The State-of-the-Art Application of Modular Construction to Multi-Story Residential Buildings

Anthony C. Jellen P.E. [1] and Ali. M. Memari PhD, P.E. [2]

[1] Department of Civil Engineering, 105 Engineering Unit B, University Park, PA 16802

[2] The Pennsylvania Housing Research Center (PHRC), Department of Architectural Engineering and Department of Civil and Environmental Engineering, 219 Sackett Building, University Park, PA 16802

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)

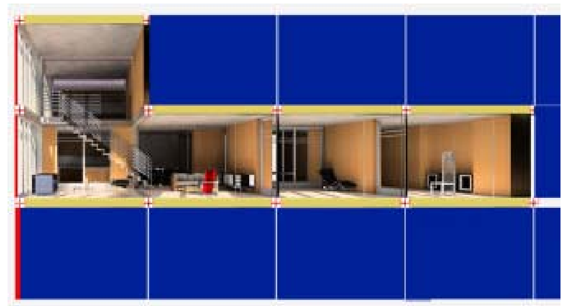
Figure 8. Hybrid structure, Lillie Rd. Fulham (Image by Lawson and Ogden, 2008)

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.

References

AMA Research Ltd. 2007. "Current Practices and Future Potential in Modern Methods of Construction". Waste & Resources Action Programme.

Birgerrson, B. 2004. *The Open House 3D Modulus System*. The Swedish Institute of Steel Construction.

CABE. 2012. "[ARCHIVED CONTENT] Murray Grove, Hackney, London | Case Studies | CABE." Accessed October 25. http://webarchive.nationalarchives.gov.uk/20110118095356/http:/www.cabe.org.uk/case-studies/murray-grove.

Cuperus, Y. 2001. "An Introduction to Open Building." In *Proceedings of the 9th Annual Conference of the International Group for Lean Construction*. Copenhagen, Denmark.

Lawson, R.M, R.G. Ogden, and R. Bergin. 2012. "Application of Modular Construction in High-Rise Buildings." *Journal of Architectural Engineering* (June) (June): 148–154.

Lawson, R.M, R.G. Ogden, R. Pedreschi, P.J. Grubb, and S.O. Popo-Ola. 2005. "Developments in Pre-fabricated System in Light Steel and Modular Construction." *The Structural Engineer* (March 15): 28–35.

Lawson, R.M., and R.G. Ogden. 2008. "'Hybrid' Light Steel Panel and Mdular Systems." *Thin-Walled Structures* (46): 720–730.

MBI. 2010. *Improving Construction Efficiency & Productivity with Modular Construction*. Charlottesville, VA: Modular Building Institute.

MBI. 2013a. "19 Story Dorm in UK." Accessed January 7. http://www.modular.org/HtmlPage.aspx?name=19_Story_Dorm_UK.

MBI. 2012b. "O'Connell East Architects Design 24-story Modular | Modular.org." Accessed October 25. http://www.modular.org/htmlPage.aspx?name=24_story_modular.

McGraw-Hill Construction. 2011. "Prefabrication and Modularization: Increasing Productivity in the Construction Industry". McGraw-Hill Construction.

"MIT House_n." 2012. Accessed October 30. http://architecture.mit.edu/house_n/index.html.

MBI. 2011. "Permanent Modular Construction, 2011 Annual Report". Modular Building Institute.

Parkins, J. 2012. "Are Skyscrapers the Cities of the Future?" *DesignBuild Source*. Accessed October 19. http://designbuildsource.com.au/super-dense-china.

SCI. 2003a. *Worlds Largest Modular / Steel Framed Building in Manchester*. Case Study. Residential Buildings Case Study 6. Berkshire, U.K.: The Steel Construction Institute.

SCI. 2003b. *Six Storey Housing Using Light Steel Framing and Bathroom Modules*. Case Study. Residential Buildings Case Study 8. Berkshire, U.K.: The Steel Construction Institute.