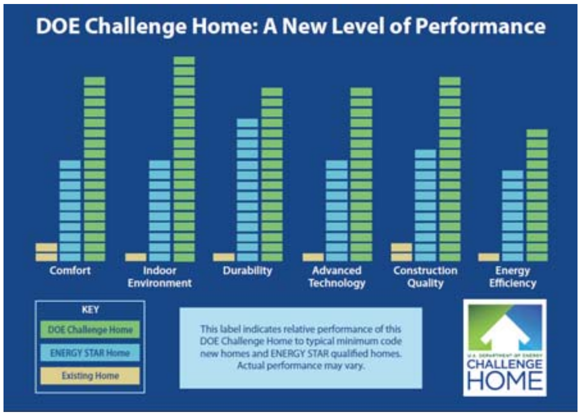
U.S. DEPARTMENT OF ENERGY CHALLENGE HOME

Look for the label that delivers the future of housing today.

To learn more, visit the Challenge Home website at www.buildings.energy.gov/challenge

Proposed Label

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Compare and Contrast Displays

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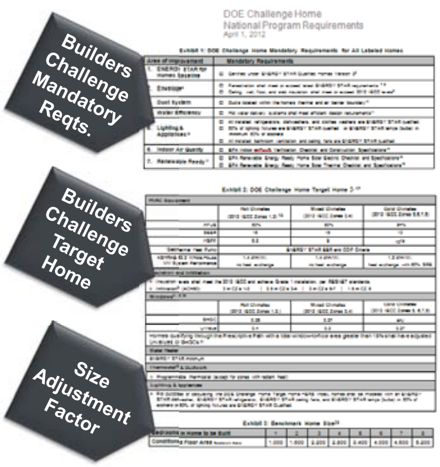
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Zero Net-Energy Ready

Technical Specifications

Alignment with ENERGY STAR v3

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Mandatory Requirements

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Exhibit 1: DOE Challenge Home Mandatory Requirements for All Labeled Homes

Area of Improvement	Mandatory Requirements
1. ENERGY STAR for Homes Baseline	☐ Certified under ENERGY STAR Qualified Homes Version 3[5]
2. Envelope[6]	☐ Fenestration shall meet or exceed latest ENERGY STAR requirements[7 8] ☐ Ceiling, wall, floor, and slab insulation shall meet or exceed 2012 IECC levels[9]
3. Duct System	☐ Ducts located within the home's thermal and air barrier boundary[10]
4. Water Efficiency	☐ Hot water delivery systems shall meet efficient design requirements[11]
5. Lighting & Appliances[12]	☐ All installed refrigerators, dishwashers, and clothes washers are ENERGY STAR qualified. ☐ 80% of lighting fixtures are ENERGY STAR qualified or ENERGY STAR lamps (bulbs) in minimum 80% of sockets ☐ All installed bathroom ventilation and ceiling fans are ENERGY STAR qualified
6. Indoor Air Quality	☐ EPA Indoor airPLUS Verification Checklist and Construction Specifications[13]
7. Renewable Ready[14]	☐ EPA Renewable Energy Ready Home Solar Electric Checklist and Specifications[15] ☐ EPA Renewable Energy Ready Home Solar Thermal Checklist and Specifications[16]

Encouraged:

- Quality Management
- WaterSense Label (indoor and outdoor)
- Disaster Resistance (IBHS Fortified Home)

Reference Design

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Exhibit 2: DOE Challenge Home Target Home 3-[17]

HVAC Equipment			
	Hot Climates (2012 IECC Zones 1,2)[18]	Mixed Climates (2012 IECC Zones 3,4)	Cold Climates (2012 IECC Zones 5,6,7,8)
AFUE	80%	90%	94%
SEER	18	15	13
HSPF	8.2	9	10[19]
Geothermal Heat Pump	ENERGY STAR EER and COP Criteria		
ASHRAE 62.2 Whole-House MV System Performance	1.4 cfm/W; no heat exchange	1.4 cfm/W; no heat exchange	1.2 cfm/W; heat exchange with 60% SRE
Insulation and Infiltration			
• Insulation levels shall meet the 2012 IECC and achieve Grade 1 installation, per RESNET standards. • Infiltration[20] (ACH50): 3 in CZ's 1-2 | 2.5 in CZ's 3-4 | 2 in CZ's 5-7 | 1.5 in CZ 8			
Windows[21, 22, 23]			
	Hot Climates (2012 IECC Zones 1,2,)	Mixed Climates (2012 IECC Zones 3,4)	Cold Clim (2012 IECC Zones
SHGC	0.25	0.27	any
U-Value	0.4	0.3	0.27
Homes qualifying through the Prescriptive Path with a total window-to-floor area greater than 15% shall have a U-values or SHGCs.[24]			
Water Heater			
ENERGY STAR minimum			
Thermostat[25] & Ductwork			
• Programmable thermostat (except for zones with radiant heat)			
Lighting & Appliances			
• For purposes of calculating the DOE Challenge Home Target Home HERS Index, homes shall be modeled with an ENERGY STAR dishwasher, ENERGY STAR refrigerator, ENERGY STAR ceiling fans, and ENERGY STAR lamps (bulbs) in 80% of sockets or 80% of lighting fixtures are ENERGY STAR Qualified.			

Higher Eff. HVAC Equip.

2012 vs. 2009 IECC Insul.

More Eff. Windows

Half ACH50

ENERGY STAR Water Htg.

Performance

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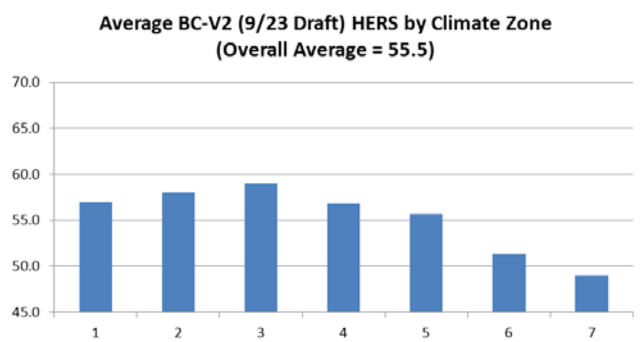


Verifying Homes

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Framework: Same as ENERGY STAR Homes
- New: Indoor airPLUS; Renewable Energy Ready Home checklists
- Software: compliance reporting to be built within EnergyGauge and REM/Rate
- Submissions: RESNET National Homes Registry

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Thank You

Questions?

For More Information:

http://www1.eere.energy.gov/buildings/challenge/

e-mail Contact:

builderschallenge@newportpartnersllc.com

Resisting the Monolithic:
The Influence of Construction Innovation on Single-Family House Spatialities in the Work of Gomes and Staub

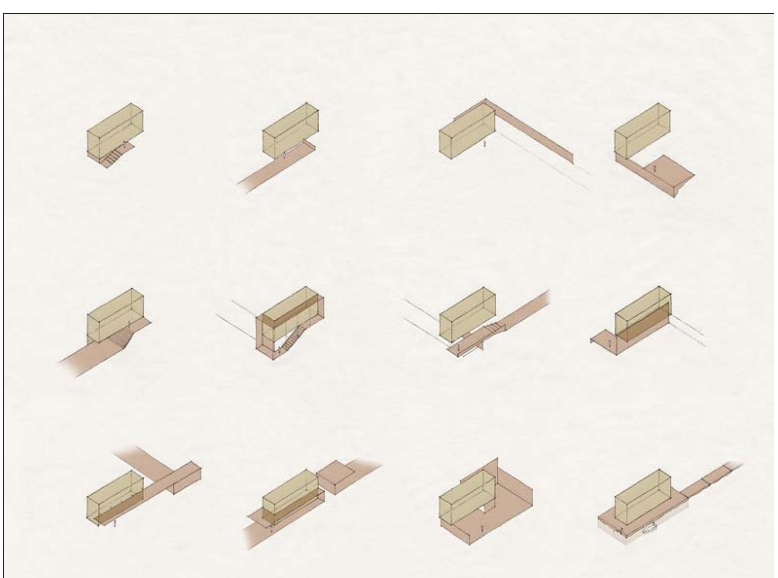
Francisco Gomes, AIA   The University of Texas at Austin School of Architecture



1st Residential Building Design and Construction Conference   The Pennsylvania State University

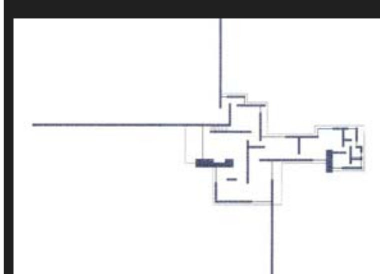
STITCH HOUSE

WIELER

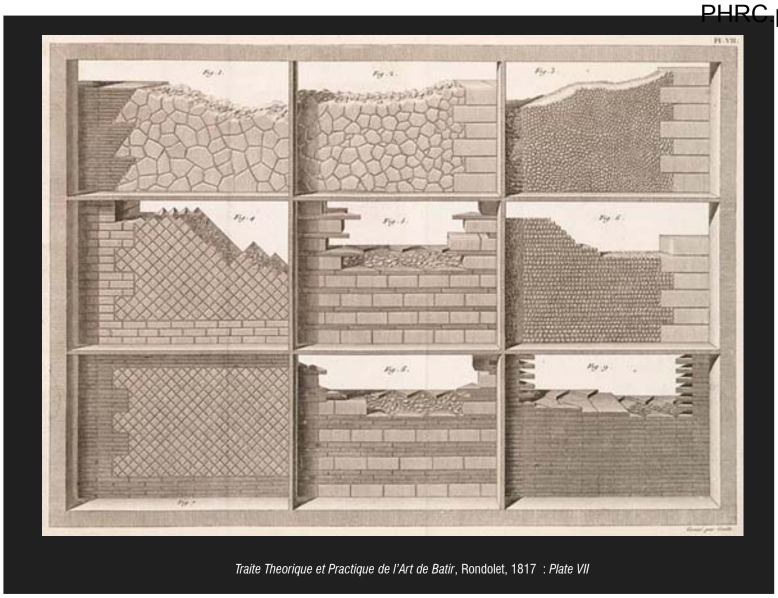


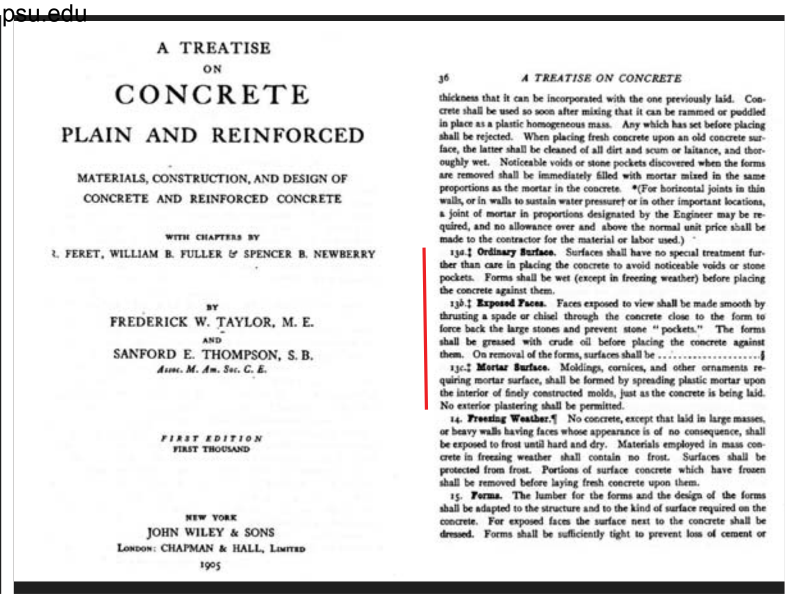
The Myth of the Monolithic

pre-modern mass walls were not imagined to be monolithic by those involved in their construction



Project for a Brick Country House
Mies van der Rohe, 1923





A TREATISE
ON
CONCRETE
PLAIN AND REINFORCED

MATERIALS, CONSTRUCTION, AND DESIGN OF
CONCRETE AND REINFORCED CONCRETE

WITH CHAPTERS BY
R. FERET, WILLIAM B. FULLER & SPENCER B. NEWBERRY

BY
FREDERICK W. TAYLOR, M. E.
AND
SANFORD E. THOMPSON, S. B.
Assoc. M. Am. Soc. C. E.

FIRST EDITION
FIRST THOUSAND

NEW YORK
JOHN WILEY & SONS
LONDON: CHAPMAN & HALL, LIMITED
1905

36 *A TREATISE ON CONCRETE*

thickness that it can be incorporated with the one previously laid. Concrete shall be used so soon after mixing that it can be rammed or puddled in place as a plastic homogeneous mass. Any which has set before placing shall be rejected. When placing fresh concrete upon an old concrete surface, the latter shall be cleaned of all dirt and scum or laitance, and thoroughly wet. Noticeable voids or stone pockets discovered when the forms are removed shall be immediately filled with mortar mixed in the same proportions as the mortar in the concrete. *(For horizontal joints in thin walls, or in walls to sustain water pressure† or in other important locations, a joint of mortar in proportions designated by the Engineer may be required, and no allowance over and above the normal unit price shall be made to the contractor for the material or labor used.)

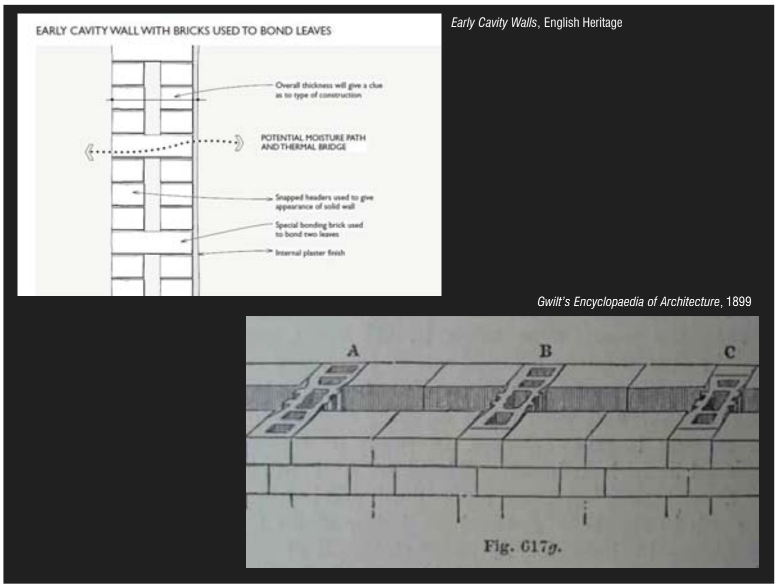
13*a*.‡ **Ordinary Surface.** Surfaces shall have no special treatment further than care in placing the concrete to avoid noticeable voids or stone pockets. Forms shall be wet (except in freezing weather) before placing the concrete against them.

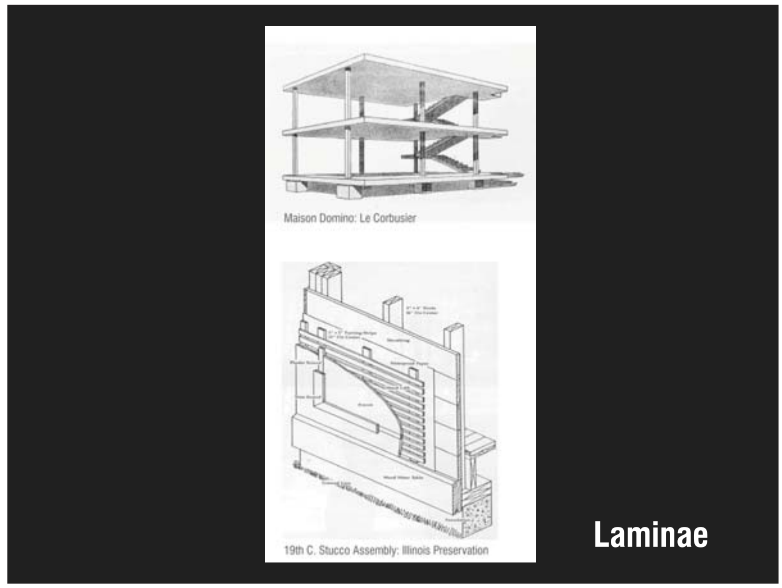
13*b*.‡ **Exposed Faces.** Faces exposed to view shall be made smooth by thrusting a spade or chisel through the concrete close to the form to force back the large stones and prevent stone "pockets." The forms shall be greased with crude oil before placing the concrete against them. On removal of the forms, surfaces shall be ....§

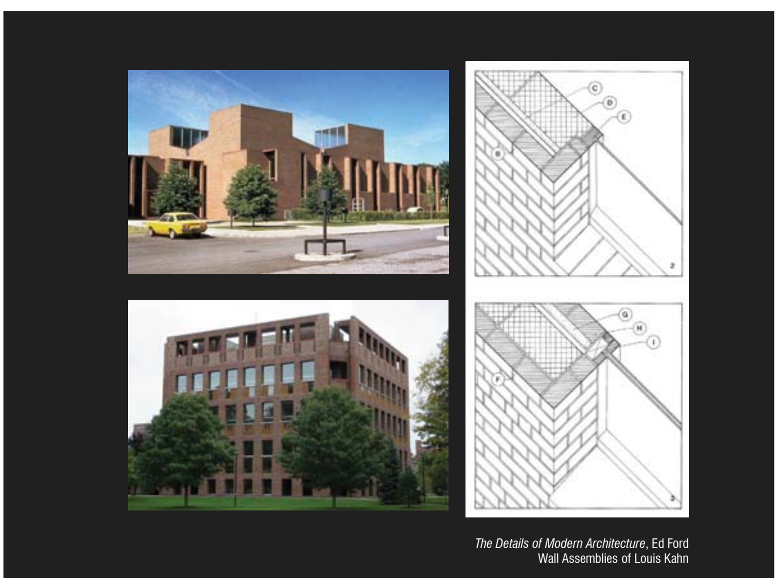
13*c*.‡ **Mortar Surface.** Moldings, cornices, and other ornaments requiring mortar surface, shall be formed by spreading plastic mortar upon the interior of finely constructed molds, just as the concrete is being laid. No exterior plastering shall be permitted.

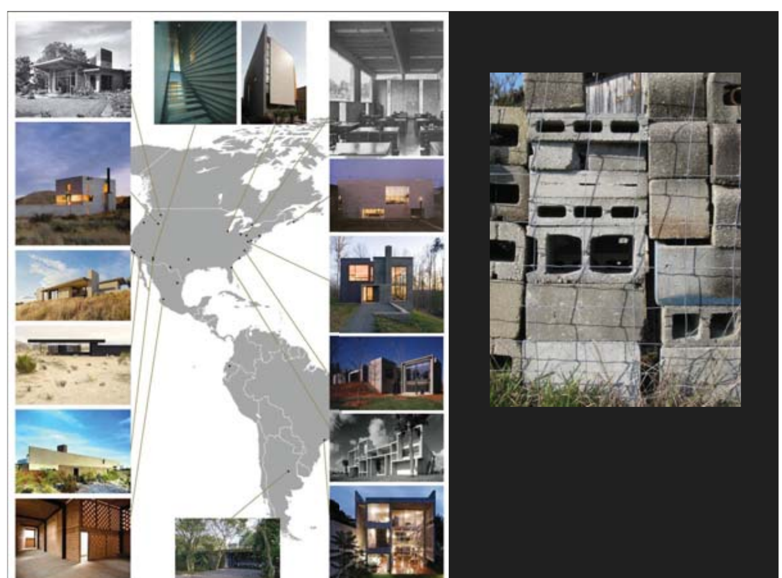
14. **Freezing Weather.**¶ No concrete, except that laid in large masses, or heavy walls having faces whose appearance is of no consequence, shall be exposed to frost until hard and dry. Materials employed in mass concrete in freezing weather shall contain no frost. Surfaces shall be protected from frost. Portions of surface concrete which have frozen shall be removed before laying fresh concrete upon them.

15. **Forms.** The lumber for the forms and the design of the forms shall be adapted to the structure and to the kind of surface required on the concrete. For exposed faces the surface next to the concrete shall be dressed. Forms shall be sufficiently tight to prevent loss of cement or





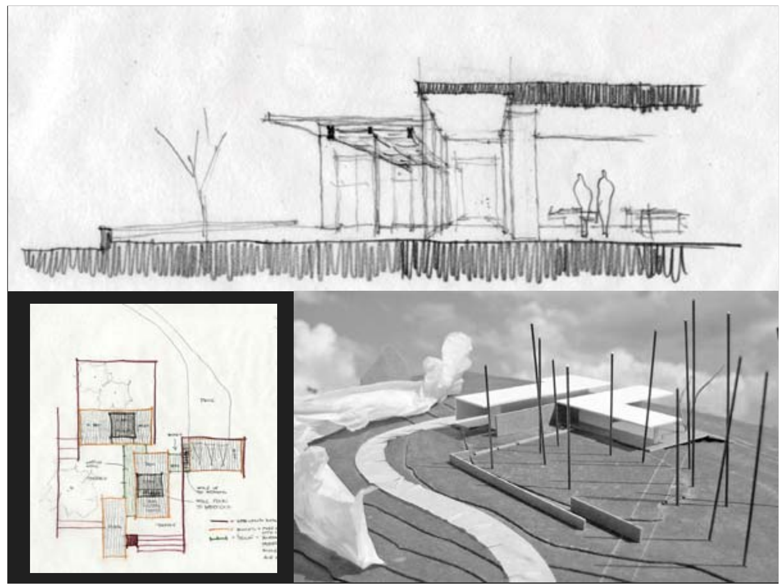


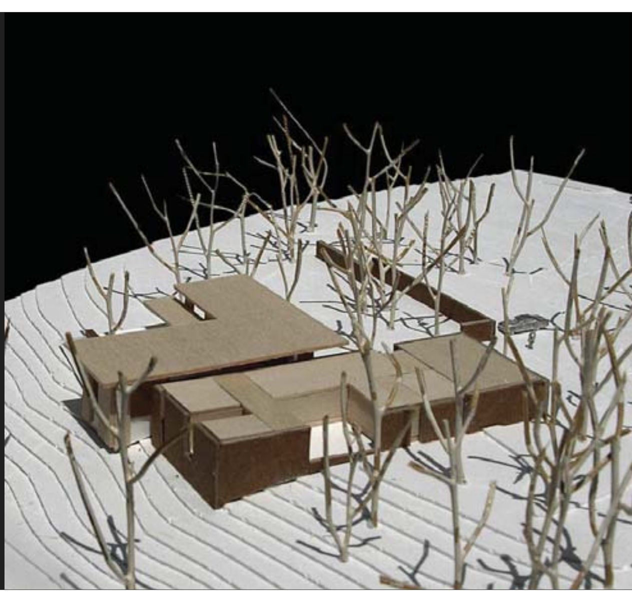


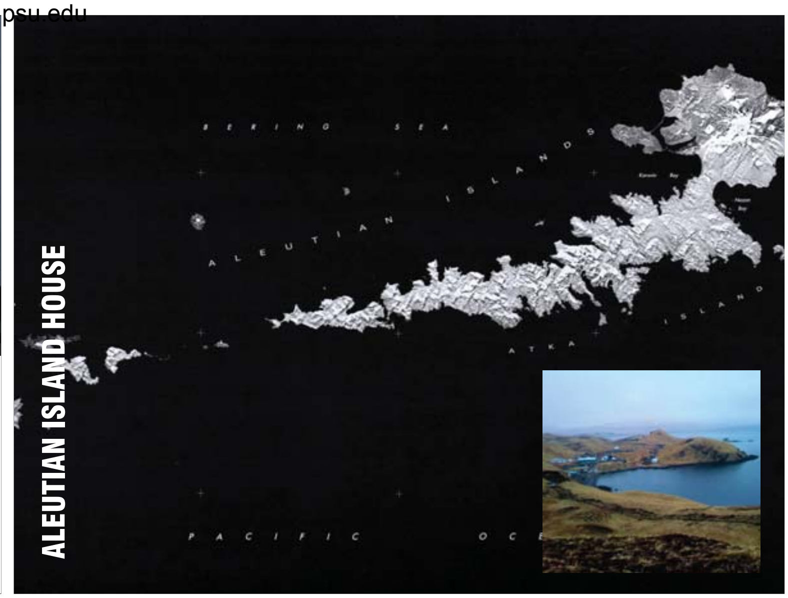
"The progressive substitution of thin, lightweight, and transparent elements of enclosure for thick, heavy, and opaque walls would seem to have completed itself in our time, were it not for the fact that many of the opportunities for figuration in architecture especially those associated with thick-wall construction remain unexplored within the context of modern building."

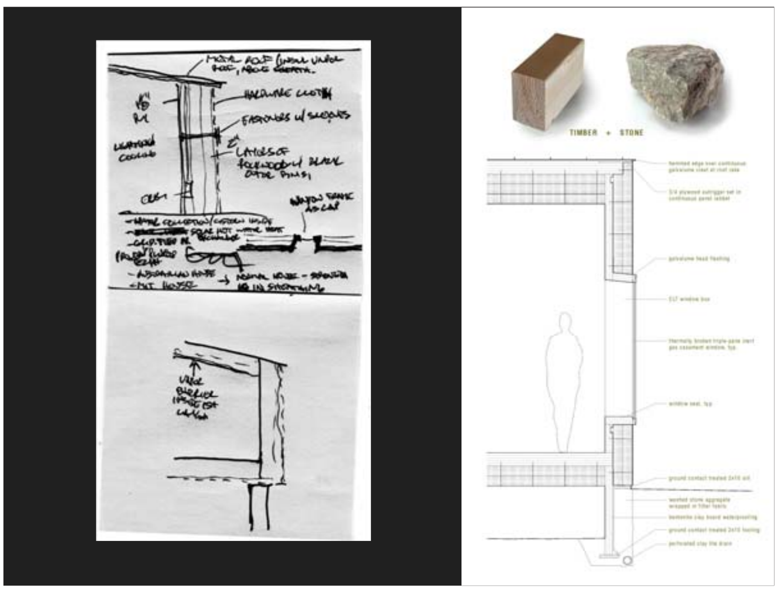
- *Surface Architecture*, Leatherbarrow and Mostafavi

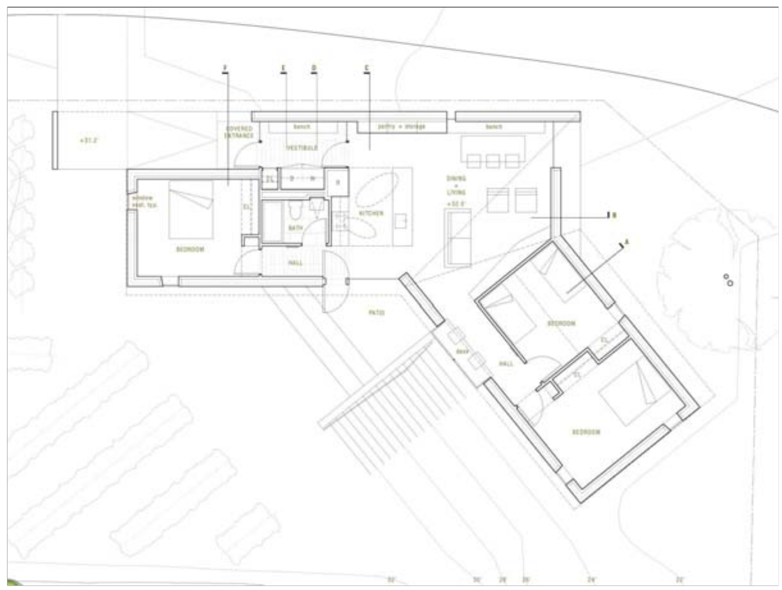
POSS-PAS HOUSE

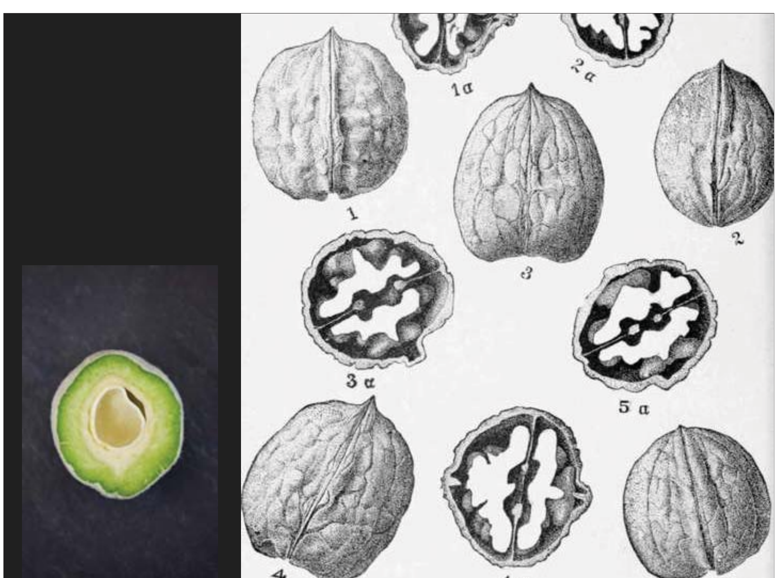


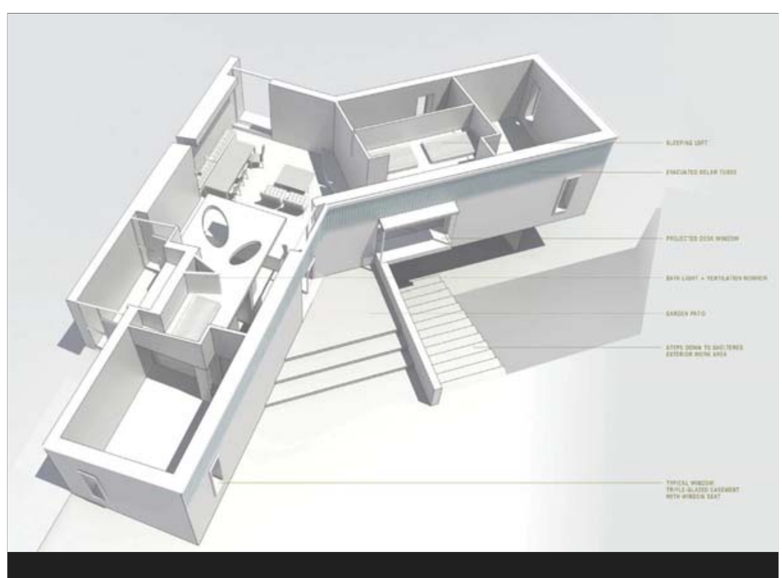



ALEUTIAN ISLAND HOUSE
BERING SEA
ALEUTIAN ISLANDS
PACIFIC


TIMBER + STONE



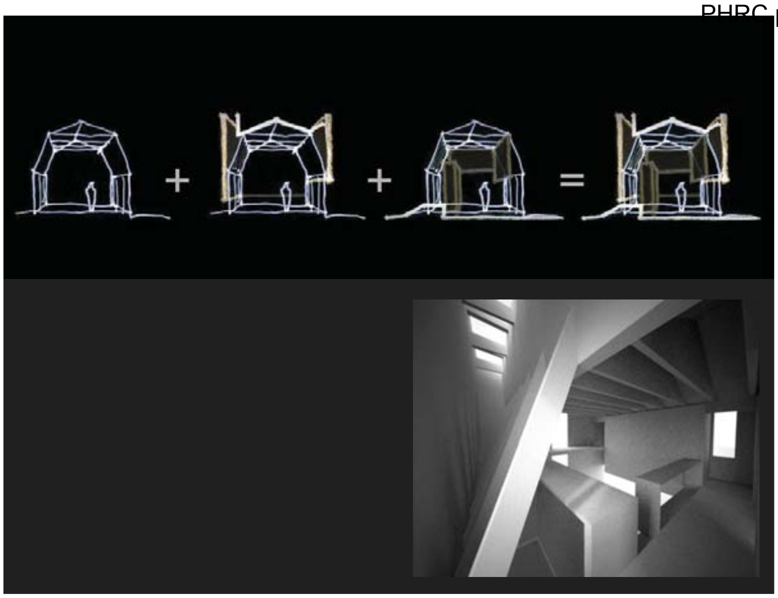


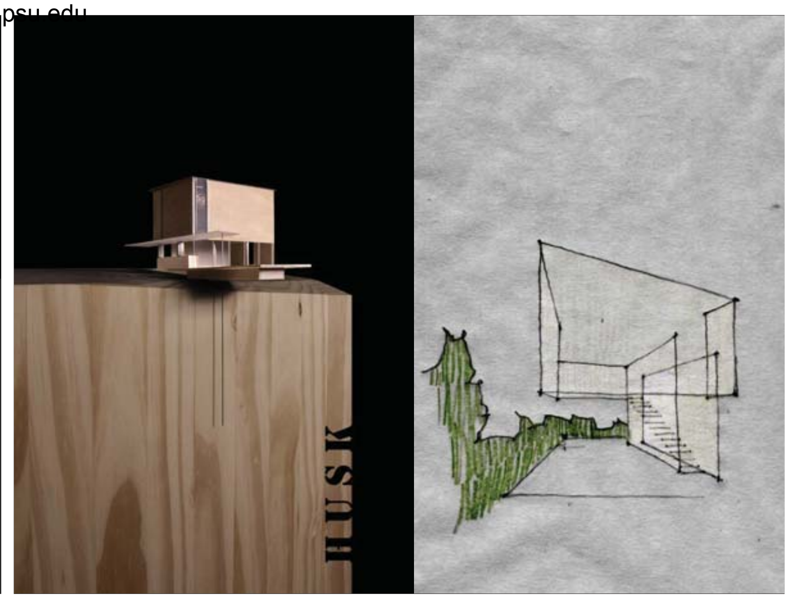



tryma
SECTION PERSPECTIVE

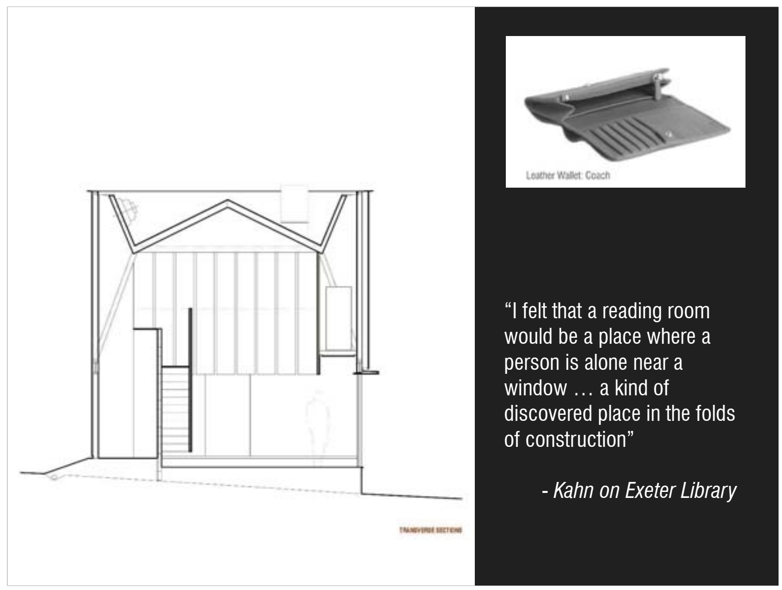

tryma
INTERIOR PERSPECTIVE

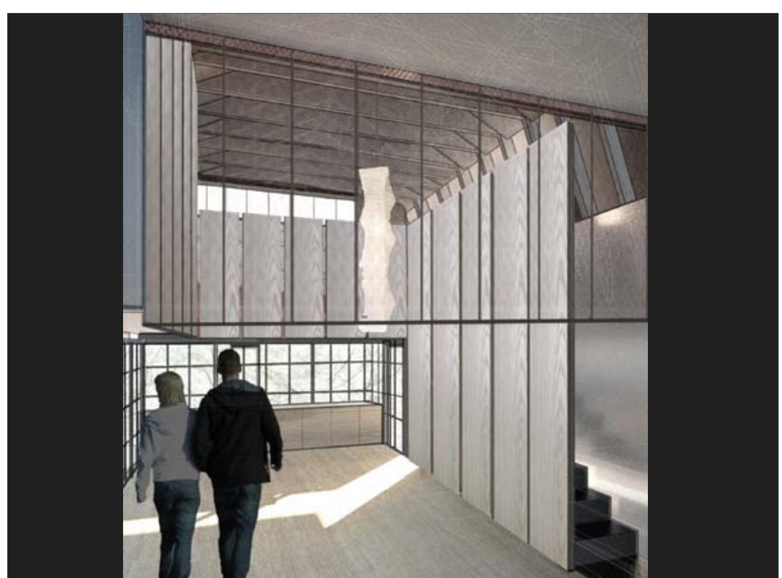

HUSK HOUSE




HUSK


LIVING
BATH
DINING
KITCHEN
ENTRY PORCH
CISTERN
GROUND LEVEL PLAN
SLEEPING LOFT
LIGHT + VENTILATION MONITOR
OPEN TO BELOW
MECH
BEDRM
BEDRM
BALCONY
UPPER LEVEL PLAN


Leather Wallet: Coach
"I felt that a reading room would be a place where a person is alone near a window … a kind of discovered place in the folds of construction"
- Kahn on Exeter Library



NewHolland CONCRETE
Architectural Products
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Introduction to Insulating Concrete Forms (ICF)

CONSTRUCTION SUPPLY CENTERS BY NEW HOLLAND CONCRETE

REWARD WALL SYSTEMS

AIA Best Practice Notice

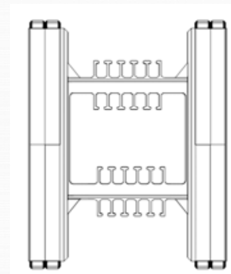
- New Holland Concrete is a registered Provider with AIA CES. Credit earned on completion of this program will be reported to CES Records for AIA members. Certificates of Completion will be mailed to the firm.
- This program is registered with AIA/CES for continuing professional education. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the AIA of any material or any construction method or manner of handling, using, distributing, or dealing in any manner or product. Questions related to specific materials, methods and services will be addressed at the conclusion of this presentation.

We will discuss the hows & whys of ICF's.

- ✓ Savings through:
  - ✓ reduced energy costs,
  - ✓ smaller HVAC systems,
  - ✓ smaller monthly payments,
  - ✓ no mold repairs,
  - ✓ less air infiltration,
  - ✓ smaller insurance premiums,
  - ✓ less life cycle costs,
  - ✓ shorter schedule
- ✓ Easier for subcontractors.
  - ✓ less skilled workers needed.
- ✓ Provide all the benefits of concrete walls:
  - ✓ indoor air quality,
  - ✓ fire resistance,
  - ✓ sound,
  - ✓ storm safety,
  - ✓ longevity.
- ✓ Use any exterior and interior finishes
- ✓ Contributes to LEED points

Functions of ICF Wall

- Structural Concrete Wall With Stay in Place Forms
- Insulation
- Finish Attachment
- Chase for Utilities
- Air Barrier
- Vapor Barrier

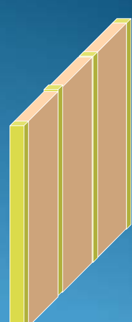


Frame Wall

Typical Stud Wall

20% framing (R-4.38)

80% insulation (R-11)



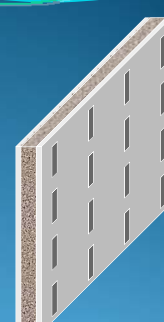
Typical ICF Wall

100% insulation (R- 16 to 22)

100% monolithic structure

Integral furring

Fully insulated concrete wall



Residential-Any Shape, Any Finish

Commercial-Hotels to City Infill Sites

History

- Invented in 1946 as Durisol
  - Wood waste and cement in post-war Europe
- Polystyrene foam
  - Introduced in 1970s
- Growth Industry
  - 1990s to present

Trends

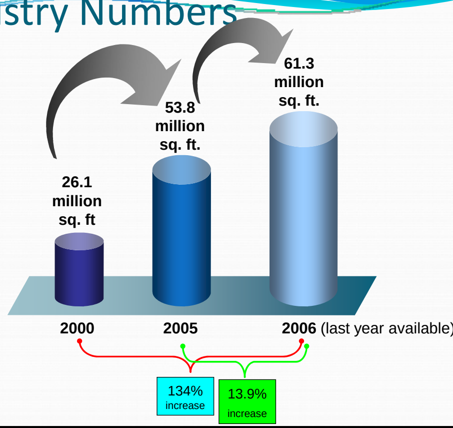
ICF construction has become popular in various commercial applications, especially those involving habitation such as:

- Condominiums
- Theaters
- Schools
- Hotels
- Hospitals
- Churches

Commercial ICF construction grew 17.7% in 2007

-Ed Sullivan, chief economist for the Portland Cement Association

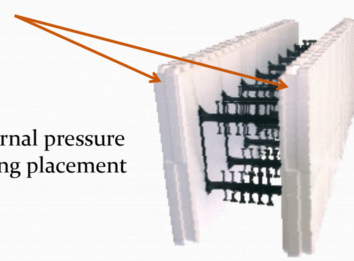
Industry Numbers



Components

Face Shell

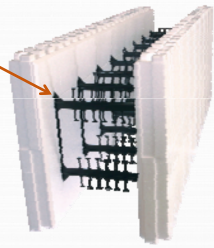
- 2 to 2.5" thick
- R-18 to R-22
- EPS or XPS
- Withstands internal pressure of concrete during placement



Components

Form Tie

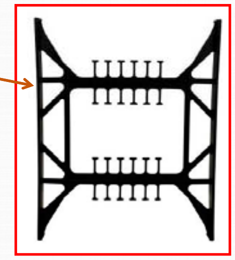
- Plastic or metal
- 6" to 12" o.c.
- Rebar saddles



Components

Form Tie Face

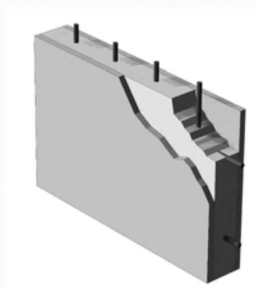
Tie face for attachment of finishes can be exposed or recessed



Components

Reinforced Concrete Core

- 4", 6", 8", 10" or 12"
- Cast-in-place Monolithic
- 2,500 to 4,000 psi
- 6" slump
- Up to ¾" aggregate
- Rebar = 40 or 60 ksi



End Result

Exterior shell with:

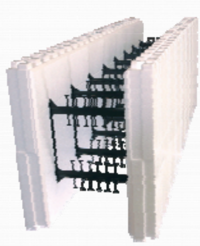
- LEED™ Rating System Contributions
- Thermal Performance
  - High R-value
  - Thermal Mass
  - Virtually no thru wall infiltration
- Acoustical Attenuation
- Disaster Resistance
- Low Maintenance

Form Variations

50+ ICF Manufacturers

- Assembly Method affects contractor
- Tie Configuration affects

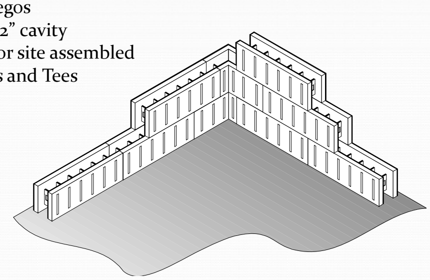
structural designer and contractor.



Assembly Methods

Block System

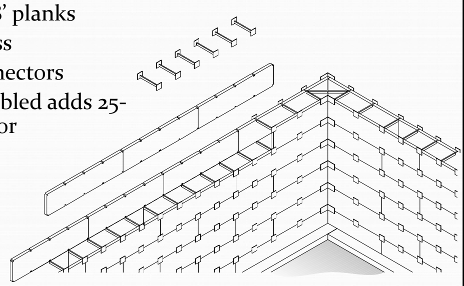
- Typically 16" high x 48" long interlock like Legos
- 4", 6", 8", 10" or 12" cavity
- Pre-assembled or site assembled
- Corners, Ledges and Tees



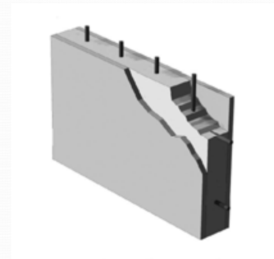
Assembly Methods

Horizontal Plank

- 12" x 4' or 8' planks
- 2" thickness
- Loose connectors
- Site Assembled adds 25-30% in labor



Provides a Flat Concrete Wall With Foam on Both Sides



Installation

Lightweight

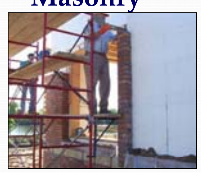
Rough Openings

Common Hand-tools

Versatile-to a 2′ Radius

Allied Trades

Masonry



Lath for Stucco or Stone

Drywall

Electrical

Plumbing

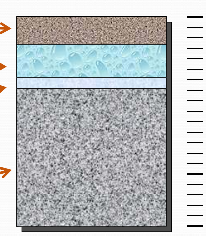
Benefits of ICFs

- Sustainability
- Thermal Performance
- Disaster Resistance
- Acoustical Attenuation
- Maintenance and Durability
- Fire Safety

Sustainable

Cement 10-15%
Water
Air
Coarse and Fine Aggregates

Locally derived 85-90% by weight



Cement Manufacturing

- CO^2 generated by fuel combustion & calcining
- Production research has led to 29% reduction of CO^2 and embodied energy in the past 3 decades
- Concrete research has led to more efficient mix design and admixture substitutions, reducing the cement content.

Cement Manufacturing

- Alternative fuel sources include TDF (tire derived fuel)
- Pound per pound, tires contain more energy than coal. 25 Mil Tires in 2008.

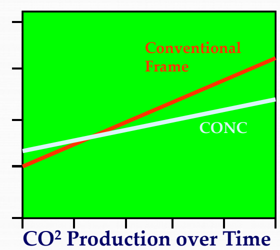
Concrete Research

- Industrial by-products such as fly-ash, blast furnace slag, and silica fume reduce cement requirements for concrete.

- 180,000,000 pounds of fly-ash were used in concrete in 2000 instead of heading to landfills.

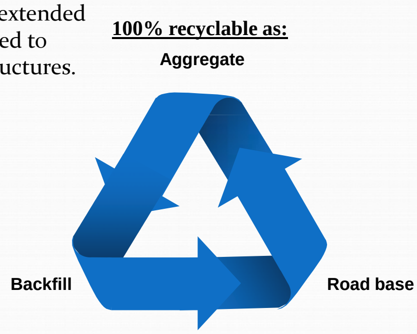
Life Cycle Inventory

- "Cradle to grave" analysis revealed 90% of CO^2 production for a home is during operation (heating/cooling)
- Concrete homes have a burden of CO^2
- After 5-7 years, the CO^2 generated by a conventionally built house exceeds that of an ICF home.

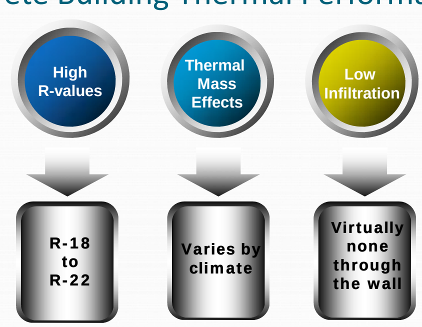


Recycling

Concrete has an extended life span compared to wood or steel structures.



Concrete Building Thermal Performance

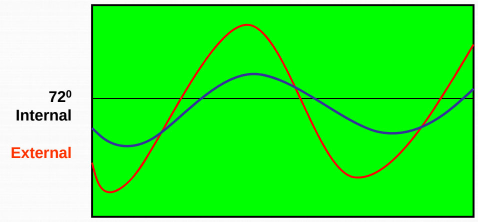


Thermal Mass

Thermal mass principles have been used for centuries to Store and Release Heat Energy..

Thermal Mass

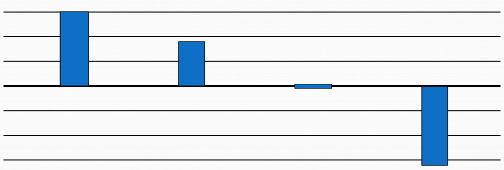
- Moderates internal temperature swings
- Increases occupant comfort
- Reduces energy requirements.



Air Infiltration

Energy Savings related to Air Changes / Hour

.03 to .16 ach	.39 ach	.78 ach	1.5 ach
Tight (ICF)	Moderate	Average	Leaky
15%	9%	0%	-16%



Acoustic Performance

STC Rating

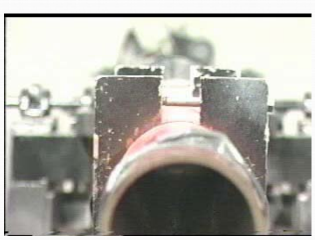
- 6" 18 gauge metal studs o.c. = 36-51
- 8" cmu #4 @ 32" o.c. = 44-48
- 6" ICF wall = **51**

- Beneficial in various commercial building applications, including hotels, multi family condominiums, theaters or structures near airports or interstates.

Disaster Resistance

- Concrete is inherently resistant to tornados, hurricanes, fire, insects, rot and rusting

- 1997 Texas Tech University testing of wind blown debris with the "Tornado Cannon" 250 mph wind



Durability & Maintenance

- In-place thermal performance is not highly dependent on installer quality
- Minimal thermal or moisture induced movement or shrinkage
- No rot, rust or thru-wall condensation.

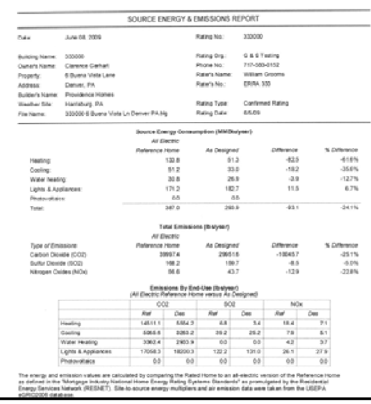
LEED™ - New Construction (NC)

Energy and Atmosphere

- *Prerequisite 2:* Minimum Energy Performance
- *Credit 1:* Optimized Energy Performance

Building the exterior walls with Insulating Concrete Forms contributes to this requirement and credit by providing superior air tightness, insulating value and thermal massing. Thermal mass of ICFs are equivalent to Conventional R30 (MN) to R48 (FL) walls.

Energy Star Report



SOURCE ENERGY & EMISSIONS REPORT

Date:	June 08, 2009	Rating No.:	330000
Building Name:	330000	Rating Org.:	G & S Testing
Owner's Name:	Clarence Gerhart	Phone No.:	717-[illegible]
Property:	6 Buena Vista Lane	Rater's Name:	William Grooms
Address:	Denver, PA	Rater's No.:	ERRA 330
Builder's Name:	Providence Homes		
Weather Site:	Harrisburg, PA	Rating Type:	Confirmed Rating
File Name:	330000 6 Buena Vista Ln Denver PA.blg	Rating Date:	6/5/09

Source Energy Consumption (MMBtu/year)

	All Electric Reference Home	As Designed	Difference	% Difference
Heating:	132.8	51.2	-82.5	-61.6%
Cooling:	51.2	33.0	-18.2	-35.6%
Water heating:	30.8	26.9	-3.9	-12.7%
Lights & Appliances:	171.2	182.7	11.5	6.7%
Photovoltaics:	0.0	0.0		
Total:	387.0	293.9	-93.1	-24.1%

Total Emissions (lbs/year)

Type of Emissions	All Electric Reference Home	As Designed	Difference	% Difference
Carbon Dioxide (CO2)	39957.4	29951.6	-10045.7	-25.1%
Sulfur Dioxide (SO2)	168.2	159.7	-8.5	-5.0%
Nitrogen Oxides (NOx)	56.6	43.7	-12.9	-22.8%

Emissions By End-Use (lbs/year)
(All Electric Reference Home versus As Designed)

	CO2		SO2		NOx	
	Ref	Des	Ref	Des	Ref	Des
Heating	14511.1	5554.3	6.8	5.4	18.4	7.1
Cooling	4064.6	3283.2	39.2	29.2	7.8	6.1
Water Heating	3362.4	2903.9	0.0	0.0	4.2	3.7
Lights & Appliances	17058.3	18200.3	122.2	131.0	26.1	27.9
Photovoltaics	0.0	0.0	0.0	0.0	0.0	0.0

The energy and emission values are calculated by comparing the Rated Home to an all-electric version of the Reference Home as defined in the "Mortgage Industry National Home Energy Rating Systems Standards" as promulgated by the Residential Energy Services Network (RESNET). Site-to-source energy multipliers and air emission data were taken from the USEPA eGRID2006 database.

LEED™ - NC

Material and Resources

- *Credit 2:* Construction Waste Management
- *Credit 4:* Recycled Content
- *Credit 5:* Regional Materials

Incorporating ICFs can help a project qualify for points by reducing waste, increasing recycled content, and by increasing the use of locally derived materials.

LEED™ - NC

Indoor Environmental Quality

- *Credit 7.1:* Thermal Comfort
  - Tight construction reduces air infiltration
  - Thermal mass tempers wall surface temperature swings
  - Dry inert materials to start with prevent accidental humidification and condensation

LEED™ - NC

Innovation and Design

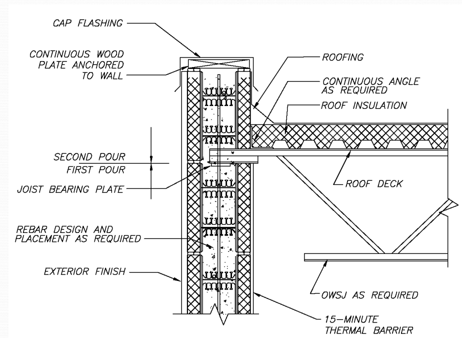
- *Credit 1:* Innovation in Design
  - *No off gassing or VOCs*
  - *Long Life Cycle*
  - *Mold Growth Control*

Commercial

Medical Office Building
Shawnee, KS

Silverton Medical Properties
Silverton, OR

Parapet Detail CAD on CD

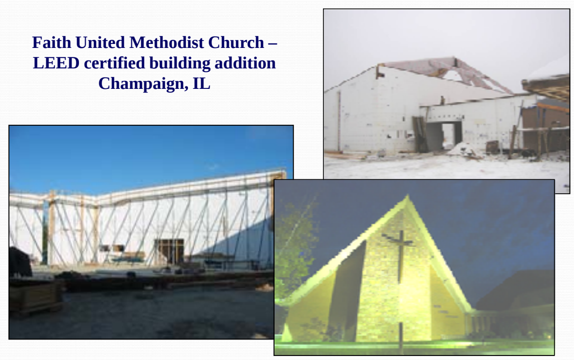


Commercial - Curves

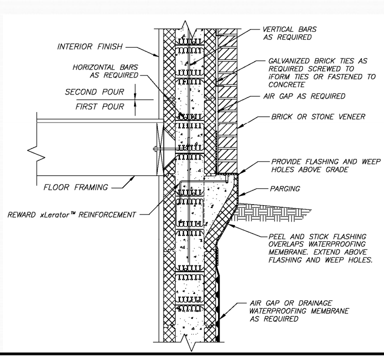
Butterfly Palace
Branson, MO

Commercial

Faith United Methodist Church – LEED certified building addition
Champaign, IL



Brick Ledge Application



Commercial

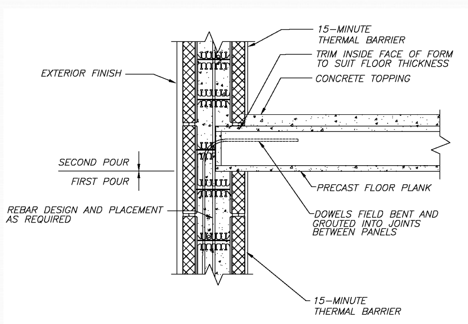
E^2 City Homes –
"LEED for Homes" pilot project
Minneapolis, MN

Commercial

Fairfield Inn
Williamsport, PA

Carleton College Dorms Minn.

Precast Hollowcore Plank Detail



Commercial Infill

Waterside IV and V
Fort Meyers, FL

Commercial

8 Story Trendwest Seaside Resort, Oregon

Commercial

Seaside Resort

Commercial


**Best Western
Pelican Beach, FL**

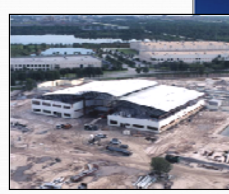
Commercial – 46' to 54' High walls


**JW Marriott Grande Lakes Exhibition Hall
Orlando, FL**


**Hampton Inn
Oneonta, NY**

Commercial – Schedule and Force Containment

**140,000 Sq Ft Florida Armed Forces Reserve Center
Tampa, FL**

Commercial

Florida Armed Forces Reserve Center

Commercial


**7 Story-The Resort at Pigeon Forge
Pigeon Forge, TN, Dollywood – Weather
Little Factor**

Commercial

Megaplex 20 at the District Movie Theater, South Jordan, UT 206,000 SF, 50 Ft Walls

Commercial

Megaplex 20 at the District Movie Theater, UT

Commercial

Atlantis 15 Theater
Burnsville, MN

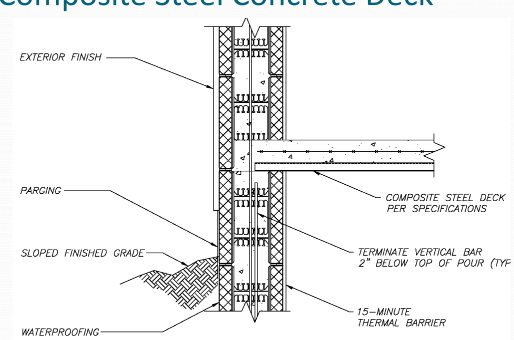
Commercial

Atlantis 15 Theater, 54 Ft Walls, MN

Commercial

Surrey Grand Crowne Resorts
Branson, MO

Composite Steel Concrete Deck



Commercial

Lakemont Landing – offices/warehouses
Lakemont, CO

Commercial

Office/Warehouse
Omaha, Nebraska

ICF Resources

ICFA
www.forms.org
(888) 864-4232

Insulating Concrete Form Association

Portland Cement Association
www.cement.org
(847) 966-6200

pca

National Ready-Mixed Concrete Association
www.nrmca.org
(301) 587-1400

NRMCA

Resources

- Reward Product Manual & CD
- Architect Design Guide
- Dynamic Block Library CD

Questions?

- Savings through:
  - reduced energy costs,
  - smaller HVAC systems,
  - smaller monthly payments,
  - no mold repairs,
  - less air infiltration,
  - smaller insurance premiums,
  - less life cycle costs,
  - shorter schedule
- Easier for subcontractors.
  - less skilled workers needed.
- Provide all the benefits of concrete walls:
  - indoor air quality,
  - fire resistance,
  - sound,
  - storm safety,
  - longevity.
- Use any exterior and interior finishes
- Contributes to LEED points

CONTINUING EDUCATION AIA

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Architectural Consultant
dgerdel56@msn.com
717-381-7006

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REWARD WALL SYSTEMS