Building Enclosure Design for Modular Construction

Tammy J. Harrell[1], Joseph P. Piñon[2], and Colin D. Shane[3]

[1] Building Science Engineer, RDH Building Science Inc., 360 22nd Street, Suite 710, Oakland, CA 94612, 510-788-8918, tharrell@rdh.com.
[2] Principal, Building Science Specialist, RDH Building Science Inc., 510-788-8917, jpinon@rdh.com.
[3] Associate, Senior Project Manager, RDH Building Science Inc., 510-788-8916, cshane@rdh.com.

ABSTRACT

Many of the purported advantages associated with modular wood-frame construction compared to traditional stick-built framing are generally well accepted in the industry: increased quality control, indoor construction, shorter project schedules, ability to service remote locations, and in some cases favorable labor and material pricing. Despite all of these advantages, special attention needs to be given to the integration and assembly of the building enclosure components, both within and between building modules, to ensure that the performance of these modular buildings meet the expectations of all parties involved.
This paper will focus on the building enclosure functions of heat, air, and moisture control in wood-framed residential buildings, and will apply these concepts to the realities of modular construction. Specifically, this paper will detail lessons learned through design and construction of two recently completed modular construction projects. The first project is a multi-unit dormitory located in an isolated northern climate and incorporates super-insulated assemblies and Passive House certification requiring a high performance building enclosure. The second project is a multi-unit transit-oriented and affordable housing development in the San Francisco Bay Area. This paper will inform designers and builders about building enclosure design considerations and challenges specific to modular construction.

INTRODUCTION AND BACKGROUND

Modular construction is a type of prefabrication method where three-dimensional living spaces are built off-site and transported to site and assembled into the final building structure. At one end of the spectrum, modules could consist of only the primary structural elements (walls, floors, etc.); however, we are increasingly seeing modular units with factory-built windows and cladding systems; mechanical, electrical, and plumbing systems; and complete interior finishes. Modular construction is similar in intent, yet different in scale than unitized, panelized and component construction where smaller components of the building are constructed off site, such as unitized curtain walls, panelized wall cladding systems, or pre-fabricated roof trusses.

There are numerous reported advantages to modular construction: shorter construction schedule, favorable and safer working conditions in a factory setting, better quality control, reduced material waste, and less time lost due to weather. From an owner's perspective, one of the most appealing advantages of modular construction is the potential for greater financial return due to the reduced construction time. Since modules are constructed off site, preliminary site work and modular production can occur in parallel, reducing costs associated with construction general conditions. The Modular Building Institute reports that commercial housing such as apartment buildings and student housing can be built and ready for occupancy in less than 90 days (MBI, 2015). A study conducted on modular housing by Ryan E. Smith, Director and Associate Professor at the University of Utah, concluded an average cost savings of 16% and schedule reduction of 45% over traditional construction methods (Smith, 2015). The MacDougal Apartment Complex in Brooklyn, New York, for instance, is a six story modular housing project consisting of 65 studio apartments constructed with 84 modules. The modules were built at a nearby facility and were placed on site in a record 12 days (MBI, 2012).

As with panelized and unitized component construction, modular construction is particularly suited for repetitive designs where the same two or three layouts can be repeated. Production-line efficiency is achieved by repetition of material cuts, worker tasks and ease of handling modules of similar size. The potential efficiencies associated with modular construction are reduced as more custom non-repetitive designs are implemented. Other instances where modular off-site construction may be advantageous include remote project locations and if labor shortages exist at the project location.

With all of these apparent benefits of modular construction, it may be surprising that permanent modular construction only makes up 2.93 percent of the North American market share value (MBI, 2015). Some commonly cited disadvantages include the architectural limitations associated with repetitive designs, the costs associated with temporary protection for rain and other elements, and the inherent double thickness walls and floors that equates to loss of space and extra material cost.

FUNCTIONS OF THE BUILDING ENCLOSURE

Regardless of the building type or the method of construction, the functional requirements of building enclosures remain the same: the building enclosure needs to provide environmental separation between interior and exterior spaces. In addition to resisting and transferring structural loads, the building enclosure needs to control the following elements:

→ Water penetration

→ Heat flow

→ Air flow and air leakage

→ Vapor diffusion and accumulation of condensation

→ Fire and smoke

→ Light, solar, and other radiation

→ Noise

The building enclosure certainly performs several other functions, including providing security, privacy, views, and the primary architectural aesthetic; however, the above list represents the key performance aspects typically associated with building science and building enclosure engineering.

Various materials are used within exterior walls to perform the control functions listed above. The term critical barrier can be used to refer to materials and components that together perform a specific control function that is necessary for the building enclosure system to perform as intended. A partial list of commonly considered critical barriers and their relationships with different building enclosure control functions is shown below in Figure 1.

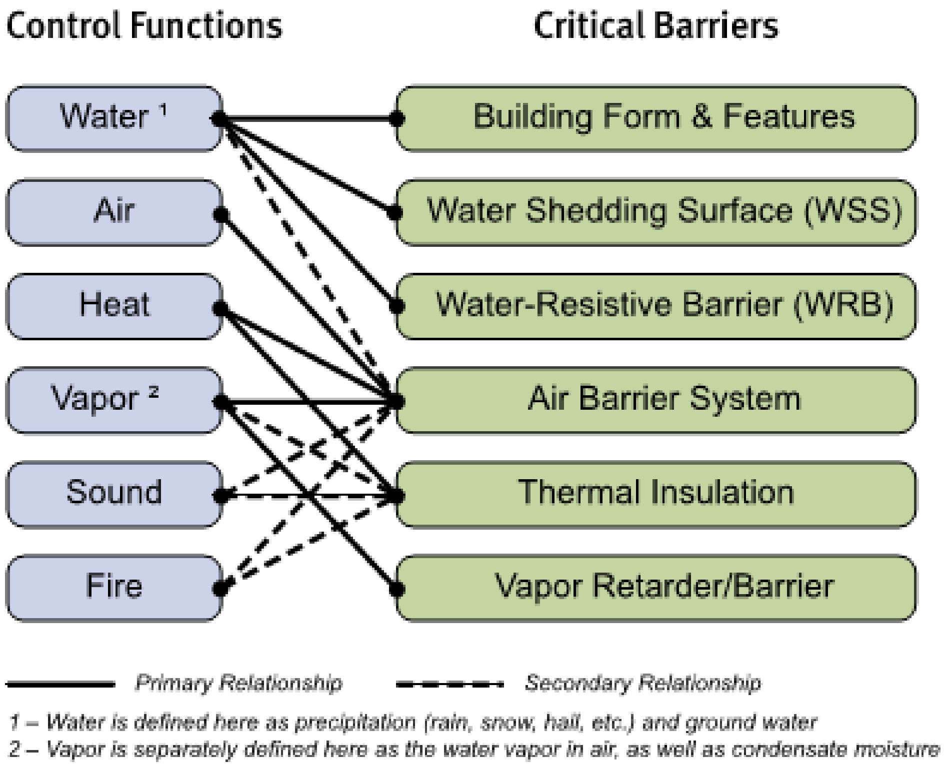

Figure 1. Relationships between building enclosure control functions and common critical barriers

THE CHALLENGES OF MODULAR CONSTRUCTION

Continuity of the various critical barriers – within and between assemblies, across details, and at other transitions – is necessary to ensure that the building enclosure functions as intended. Site-built construction sequencing and staging generally allows for the sequential installation, field inspection, and quality control of each of the critical barriers throughout the course of construction. For instance, a sheathing membrane that acts as both the air and water-resistive barrier can be fully installed prior to the installation of the cladding layers (water shedding surface (WSS)). The water control layers can also readily be installed in shingle-lapped fashion to minimize the risk of water penetration at joints. Furthermore, the installation of the water-resistive barrier (WRB) is generally fully completed prior to the installation of interior finishes and other weather sensitive components. Indeed, "weathering in" your building with a completed roofing membrane and wall WRB is a common milestone in traditional site-built construction.

In contrast, with modular construction, the interior finishes are often installed in the modules and delivered to site before the building is "weathered in" on all sides, thereby significantly increasing the risk of water damage during construction (unless each module is covered on all six sides). For no other type of construction would the owners or building officials consider allowing moisture sensitive interior finishes to proceed until the roofing and WRB were complete. The most overlooked item with modular construction is the joints between adjacent modules. While the continuity of the critical barriers within each module can generally be easily achieved during the factory installation, the joints between the modules require the following additional coordination plans to achieve continuity, listed in general order of importance:

1. How to temporarily protect the horizontal and vertical joints from rain penetration during construction. A contingency plan is also needed to address rain that might penetrate the temporary protection between units.
2. How to seal the joints between modular units:
   - → How to achieve a shingle lapped installation of the WRB or reduce the risk associated with reverse laps.
   - → If the cladding is factory installed, how to provide for a shingled lapped or protected infill cladding at the vertical joints.
   - → Coordinate the structural attachments and plan for how the modules will be lifted and installed with the building enclosure components and joints details.
3. An estimate and plan for accommodating the construction tolerances between site-built foundations and structural components and the factory build modules, including the joint openings between modules.
4. Similar to other factory-built construction such as unitized curtain wall, a comprehensive quality assurance and quality control (QAQC) plan is needed to verify that the installation of the various building enclosure components meets the project's performance requirements.
5. A field QAQC plan that includes field review from an experienced building enclosure specialist or air barrier technician to verify the joints have been sealed as required and to advise on questions quickly as they arise during construction.

Item #1 is critical for all projects but especially challenging for high rise construction or large floor plans where the modules are exposed to the elements for longer periods of time. The Habitat 67 project in Montreal, Canada (Figure 2) featured vertical and horizontal offsets between modular units that were difficult to both temporarily and permanently protect the joints reliably against water intrusion (Guardian, 2015).

Figure 2. Habitat 67, modular project featured at Expo Montreal, Canada

Item #2 requires input and planning during the design phase from both the Design and Construction Team. Our second case study features a project that was originally planned as a modular project and where careful consideration was given early in an integrated design approach on how to detail the joints between modules. In contrast, our first case study features a project that originally was planned as site-built construction and therefore very little planning was provided for the joints between modules.

Item #3 increases in importance depending on the complexity of the project. For example, the Atlantic Yards Building B2 in Brooklyn, NY was envisioned as the tallest modular building in the world at 32 stories (Figure 3). The plan to achieve this record height was to site build a steel frame and then install the modular units into the frame. However, the project completion was delayed by 2 years and is currently in litigation. The primary issue is reported to be that the construction tolerance between the modular units and structural steel frame was not accounted for during design and required extensive field modifications. There was reportedly also extensive water leakage during construction due to both the tolerance in the joints between units and also due to the difficulties of temporarily protecting the ceilings of each floor on a high rise when the site-built structural steel frame extends above and penetrates any temporary protection (Curbed New York, 2015).

Figure 3. Atlantic Yards Building 2, 33 story modular high rise project in Brooklyn, NY

Item #4 is true of all factory-built products or systems. With factory-built systems there is very little ability to modify or correct deficiencies after the system is installed in the field. Having and implementing a factory QAQC plan is therefore critical to the success of modular construction. Factory-built also does not automatically mean better quality. In our first case study we found that windows and window flashings were installed by tradesmen experienced with carpentry and gypsum board installations instead of with window and WRB installations. The errors in installation required extensive field repairs to the window installations, including the removal and reinstallation of many windows.

Item #5 requires the field presence of a building science specialist or technician who preferably also has experiences with how modular units are assembled. The field assembly with modular (and other unitized systems) proceeds so quickly that it is important to have someone on site who can respond quickly to questions or unanticipated field conditions.

CASE STUDY #1: AFFORDABLE HOUSING COMPLEX IN CALIFORNIA

The first case study project was initiated by an affordable housing company in the San Francisco Bay Area. The five-story complex is a mixed-use project comprised of 115 apartment units on the second to fifth floors, two levels of below grade parking, and storefront retail shops at the first floor built by traditional site-built construction (Figures 4 and 5).

Figure 4. Case Study #1: During construction

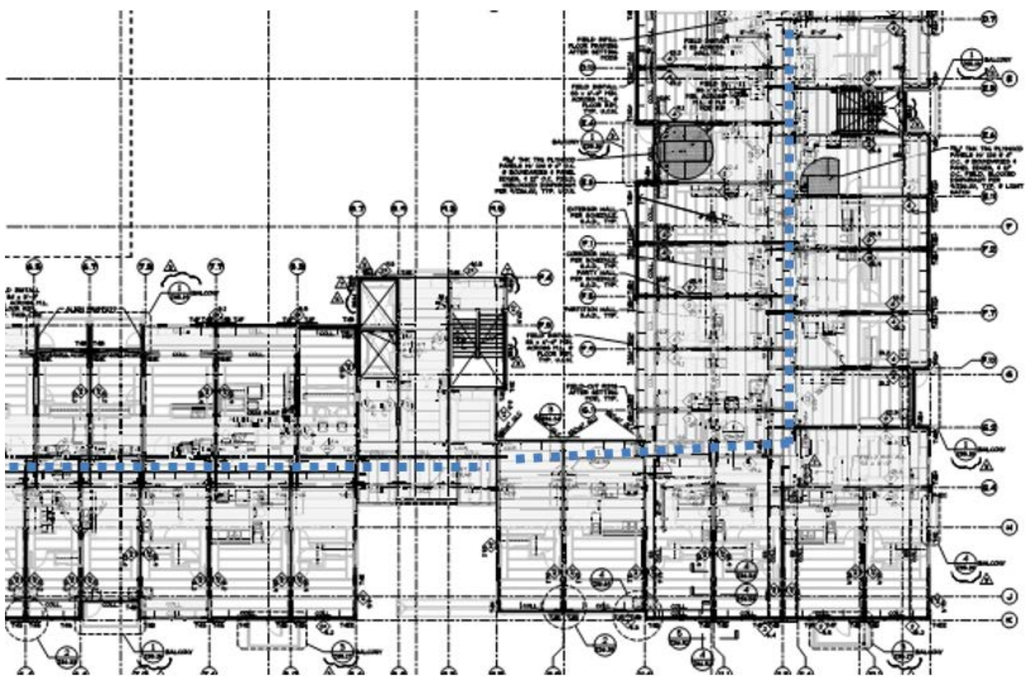

Figure 5. Case Study #1: Partial floor plan (dotted line shows common center hallway)

The project was originally conceived as traditional delivery and site-built construction. However, as the time neared for construction, it became apparent that the San Francisco Bay Area market had recovered from the recession in 2008 and that labor and material costs were rising rapidly due to rising demand. The owner made the decision to convert the project to modular from site-built construction late in the design process as a way to reduce and control against these rising labor costs. Because this is a mixed-use building with the parking and retail to be site-built, there was a redundancy in trades such as drywall installers working at both in the factory and on site. The redundant trades and field labor reduce cost savings, however it was determined that the reduced schedule time and labor savings from going modular on the residential portion of the project would still grant the owner considerable savings.

Factory Construction

The modules were built off site at a factory in Sacramento, 90 miles away, and shipped by truck to site (Figures 6 and 7). The level of interior finishes varies for individual modular projects - anywhere from open stud framing to completed flooring, cabinetry and fixtures. A high level of prefabrication was specified for this project and modules included most interior finishes such as painted drywall, millwork, laminate flooring and appliances.

Figure 6. Case Study #1: Factory construction progress photos

Figure 7. Case Study #1: Lifting and setting units in field

The windows and WRB around the windows were installed in the factory, but the top and side party walls of the modules were not protected with WRB. The exterior cladding was designed as cement plaster and was to be field installed to reduce the risk of plaster cracking during transport and to allow the plaster to continuously cover the joints between modular units. In general, installation quality for the window systems was less than what we would typically see in field construction. Based on our observations, this was more of a factor of limited worker experience and rushed work to keep the assembly line moving. For example, the window flashing sequence was a 13-step rainscreen flashing sequence, consisting of flanged windows installed in a recessed opening with self-adhered membrane flashing and an integrated drained membrane sill pan. There were twenty stations in the factory and each module was at one station for approximately two hours. Every task had to be broken into steps that could be accomplished within two hours. Sometimes workers would move with the modules to follow a task and other times, the tasks would be continued by different workers. Inexperienced window installers found it difficult to install the self-adhered membrane effectively in the short time period and it was apparent that the full concept was not understood by all of the installers or QC workers, despite detailed build sequence details in the design package. Despite these detailed installation sequences, the final installation suffered deficiencies that had to be repaired in the field, including gaps in the flashing, missing flashing pieces, missing or incomplete sealant and interior air and water seals, improperly shimmed windows and cuts in the flashing membrane (Figure 8).

Figure 8. Case Study #1: Defects in the factory installed window flashing included cuts in the membrane, tenting, and gaps that had to be field corrected

Figure 9 shows an example of all of the observed deficiencies on the second level of one elevation of the project. Some of these deficiencies required both the windows and flashing to be removed and reinstalled - a time and field labor intensive process. Material shortages added to delays and shifted resources from the factory to the field to complete the modules. About halfway through the construction of the modules, the modular fabricator determined that the windows could not adequately be installed per the construction documents in the budgeted amount of time at that station and therefore the window installation would have to be corrected in the field. In other words, to meet their contracted delivery schedule, the modular fabricator assumed the extra costs of correcting errors in the window installation in the field, thereby reducing the promised benefits of modular construction.

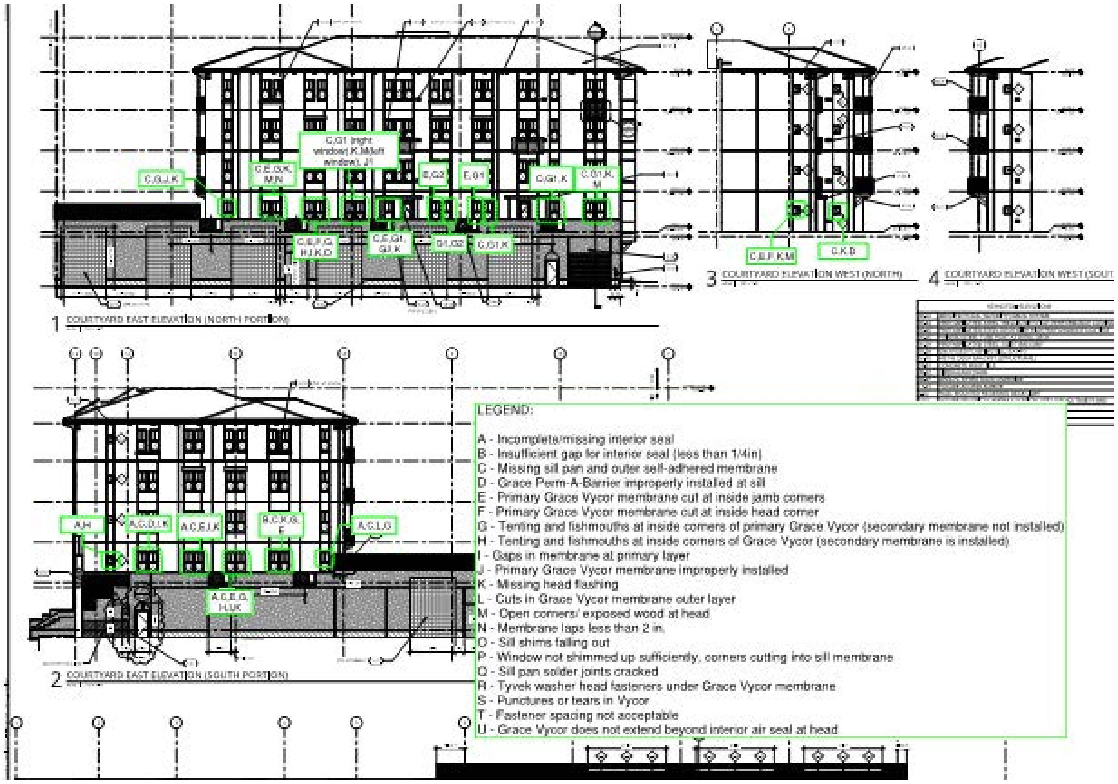

Figure 9. Case Study #1: Example elevation documenting the required extensive field repairs to the factory installed window installations

Delivery and Placement

After installation of factory components, the first finished modules were wrapped in plastic for temporary protection from inclement weather and damage before being transported to the site (Figure 10). The original plan was to complete, transport, and ship the modular units during the summer months which rarely experience rain. The San Francisco Bay Area had also experienced 2 years of sever drought which appeared to further reduce the risk of rain during construction. However, the first shipment was approximately 2 months behind schedule, and the first units arrived during the Fall of 2015 which experienced a higher than normal rainfall due to an El Niño weather pattern that year.

The first level of modules were to be placed on three inch tall concrete curbs on the cast-in-place slab, then subsequent levels stacked on top (Figure 7). Bolted connector plates on the modules with male connectors at the base and female connectors at the top enabled a positive connection but left limited room for adjustment and out-of-tolerance construction. Dimensions of the modules are set in the factory and must line up with field conditions such as pipe blockouts and module curbs, therefore both field and factory crews must adhere to precise dimensional tolerances. Several out-of-tolerance issues surfaced during module placement, including:

→ Pipe blockouts and conduit in the slab not aligning with module pipework (Figure 11).

- → As more modules were set, the weight of the modules caused the slab to deflect resulting in gaps between the curb and modules that had to be filled.
- → Several modules were up to an inch longer or shorter in one dimension. The offset distances are planned to be accommodated by changing the thickness of the stucco cladding or other finish materials at these locations. Even with a cant to taper the stucco, there is a risk the stucco may crack due to the abrupt change in thickness at these locations.

Figure 10. Case Study #1: Despite being wrapped in plastic, heavy rains resulted in water damage to some units during transport

Figure 11. Case Study #1: Misaligned pipe penetrations through slab and curbs
Temporary Rain Protection

Our recommendations to fully weatherproof the modules at the factory with waterproof membranes at the walls and roofs was not accepted during the design phase due to cost restrictions and plans of summer installations. Note that a fully waterproof temporary roofing membrane over each unit would require a continuous plywood sheathing or gypsum board substrate over each module which further reduces the cost benefits of modular construction.

The contractor used tarps and plastic to temporarily weatherproof the installed modules, which proved inadequate when the first heavy rains hit. Water infiltrated from leaks through discontinuities in the temporary roofs, through exposed walls and module joints after the modular units were placed, and pooled on the concrete deck under the modules, trapped between the perimeter curbs. Considerable water damage to interior finishes and subsequent mold required that all gypsum wallboard and insulation be removed (Figure 12). Cabinets, electric fixtures, countertops and sinks were removed and stored if they could be salvaged. Materials that were stored in the modules, such as carpet, were saturated and unusable. Water also ran through electrical conduit and mechanical duct work.

Figure 12. Case Study #1: Water intrusion during construction required extensive removal of interior finishes

Particularly challenging to weatherproof was a common hallway between rows of modules. After suffering extensive water damage, the general contractor constructed a pitched roof wrapped in tarps that could be temporarily installed after each floor of modules was installed (Figure 13). This temporary roof structure was subsequently removed and reinstalled after each subsequent floors of modules were installed.

Figure 13. Case Study #1: Improved temporary rain protection during construction

The project at this time has taken as long, or longer than traditional site-built construction. We can take away several important lessons from this project:

→ Modular construction should be considered early in the design and requires collaboration from all parties involved with the design and construction. Provide details for the joints between modules that can accommodate the construction tolerances.

→ Planning for temporary rain protection is fundamental to every modular project. Plan on wrapping all six sides the modules with at least a water resistive barrier. Also plan on providing a moveable temporary roof structure that can be removed and reinstalled after each floor of modules is installed.

→ Consider the use of all non-paper faced gypsum board. Mold was confirmed on this project at all locations with paper faced gypsum board and no mold was documented where fiberglass matt gypsum board and plywood was used.

→ Consider the use of plywood instead of oriented strand board (OSB) due to its increased tolerance of wetting.

→ Provide a roofing membrane over sheathing or other continuous substrate over each module unit. Or consider field installing all interior moisture sensitive finishes.

CASE STUDY #2: MEDICAL STAFF HOUSING FACILITY, BRITISH COLUMBIA, CANADA

This second case study project was initiated by a government health care provider who desired new housing for workers at a hospital in a remote community in northern British Columbia, Canada. The building, required to meet Passive House standards, was factory-constructed in the Lower Mainland of British Columbia, and shipped to the site on barges along the "Inside Passage", a coastal route in the Northern Pacific Ocean. Modular construction was considered early in the design in order to reduce the costs associated with the following factors:

→ Shortage of skilled labor in the remote location.

→ Costs of construction staging and field construction in a remote area.

→ Cost of shipping materials for field installation in a remote area.

Design & Construction Stage

The project incorporated an integrated design approach that included the Owner, factory builder, site installer, architect, and various consultants early in the design process. This step was critical, particularly in light of the high performance requirements of the building to meet Passive House requirements for energy efficiency.

Due in large part to the harsh weather conditions along Coastal British Columbia, and the strict air-tightness requirements of the building enclosures, the entirety of the 6-sided modules were covered in an air barrier and water control layer in the factory – even the sidewalls of modules that would end up forming interior party walls with the adjacent module (Figure 14). This compartmentalization decreased the risk of damage during transit, but also had the added benefit of controlling unintentional interior airflows between units which aids in the design and functioning of the mechanical system.

Figure 14. Case Study #2: All six sides of modular units were wrapped with WRB and temporary roofing membranes

The design included all control layers and cladding to be installed in the factory; however the joint between modules was infilled with a secondary water control layer, exterior insulation, and cladding layers on site. The coordination of this installation with construction tolerances, structural connections between modules, and other variables, and the factory mockups of these conditions were key to the successful installation on site. The integrated design approach was integral to efficiency developing solutions to these atypical details. Figure 15 shows an example vertical joint detail before and after completion. Details were also developed to show how the required temporary structural supports for lifting the modules can be removed and sealed.

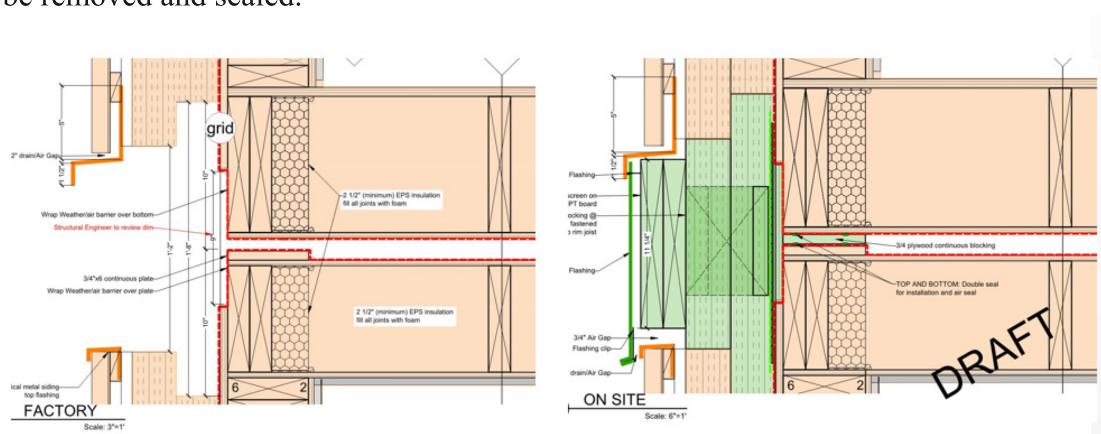

Figure 15. Case Study #2: Example detailing of horizontal stack joint between modules

Training, mockups, and quality assurance testing in the factor setting are critical steps. In many cases, the modular factories do not use specialty sub-trades to complete aspects of the work, and the methods of construction – particularly for Passive House – may not be familiar. For instance, this project included 6 inches of exterior insulation outboard of the sheathing;

the thick insulation layer has large effects on installation of cladding and windows. Despite skilled contractors and fully developed details, mockups in the factory were required for all parties to be comfortable with and to confirm the installation requirements. We also performed air leakage testing on the modules in the factory and on the completed building in the field to confirm the air barrier performance.

Delivery and Placement

Fully weatherproofed modules were shipped up the coast on barges and then erected on site using cranes (Figures 14 and 16).

Figure 16. Case Study #2: Placement of modules and photo of near complete project

Site preparation work, including foundations and crawlspaces for mechanical equipment had already been completed. Despite careful planning, site modifications were required to accommodate unanticipated buildups, interference with crane lifting straps and anchor points, and the accumulated dimensional tolerances of numerous modules placed next to each other. Despite minor construction challenges, the placement of modules and the installation of the site components was completed without significant issues. For this project, modular construction successfully resulted in a higher quality, quicker install, and overall less expensive compared to site building this project.

CONCLUSIONS

Modular construction has many potential benefits that have been successfully realized on many projects, including the potential to provide a higher quality product at a lower cost and quicker construction schedule. However, many larger more complex modular projects have suffered from extensive water leakage during construction and extra costs with field correcting factory installation errors. Based on our research and two case studies presented in this paper, we have the following recommended strategies pertaining to maximizing the performance of the building enclosure design on modular projects:

→ Weatherproof in the factory - don’t count on good weather. Plan on wrapping all six sides the modules with at least a water resistive barrier. Also plan on providing a moveable temporary roof structure that can be removed and reinstalled after each floor of modules is installed.

- → Consider using an integrated design process that includes builders, architects, installers, owners, and consultants early in the design process. Modular construction is a team sport and the opportunities to make changes in the field after the modules are placed are minimal. Develop details for the joints between modules that can accommodate the construction tolerances.
- → Consider the use of all non-paper faced gypsum board to reduce the risk of mold should modular units suffer incidental wetting during construction or transport.
- → Measure and review module deficiencies prior to placement - these may be easier to repair on the ground.
- → Include a contingency for a crew on-site to repair factory deficiencies or to deal with the inevitable field modifications that may impact the schedule.
- → Where possible, provide simple, repetitive design details of every component such as window installation. A module stays at one station in the factory for as little as 2 hours, so every task and detail should be designed to fit into this window.
- → Allow for training, numerous mock-ups, and performance testing of modules in the factory prior to proceeding with full factory mobilization. Develop a project specific factory QAQC plan.
- → Develop a field QAQC plan that includes field review from an experience building enclosure specialist or air barrier technician to verify the joints have been sealed as required and to advise on questions quickly as they arise during construction.

REFERENCES

Modular Building Institute (2015). *Permanent Commercial Housing*, http://www.modular.org/htmlPage.aspx?name=Market_Commercial_Housing.

Modular Building Institute (2012). *Modular Construction Delivers Model for New York Housing in Record Time*, http://www.bdcnetwork.com/modular-construction-delivers-model-new-york-housing-record-time#nodegallery.

Modular Building Institute (2013). *Permanent Modular Construction 2015 Annual Report*.

Smith, Ryan E., and Rice, Talbot (2015). *Off-Site Studies, Permanent Modular Construction, Process Practice Performance*, The University of Utah.

The Guardian (2015). *Habitat 67, Montreal's 'Failed Dream'*, http://www.theguardian.com/cities/2015/may/13/habitat-67-montreal-expo-moshe-safdie-history-cities-50-buildings-day-35

Curbed New York (2015). *Modular Brooklyn Tower Suffered 'Significant Water Damage'*, http://ny.curbed.com/2015/9/3/9924308/modular-brooklyn-tower-suffered-significant-water-damage