High-Rise Wood Building Enclosures

Graham Finch, MASc, PEng
Member ASHRAE

ABSTRACT

Interest in the construction of taller mid- to high-rise wood structure buildings is growing in Canada and the United States, building off of the success of dozens of projects in Europe and Australia. High-rise wood buildings utilize cross-laminated timber (CLT) and nail-laminated timber (NLT) panels, glulam beams and columns, engineered timber components, as well as steel and concrete to meet the design and construction challenges for these greater heights. The potential for increased time of exposure to weather and heavy timber construction methods pose new challenges for design and construction teams. The design of the building enclosure and the associated details requires careful attention to maintain acceptable durability, fire protection characteristics, and thermal efficiency. Prefabrication of whole floor, wall, or other modular components is utilized to speed up the time of construction and protect the wood assemblies from exposure to moisture.

This paper shares lessons learned through experience in the field and provides guidance on building enclosure design and detailing for mid- to high-rise wood buildings with a focus on control of heat, air, and moisture. Structural, fire, and acoustic considerations are not the focus of the paper nor covered here in detail. Case studies from the building enclosure designs of selected leading new, tall wood buildings are presented, including the Bullitt Center in Seattle, Washington, USA(6 storeys, ~76 ft), the Wood Innovation Design Centre (6 tall storeys, ~97 ft) in Prince George, British Columbia, Canada, and the Brock Commons UBC Student Residence building (18 storeys, ~190 ft) in Vancouver, British Columbia, Canada.

INTRODUCTION

The notion of high-rise wood buildings is gaining traction in many parts of the developed world. With advancements in engineered wood components, along with an industry push to demonstrate the safety, feasibility, and benefits of mid-rise (4- to 9-storey) and high-rise (10-storey and taller) wood buildings, several projects have taken form in Europe, Australia, and now Canada and the United States. This has not been without challenge in demonstrating the safety, durability, and economics of these buildings and moulding public perception of wood at taller heights (Perkins + Will 2014; Green 2012).

Within North America, the height of stick-built wood buildings has been restricted to three or four storeys (low-rise) depending on the jurisdiction since the introduction of the first Canadian and American building and fire codes. It has only been within the last decade that stick-built mid-rise wood buildings have been allowed to be constructed up to five and six storeys in height in some parts of Canada and the United States.

To accommodate code restrictions, the first taller wood buildings (beyond six stories) are being constructed as pilot projects, allowed by the local authority having jurisdiction by utilizing acceptable Alternate Solutions (aka Alternative Means and Methods) to meet fire, structural, life safety, and other requirements. As a result, extensive research, testing, monitoring, and engineering is going into this first cohort of taller wood buildings to demonstrate their suitability. Manufacturers of engineered wood products and the wide array of fasteners necessary to construct these buildings are also starting to innovate in Canada and the United States, joined by

Graham Finch is a principal and building science research specialist with RDH Building Science, Vancouver, BC, Canada. He is the co-author of several publications related to taller wood buildings and has designed the building enclosures for several of the first tall wood buildings in North America.

many European companies who are actively exporting materials into North America.

The North American industry has also been constructing many relatively large, but not necessarily tall, wood buildings incorporating mass timber panel components with cross-laminated timber (CLT), laminated veneer lumber (LVL), laminated strand lumber (LSL), nail-laminated timber (NLT), and glulam columns, beams, and panels. While not tall, these mass timber buildings are providing excellent experience with the durable use of these materials and lessons regarding the appropriate wall and roof systems that would be incorporated into the high-rise buildings that will follow.

A tall wood building is not necessarily constructed entirely out of wood products (see Figure 1). In fact it is likely impossible to do so. Steel and concrete components are generally incorporated into tall wood buildings where it makes practical sense to do so. Examples include concrete footing and floor slabs and concrete toppings on wood floor panels along with the wide array of steel connectors, screws, and nails necessary to connect the wood components together. Building structures that incorporate heavy timber elements along with large amounts of steel and concrete are often referred to as *hybrid structures* within the industry. Above-grade wall and roof enclosures have been wood-based and there is a common theme of prefabrication. Cross-laminated timber wall, floor, and roof panels are relatively common.

This paper describes the current state of the art of the tall wood building industry in North America with a specific focus on the design of durable and efficient building enclosures. The paper provides a discussion of the current practices for mass timber building enclosure design, a review of several lessons learned from a few mass timber buildings that experienced moisture issues during construction, and a case study review of the building enclosure designs from three of the tallest wood buildings in Canada and the United States.

BUILDING ENCLOSURE BEST PRACTICES FOR TALLER WOOD

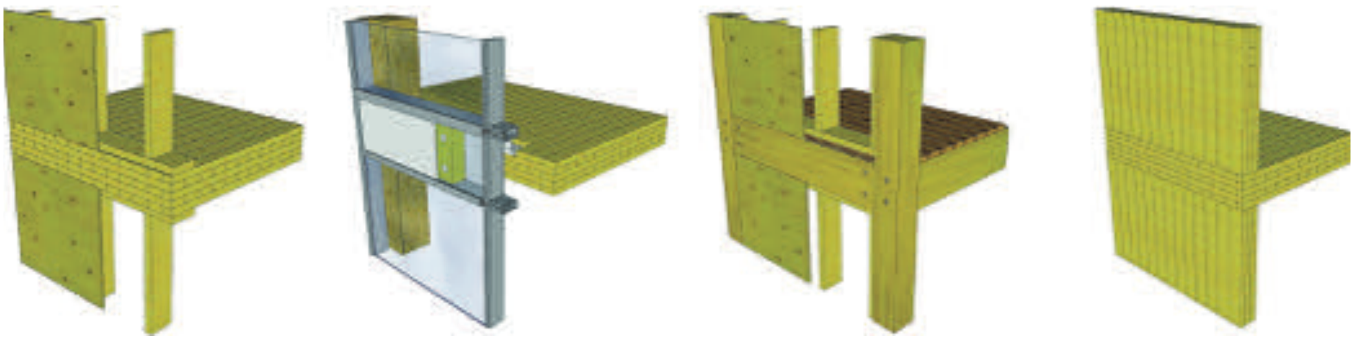
The building science and physics for a high-rise wood building enclosure are no different than for a low-rise wood-frame building. There are, however, differences in the selection of appropriate materials along with the design considerations to accommodate the increased height and exposure to weather.

Above-grade walls and roof systems may be constructed out of wood, steel, or concrete depending on the building design, economics, and other goals of the project. Local fire codes will also dictate where certain wood products can and cannot be used or left exposed, which means that a variety of structural systems and enclosure assemblies will inevitably be used for taller wood buildings across North America. A few examples of potential high-rise wood structural systems and wall assemblies are shown in Figure 2.

Whether the exterior walls are load bearing or infill will dictate the specific design and materials that can be used. In exterior load-bearing wall designs it will be more common to see CLT or other engineered wood panels designed to accommodate the gravity and lateral loads for the building. If the walls are non-load-bearing infill, subject to wind loads only (as is common for most concrete and steel high-rise buildings), then a wide variety of well-established building enclosure options are available, including wood stud and steel-stud infill walls, curtain wall systems, prefabricated insulated panels such as structurally insulated panels (SIPs) or insulated metal panels, insulated precast concrete, and a number of other wall systems.

The fundamentals of a best-practice building enclosure design for a taller wood building is the same as any other building of similar height and exposure, but with additional consideration for how the wood structure or wood enclosure elements may behave. Design considerations such as cumulative vertical wood movement of the structure (including shrinkage, compression, gap closure, and creep) are poten-

Figure 1 *Three large wood building projects showing newer wood construction components (CLT, NLT, and glulams along with steel and concrete). CLT is shown in the left and center photographs and NLT is shown in the right photograph.*



(a) (b) (c) (d)

Figure 2 *Examples of some of the different types of exterior wall enclosure systems utilizing mass wood components: (a) platform wood frame infill with CLT floor and interior wall column/panel structure, (b) curtain-wall framing over post and beam structure with CLT floor, (c) wood-stud infill with post and beam structure and heavy timber floor structure, and (d) CLT exterior wall structure (load bearing) with CLT floors.*

Figure 3 *Examples of differential movement considerations for the Wood Innovation and Design Centre in Prince George (covered in more detail in the Wood Innovation and Design Centre section of this paper). The primary consideration here is the change in seasonal thickness of the CLT floor panels and glulam beams in relation to the infill curtain wall and SIPs wall systems. The design of a flexible air and watertight joint that could accommodate up to 1 in. of differential movement was integral to the design of this enclosure at each floor line. Note that the columns run continuous from foundation to roof to limit the amount of "shrinkable wood" within the building.*

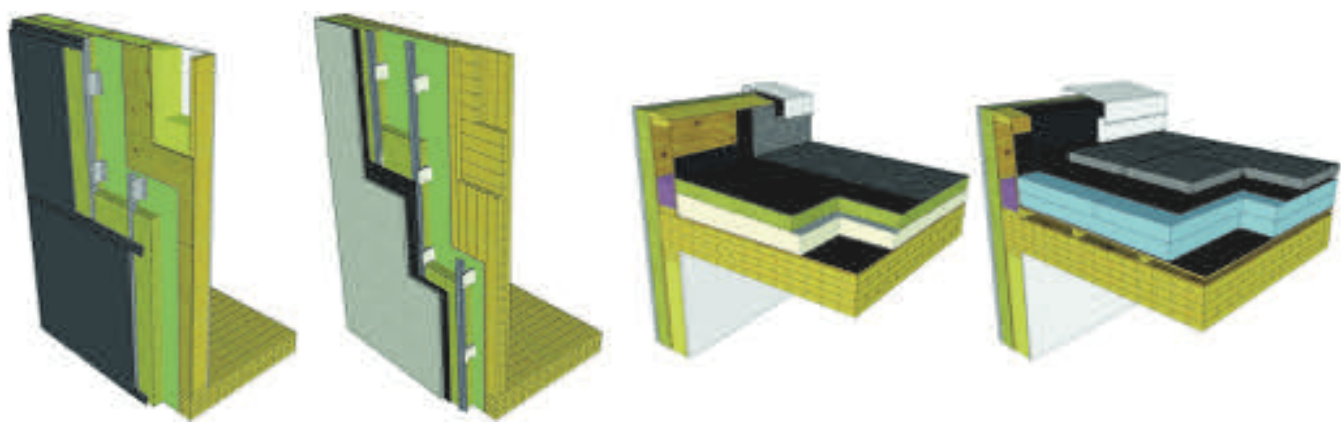
tially emphasized in taller wood buildings and need to be accommodated by the building enclosure. It is not so much the overall change in height of the building that is the primary concern but the differential movement between the structure and enclosure and allowing for anticipated initial and seasonal movement. Figure 3 provides an example of how different movement is considered during the design of the curtain wall and infill wall panels at Wood Innovation and Design Centre (WIDC). It is not so much that this strategy differs from steel or concrete buildings in terms of absolute movement but the types of available connectors and materials that need to be adapted to this purpose.

Wood has proven long-lasting performance in properly designed and constructed buildings around the world. The major threat to long-term service life durability comes from decay fungi and mold growth. The key to achieving durability is to prevent excessive moisture accumulation and to allow wood to dry should it get wet during construction or while in service. The risks will be greater in a tall wood building due to greater exposure to weather and potentially longer construction schedules spanning rainy seasons. Addressing this greater risk will typically mean applying appropriate materials to control water, air, and vapor and thermally insulating wood building enclosure elements such as CLTs, NLTs, glulams, etc., on the exterior side. In addition, wood must be properly protected with the use of preservatives or barrier membranes against termites in affected areas of Canada and the United States.

A number of building enclosure design publications, building science textbooks, and other building science references are available and provide general guidance regarding the design and construction of durable and energy-efficient wood-based building enclosures, such as *Guide for Designing Energy-Efficient Building Enclosures* (RDH 2013), *Building Enclosure Design Guide* (RDH 2011), *CLT Handbook* (FPI 2011, 2013), and *High Performance Enclosures* (Straube 2012). The building enclosure design fundamentals described within these publications are typically only for wood-frame buildings up to six storeys; however, they can be applied with caution and consideration for taller wood buildings. The use of CLT and other heavy timber components are covered in detail. It should be noted that many assemblies, details, and materials appropriate for use in low-rise wood-frame buildings may not be suitable for taller buildings due to the increased environmental loads and increased durability expectations.

Technical Guide for the Design and Construction of Tall Wood Buildings in Canada (FPI 2014) provides specific guidance for the construction of taller mid- to high-rise wood building enclosures. Some examples of more robust wood-based building enclosure assemblies suggested for taller wood buildings are provided in Figure 4. The following guidance is suggested for designers of mass timber wall systems in tall wood buildings:

- Use noncombustible drained and ventilated exterior insulated rainscreen claddings. Avoid the use of open rainscreen claddings where large volumes of water may bypass the cladding and excessively wet the cavity materials and/or wood structure.
- Design the cladding with properly flashed movement joints (i.e., cross-cavity flashings at each floor) to accommodate initial and seasonal wood and building movement and provide drainage and ventilation behind the cladding.
- Use noncombustible exterior insulation materials with thermally improved clip and rail or long-screw cladding support systems to minimize thermal bridging through the insulation. Wind loads will typically govern the design of these connections.



(a) (b) (c) (d)

Figure 4 *Examples of some of the different wood-based building enclosure assemblies suggested as more durable and robust for taller wood buildings in North America (FPI 2014). Note that in all of the assemblies, the wood is well protected by waterproof or water-resistant membranes and that, where possible, the majority of insulation is placed on the exterior of the wood structure. (a) Split insulated wood-frame infill wall with thermally efficient intermittent clip supported metal cladding. Note the use of a self-adhered sheet or liquid-applied vapor-permeable membrane for the air barrier and water-resistive barrier over plywood sheathing. (b) Exterior insulated CLT load-bearing wall with thermally efficient intermittent clip supported stucco cladding. Note the use of a self-adhered sheet vapor permeable membrane for the air barrier and water-resistive barrier over the CLT panels. (c) Conventional roof assembly over sloped CLT roof panels. Note the use of a robust roofing membrane and separated fully adhered air barrier/vapor barrier and temporary roof membrane preapplied to the CLT panels prior to site delivery. (d) Protected membrane roof assembly over tapered wood structure over CLT roof panels. Note the use of a robust fully adhered two-ply SBS waterproofing membrane over the plywood sheathing and venting of the tapered structure to the interior of the building.*

- At minimum, provide cladding and insulation systems that have demonstrated acceptable fire performance in line with NFPA 285 (NFPA 2012) or equivalent.
- Use vapor-permeable exterior insulation and vapor-permeable air barrier (AB)/water-resistive barrier (WRB) materials to facilitate drying from heavy timber wood panels. Where impermeable membranes or insulations are used, care must be taken to ensure the wood is factory dry before applying, and it is preferred that preapplied membranes be used in lieu of site-applied membranes in this application.
- Use self-adhered AB/WRB materials in lieu of mechanically attached AB/WRB materials. Liquid-applied membranes can be considered but are not suitable over the dimensionally unstable faces of CLT or NLT.
- Avoid insulating on the interior of heavy timber panels with more than one-third of the total insulation value unless a more detailed climate-specific hygrothermal analysis is performed. Where stud insulated infill is used, it is suggested to use more exterior insulation to improve durability of the sheathing in this more-exposed assembly.
- Consider prefabrication of panels complete with AB/WRB membranes and potentially cladding and insulation preinstalled.
- Not all tall wood buildings will incorporate wood-based exterior wall assemblies. Steel-stud, precast concrete or aluminum curtain wall systems may also be used. Follow best practices for the design of these materials with consideration for unique connections to wood floor slabs, beams, and columns (instead of concrete) and potentially greater seasonal and long-term building movement.

The following guidance is suggested for heavy timber roof assemblies in taller wood buildings:

- Insulate heavy timber roofs entirely on the exterior side with conventional or protected membrane/inverted membrane assemblies. Avoid use of interior insulation wherever possible with mass timber as to keep the wood warm and allow drying to the interior.
- Strongly consider the application of appropriate temporary roofing and air/vapor barriers to the panels prior to installation on site to protect from construction wetting. These materials tend to be impermeable, so ensure that the panels are factory dry at the time of application.
- Consider roof assembly designs that allow for faster drying of mass timber components such as CLT panels in the event of a roof leak. This could include provisions for venting of interior air above the mass timber components so that leaks can be detected early and may be able to be dried out in both directions. This could take the form of a sloped wood taper package above the CLT deck provided local fire code requirements are also met (Figure 4d).
- Take care when using NLT within roof assemblies as construction wetting will cause the panels to swell significantly and potentially cause damage to the building and/or applied materials. Typically plywood is installed on top of NLT to provide a more dimensionally stable surface for roofing and membrane application as well as to structurally connect panels together.
- Consider sloping the structure of the roof panels in lieu of using tapered insulation or wood-framing systems.
- Consider the use of noncombustible insulation materials and/or gypsum protection boards as additional protection against fire even where fire-rated roof assemblies are not required.

LARGE WOOD BUILDING ENCLOSURES—INDUSTRY LESSONS LEARNED

The building industry is constantly learning from the successes and failures of buildings. For example, the industry is aware of the many hard lessons learned with inappropriately designed and constructed low-rise wood-frame buildings in North America in the past couple of decades. However, as there are very few tall wood buildings to directly learn from (as very few have been built to date), we need to learn from the construction of larger wood buildings incorporating similar wood structural and enclosure systems.

Experience with these recent large and taller wood buildings has identified a few issues and risky practices with mass timber components that could lead to durability problems. Many of the issues can be addressed with construction practices that limit wetting and better accommodate wetting when it does occur, including diligent site protection, changes to sequencing to preprotect wood elements from rainwater, or the selection of more robust materials. These practices are covered in the following section, using unnamed buildings to examine how the industry has learned and is continuing to learn about the construction of larger mass timber projects—particularly in wet environments.

It is important to limit the amount of wetting that occurs as wood assemblies are shipped, as they are stored on-site, and through various construction stages, to the point where the building is closed in or at least protected from exposure to rain. This becomes even more critical where mass timber wood products such as CLT, NLT, LVL, LSL, and glulam panels, beams, and columns are used because these thicker wood elements may absorb and store more moisture than plywood or dimensional lumber and swell when exposed to liquid water sources. In addition, they also dry slowly due to their mass. Large wood members suffer volumetric changes, causing bowing or splitting during severe wetting and drying cycles. Moreover, it can be difficult for enclosure assemblies that are wetted to dry out after insulation and air/vapor/water control membranes are installed. A standard target for wood moisture content (MC) is to keep the wood below 20% MC during storage and construction to provide a margin of safety and reduce long-term differential shrinkage after installation. Evidence from recent North American projects is also showing that the moisture content of mass timber elements should ideally be kept below a lower threshold of 15% MC (closer to its manufactured moisture level of 11%–14%) to reduce dimensional movement and allow the elements to dry out faster in service.

Factory-finishing with special coatings and sealers can provide temporary rainwater protection for wood products such as glulam and CLT, but depending on their properties these products may also trap moisture and slow down drying if water gets into the wood. Good construction sequencing can be used to protect wood and minimize wetting, such as applying wall and roof membranes as soon as the construction allows. In cases of roofs or even floors, this would mean potentially applying temporary or permanent waterproof membranes prior to erection so as to provide a temporary construction roof and protect the underlying wood. Experience has also revealed that some self-adhered or liquid-applied waterproofing or air barrier membranes do not adhere well to damp wood—additional reasons to preprotect wood elements in a tall wood building. The prefabrication of partially or completely finished enclosure wall and roof assemblies is also suggested to reduce the exposure of wood enclosure and structures to weather.

Lesson 1—Protecting Large Prefabricated Roofs from Wetting

This first lesson comes from a large recreational wood structure building constructed in the Pacific Northwest within the past five years. The wood roof consists of a long-span prefabricated curved roof truss with a double layer of plywood as the finished deck. During the tendering and construction of the roof panels, a fully adhered temporary roof membrane that was specified by the designers was value-engineered out of the assembly as a cost-saving measure, leaving the wood panels exposed to weather during storage and until the roofing membrane was installed. It should be noted that the roof was also too large to effectively protect with a scaffold structure or tarps and was exposed to rain for several months in early fall to mid-winter as a result.

Once the panels were erected, plywood sheets were installed along the joints between the trusses to complete the structural diaphragm. The roof was erected in the late summer—later than initially scheduled—and roofing commenced in the fall during the rainy season. As a result, large areas of the double plywood-skinned roof were left exposed to rain and night-sky condensation for several months until the roofing could be completed. Water was readily able to be absorbed into the upper plywood layer as well as reach down between the layers of plywood to wet the lower layer and leak into the interior of the building.

Roofing proceeded with the addition of two layers of paper-faced polyiso insulation and a welded white PVC roof membrane. About halfway through the roofing process, a setback occurred when fungal growth was observed on the surface of the paper-faced polyiso insulation and the surface of plywood decking in an area that had been completed a month or so prior. An extensive investigation and eventual full tear-off of the partially completed roof uncovered that the problem was widespread. It was observed that water from the plywood deck was not drying out to the interior as quickly as anticipated by the designers and was also being readily adsorbed into the polyiso insulation. This was unique in that it is fairly common to see roofing occur over single thinner layers of plywood in this market without the same issue. Figure 5 provides photographs taken during the investigation performed by RDH Building Science.

The repair consisted of attempting to dry the roof, treating the wood with a fungicide, and applying a fully adhered waterproofing membrane to the plywood deck (the same one that was removed earlier as a cost savings) prior to re-roofing with non-paper-faced polyiso and new reflective white PVC.

The primary lesson learned from this project was seeing firsthand how difficult it is to dry out a roof to the inside through two layers of plywood under an insulated and light-colored roof in service. The project also demonstrated how sensitive paper-faced polyiso is to fungal growth when in contact with damp to wet wood and reinforced the need for temporary/construction roof membranes for large panelized roof structures.

Lesson 2—Careful Selection of Preapplied Temporary Roof Membranes over Mass Timber

It should be obvious that preprotecting mass timber roof panels with water-resistant membranes should help protect

Figure 5 *Photographs taken during removal of the roofing showing wetting patterns and absorption of water from the wet double layer of saturated plywood into the polyiso, particularly at the plywood joints.*

them from wetting during shipping and erection and may even speed up construction. The challenge, however, is deciding what type of membrane to use. There are two primary categories of water-resistant membranes: those that are permeable and those that are not. Permeable waterproofing/water-resistant membranes include products such as synthetic house wraps and allow the wood to dry out from beneath the membrane should it get wet. These types of membranes are typically used on walls but are used less so on roofs, as they are not that resistant to standing water. Impermeable waterproofing membranes, such as roofing membranes or asphaltic peel-and-sticks, while they do a good job at protecting from external moisture, do not allow for drying to the exterior should the wood get wet or be wet prior to application of the membrane.

In the second lesson here, the project team used an asphaltic peel-and-stick waterproofing membrane to preprotect a unique exposed LSL roof panel system during construction. Once the panels were installed, the laps were stuck together. Unfortunately, on this project, the peel-and-stick laps were not adequately sealed and penetrations through the roof were not well sealed. Ponding water on the relatively flat surface for several months led to leakage into the LSL panels at many of the peel-and-stick laps and penetrations. Once water was able to get beneath the peel-and-stick, it became essentially stuck within the LSL and unable to dry out fast enough for what the project team deemed safe to the durability of the roof. As an expensive consequence, the membrane had to be stripped off in wetted areas and the panels dried by erecting a temporary roof scaffold and providing a combination of heat and desiccated air on top and below the panels. Figure 6 provides photographs of the roof showing the erection, investigation, and later drying of the roof.

The primary lesson here is discovering that the use of a peel-and-stick membrane with pressure-adhered laps may not have been the best choice for a temporary roof membrane for this type of structure. The tolerance for defects in application is very low. A more robust choice would be the use of a peel-and-stick membrane with torch-welded laps. Care must be taken when using torch-applied roofing around wood and the use of protective elements such as protection boards or self-adhered or cold-applied base/protection sheets applied before torching. Several commercially available peel-and-sticks are available that incorporate cold adhesives with torched laps. An example of such application is shown in Figure 7.

Lesson 3—Caring for NLT and Protecting Wood Before it is Too Late

As NLT consists of 2× nominal lumber stacked together, it is prone to dimensional movement (unlike CLT, which does not have all of the wood grain aligned) and it is able to store a substantial amount of water within the panels. NLT is more sensitive to construction wetting than CLT and requires additional design considerations to accommodate dimensional movement. The author has observed and anecdotally heard of a number of NLT panel projects where moisture movement was not adequately designed for, resulting in the walls being pushed out of plumb by the swelling of panels wetted during construction. Considering that wood will expand/contract by approximately 0.20% to 0.25% in dimension in the radial/tangential grain for every 1% change in moisture content, keeping the wood dry should be paramount.

In the third lesson here, NLT panels were utilized for the floor and roof structure of a four-storey office building in the Pacific Northwest. During construction, the NLT panels of the roof became completely saturated as very little site protection from wetting was provided (Figure 8). It appears that the site was treated like that of a concrete frame building. While expansion of the NLT was allowed by large gaps left between the panels, it became very wet to the point where fungal growth was initiated and a moisture monitoring system was installed to track its drying. To dry the NLT panels and be able to apply the roofing materials within the construction schedule, an expensive scaffold system needed to be erected to cover the entire building. This expense arguably could have been avoided by properly protecting the NLT from wetting in the first place. If the scaffold tent had been erected initially then the construction of the roof would not have been delayed or led to damage to the NLT.

Figure 6 *Photographs taken during the construction, investigation, and later drying process of an LSL panel roof wetted by defects in the laps and damage to the temporary roof membrane.*

Figure 7 *Prefabricated mass timber truss system incorporating a temporary roof membrane consisting of a single-ply SBS peel-and-stick membrane with torch-welded laps immediately sealed after connection is made. Note how the membrane laps protect the sides and edges of the panels during shipping and erection. (Photos courtesy of StructureCraft.)*

Figure 8 *An NLT project where the roof panels were not protected during construction and became saturated, leading to swelling and fungal contamination coupled with a very long drying-out period. As a result of this wetting, a scaffold tent system needed to be erected over the entire building to protect and allow complete drying before roofing could be applied. (Photos courtesy of SMT Research.)*

TALL WOOD BUILDING ENCLOSURE DESIGN CASE STUDIES

Three case studies are included here to discuss the variety of building enclosure designs and assemblies that are currently being incorporated into taller wood buildings in North America. This includes The Bullitt Center in Seattle, Washington, USA (six storeys, ~76 ft), the Wood Innovation Design Centre in Prince George, British Columbia, Canada (six tall storeys, ~97 ft), and the Brock Commons UBC Student Residence building in Vancouver, British Columbia, Canada (18 storeys, ~190 ft).

Bullitt Center

The Bullitt Center is a six-storey, ~76 ft tall wood hybrid office building in Seattle, Washington, USA. The building was designed by The Miller Hull Partnership of Seattle, and RDH Building Science was responsible for the building enclosure design, field review during construction, and air barrier commissioning testing. The Bullitt Center is not only unique in that it was one of the first modern taller wood structures in the United States, but also in that it was the first Living Building Challenge office building in the world (bullittcenter.org). Wood was chosen as one of the primary structural materials for its resource efficiency, weight, and environmental impact. Reinforced concrete was used for the below-grade and podium levels as well as topping for the wood floors; structural steel was utilized for the elevator core and lateral load resisting system.

The roof consists of an R-40 effective insulated conventional roof assembly over wood deck with exposed white TPO roof membrane to harvest rainwater and is not particularly unique for a wood building. The exterior wall assembly consists of a steel-framed wall with studs supported off the exterior of the slab edge to improve thermal performance. The assembly is split-insulated with mineral fiber insulation and incorporates a thermally efficient cladding support system to achieve an effective thermal performance of R-26.6 overall, exceeding the local energy code requirements and living building challenge design target (Figure 9). The wall assembly is unique in its overall thermal performance for a steel-framed wall and demonstrates that a tall wood building does not necessarily need to have wood-framed exterior walls. Windows for the building consist of a high-performance triple-glazed unitized curtain wall system that is air- and water-sealed to the liquid-applied WRB membrane with silicone sealant and EPDM rubber transition strips (Figure 10).

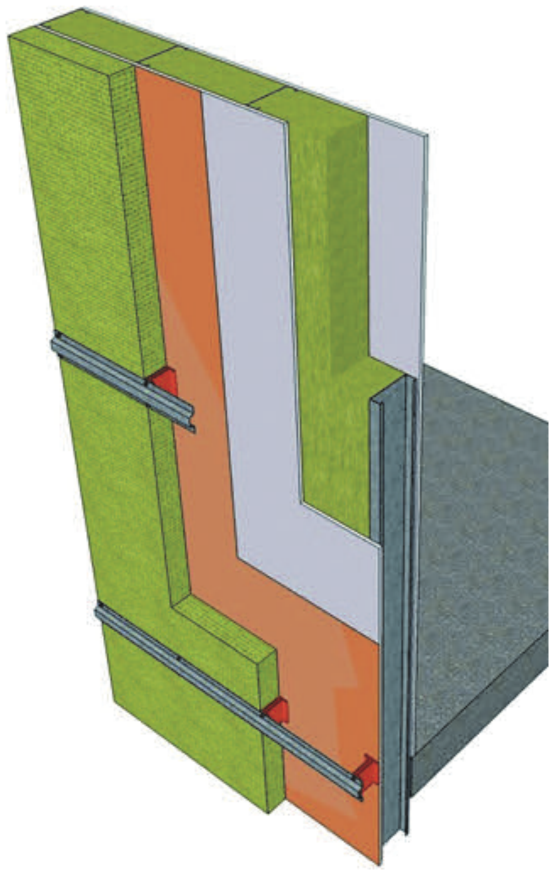


Figure 9 *High R-value steel-stud framed wall assembly utilized at the Bullitt Center.*

The Bullitt Center demonstrates the use of mass timber in a taller building, mainly NLT floor panels and glulam columns and beams in an extremely environmentally sustainable building. The wood elements were protected from excessive wetting during construction and the NLT panels incorporated gaps to facilitate movement due to moisture. Steel and concrete materials were also utilized by the design team, creating a hybrid structure and building enclosure.

Wood Innovation and Design Centre

The Wood Innovation and Design Centre (WIDC) is a six-storey, ~97 ft tall institutional building in Prince George, British Columbia, Canada. WIDC was the first tall wood building in North America and was seen as a pilot project to demonstrate the potential for high-rise wood buildings. Envisioned and designed by Michael Green Architecture (MGA) of Vancouver, the building incorporates a mass timber structure utilizing CLT floor and wall panels along with glulam columns and beams (Figure 9). The columns run continuously the height of the building to minimize dimensional movement, and the beams are hung from the columns to support the floor system. A staggered CLT floor system was innovated by MGA and incorporates spaces for HVAC, plumbing, and electrical services above and below alternate panels (Figure 11).

The author was directly involved with the design and detailing of the building enclosure, which consists of a unique conventional roof assembly over intermittent CLT panels, an exterior wall system consisting of infill prefabricated SIP panels, and a triple-glazed wood-veneer curtain wall system

Figure 10 *Photographs from the construction of the Bullitt Center exterior walls showing fluid-applied AB/WRB and joint sealants being applied to the sheathing, installed curtain wall system, and exterior insulation and cladding. (Photographs by John Stamets.)*

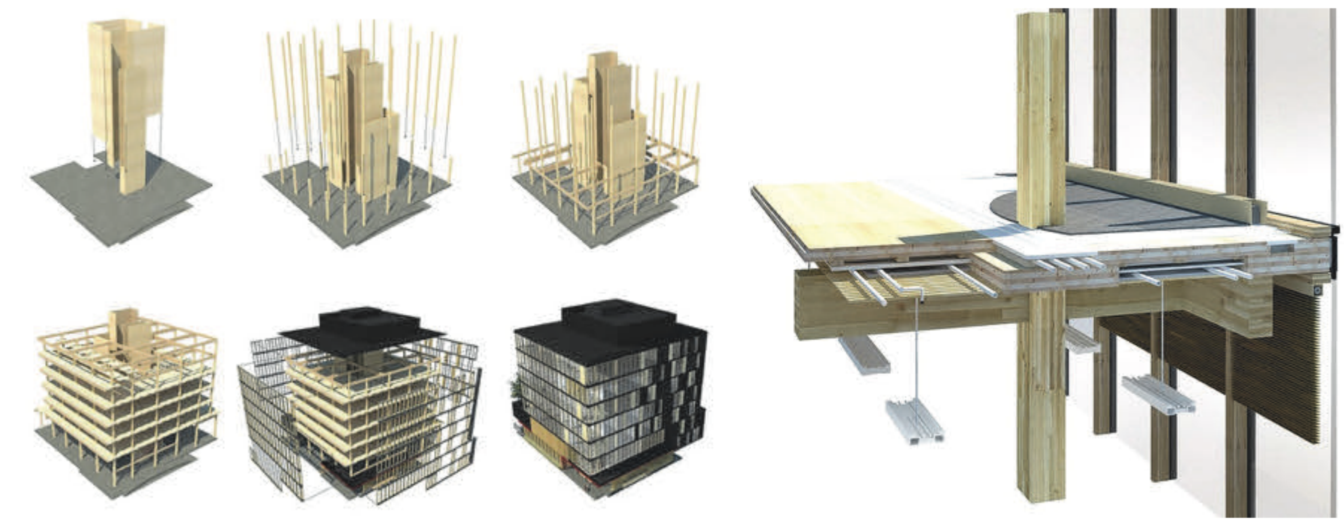
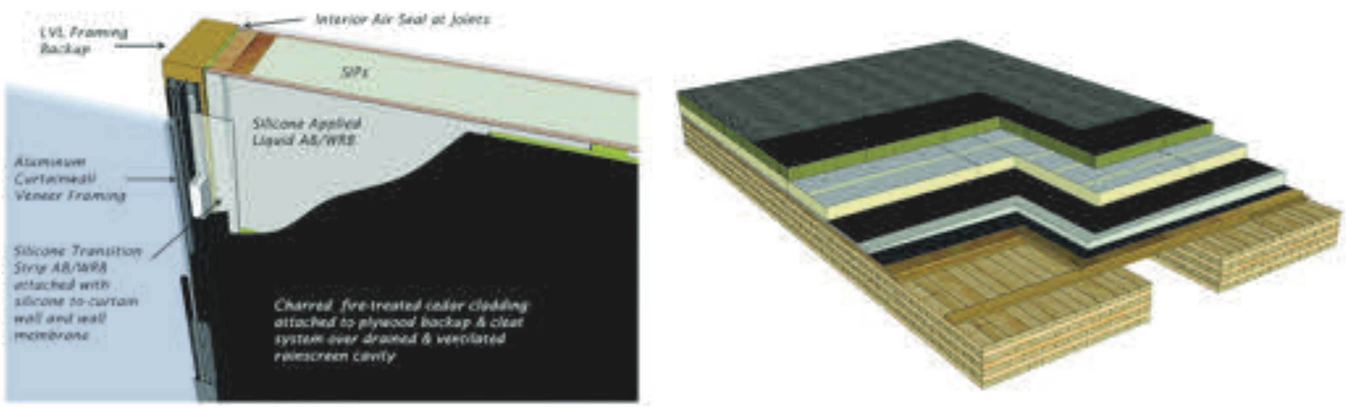


***Figure 11** Architectural renderings showing the unique wood structure and building enclosure elements of WIDC. The same structure and enclosure design can be readily adapted for 20+ storey high-rise wood buildings. (Renders courtesy of MGA.)*



(a) **(b)**

***Figure 12** Primary building enclosure assembly designs showing (a) SIPs wall panel and wood veneer curtain wall details and (b) interior vented conventional roof over intermittent CLT roof panels.*

that was stick built and site glazed (Figure 12). A fluid-applied silicone AB/WRB was preapplied to the oriented strand board (OSB) sheathing of the SIPs in the factory and all joints were sealed in the field. Flexible silicone transition strips were used to span movement joints and to seal the curtain wall and other penetrations in the wall. Because of the simplicity of a single-component fluid-applied system that could be applied in conditions below freezing, detailing of the building enclosure was simple to implement in the field. The use of two colors of silicone (black and grey) were used as contrast between the field-applied wall membrane and joints, which facilitated easier quality assurance and field review. Photographs showing construction of the exterior walls and roof assembly are shown in Figures 13 and 14.

As part of this project, field monitoring was performed by FPInnovations to measure the long-term movement and moisture levels of the heavy timber structure (Wang et al. 2016). Monitoring found initial moisture contents of glulam and CLT components was on average 13% during construction and dropped as low as 4% during the wintertime due to very low indoor relative humidity (below 20%). The total shortening of the building columns was measured to be approximately 11 mm in 24,500 mm (0.044%). Shrinkage in thickness of the CLT floor slabs was measured to be approximately 5 mm in 169 mm (3.0%) on average, which was taken up by the flexible movement joints at the curtain wall and SIPs wall panels (Figure 3). Moisture content monitoring of the CLT panels of the roof assembly demonstrated dry initial and in-service

Figure 13 *Exterior walls of WIDC under construction. Note the use of silicone-applied AB/WRB to walls with flexible silicone transition strip movement joints at the curtain wall interfaces. A combination of both charred and bare-stained western red cedar was preapplied to treated plywood panels and the mounted-on French-clip connections and screwed in place to the rainscreen strapping in the field.*

Figure 14 *Conventional roof assembly of WIDC under construction. Note the use of a torch-applied SBS membrane over asphalt protection board functioning as a temporary roof and later air/vapor barrier over the interior vented wood roof deck over the CLT panels.*

conditions at all locations with the exception of one location that was initially wetted during construction but dried out prior to occupation due to the vented design.

The WIDC project demonstrates the use of an all-wood structure over a concrete foundation utilizing CLT walls and floors and glulam beams and columns. The walls incorporated SIPs panels and a wood veneer curtain wall within an infill non-load-bearing exterior wall application with simple connection and sealing details. The roof system demonstrated how the inclusion of a simple vent space above the mass CLT panels can improve the durability of this type of roof system.

Due to the arid inland environment and winter construction season, wetting of the wood components from rain was less of a factor to the construction team. Scaffolding and hoarding was used to facilitate wintertime construction in freezing weather and did protect the walls and curtain wall during erection. The roof was protected by a temporary full-torched roof membrane installed as soon as possible after installation, and the timing avoided heavy rain events (snow was swept off instead). Tarps were used in a few instances by the contractor to protect upper roof areas from wetting in the wetter spring months. All being said, these moisture-management practices would have likely allowed for excessive wetting and potentially delays and drying costs if the building had been constructed during the wet season of a coastal environment, similar to the examples discussed in the Large Wood Building Enclosures—Industry Lessons Learned section.

Brock Commons UBC Student Residence Building

The UBC Brock Commons project is an 18-storey, 180 ft tall hybrid wood residence building currently being constructed in Vancouver, British Columbia, Canada. Completion of the structure and building enclosure is anticipated by early 2017. The building structure consists of a reinforced concrete foundation and first-level and twin elevator cores extending up through the building. The wood structure sits on top of the first level (17 storeys tall) and consists of continuous glulam columns and beams with a five-ply CLT floor plate. A cementitious screed is placed on top of the CLT floor panels, which are encapsulated with gypsum on the underside for fire and acoustic separation. Related to the floor system, research was performed by RDH Building Science to evaluate the impact of construction wetting from rainwater and cementitious screeds on the wetting and drying of CLT panels during construction and to evaluate the benefits of different coatings and membranes applied to the CLT in the factory. Testing of CLT panels indicates that hydrophobic water-resistant coatings are beneficial to reduce rainwater uptake into CLT panels and that some barrier coatings will also reduce the uptake of moisture from the screed into the CLT. The testing found that uncoated CLT panels would be subject to excessively wet conditions if exposed to rain or from the application of the concrete topping and therefore coatings are recommended for CLT floors. Of particular concern is the penetration of water into gaps and cracks between boards past the surface of the panels both within panels and between panels where water is able to bypass taped joints. Based on our research and field experience to date, further research is needed to find optimal factory-applied coatings to protect CLT and other mass timber panels from construction wetting, to allow floors to be made watertight during construction, and to protect the wood from concrete topping moisture.

The building enclosure design process for this building was unique in that four different prefabricated wall systems were designed and prototyped for the project. Prefabrication of wall assemblies including exterior cladding with windows installed was chosen by the design and construction team to speed up site erection and allow a floor to be enclosed within a week. Different panel sizes were considered in early design stages, and it was determined that a module of approximately 30 ft in length by the floor height would be ideal for shipping and erection using the site cranes. Exterior scaffolding is not being utilized for the project, so the preclad panels will need to be air and moisture sealed using a combination of gaskets and sealants incorporated with the panel anchors.

Three of the four prefabricated wall options were prototyped, mocked up (Figure 15), and priced by the construction team and wall subcontractors: 1) steel-stud exterior insulated panel, 2) lightweight insulated precast concrete panel, and 3) wood-stud panel. The fourth option, a solid CLT panel, was eliminated early on and not mocked up, as the CLT panels were determined to be too costly for an infill wall application on the project.

At the end of the mock-up phase, the steel-stud panel option was selected by the owner due to the fact that the wall prefabricator had experience with panelizing similar-size projects and quoted a competitive price on budget for the project. A full laboratory mock-up was then constructed to test the panels and connections against air/water/structural/thermal loads (Figure 16) and tweak the design prior to fabrication of panels for the project.

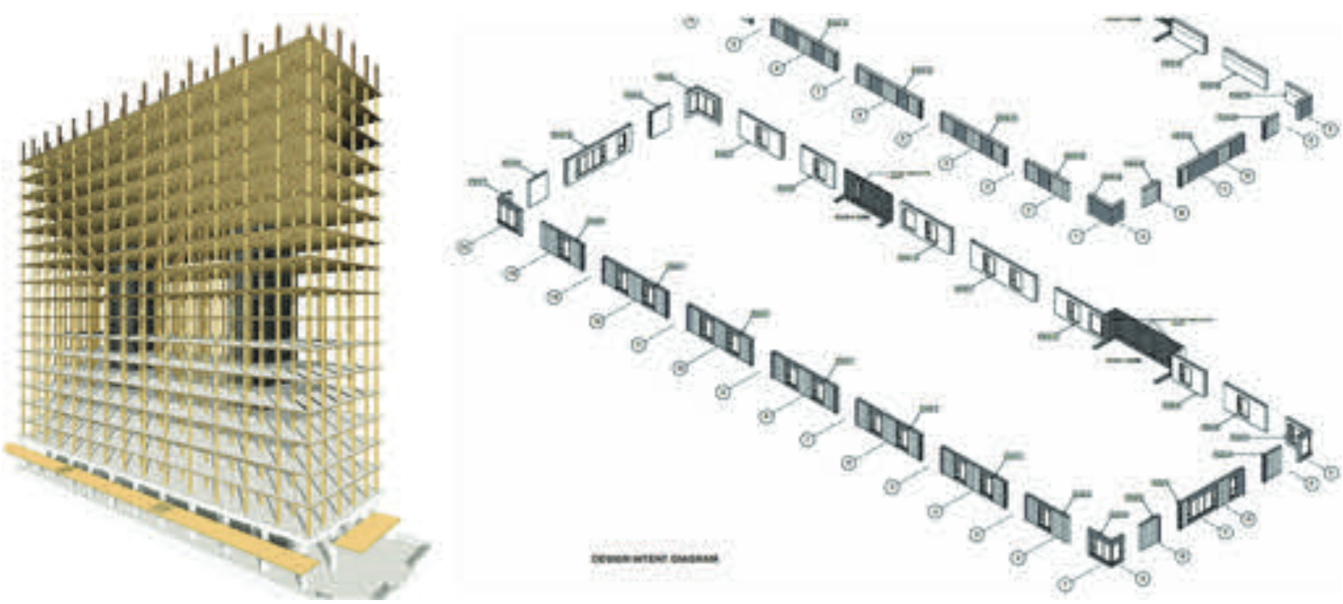
It should be noted that the lightweight precast concrete panels were also a viable option and the wood structure could easily accommodate the weight of the concrete panels. The wood-stud option was also viable and fully prototyped; however, it ended up being more expensive than the other options and, more critically, there were no local wood panel fabricators capable of taking on such a large and complex project. With time and projects it is hoped that industry capacity will grow to improve the cost-competitiveness of wood options.

The concrete foundation and core, coupled with the wood primary structure and steel-stud prefabricated walls, truly demonstrates the hybrid all-inclusiveness of future high-rise wood buildings (Figure 17). Construction is ongoing and will be completed in 2017; some early construction photos are provided in Figure 18. The intent is to erect the wood structure and install the wall panels during the dry summer months;

(a) (b)

Figure 15 *Partial two-storey structure and wall panel mock-up constructed to evaluate different wall prefabrication options and to test field exposure wetting, concrete toppings, and structural connections: (a) lightweight precast concrete wall system and (b) wood stud system with metal cladding.*

Figure 16 *Construction of mock-up of the final prototyped preclad steel-stud wall assembly for air/water/thermal/structural load testing at a testing laboratory prior to fabrication and installation on site. Cladding consists of a fire-resistant high-pressure laminate board attached to galvanized steel girts over a fiberglass clip support. The exterior fiber-glass-faced gypsum sheathing attached to the steel studs is coated with a liquid silicone AB/WRB that returns around the edges of the panels for ease of sealing at the interior.*



(a) **(b)**

Figure 17 *Architectural renderings of (a) the wood and concrete hybrid structure for the Brock Commons UBC Student Residence building and (b) the prefabricated wall panels.*

Figure 18 *Concrete cores, mass timber structure, and prefabricated steel-stud wall system with integrated aluminum windows.*

however, provisions have been made to address construction wetting (use of moisture-resistant materials within walls and a protective hydrophobic coating on the interior CLT columns and floors). The roof system consists of a traditional steel deck with insulation and exposed membrane in a conventional assembly. Through the summer of 2016, construction demonstrated that one to two floors of structure and enclosure panels can be erected per week, highlighting some of the benefits of both CLT and prefabricated wall construction.

CONCLUSION

Taller mid- and high-rise mass timber buildings are on the near horizon in North America. Through experiences in Europe and the construction of demonstration pilot projects and large mass timber buildings throughout Canada and the United States, the building industry is observing and learning how to design and construct these taller buildings and gaining a better appreciation for which building enclosure assemblies and details work and which are more risky. Best practices for design and construction become even more critical for high-rise wood buildings due to the use of more massive wood components, increased exposure to weather and wetting, and longer construction periods. Recommendations include the design of assemblies with redundancy and the ability to dry out, preapplication of waterproof elements prior to transport and erection, and more diligent protection of large wood components from wetting. The increased use of prefabrication is being observed within many of the larger and taller buildings built to date to allow for more efficient construction techniques and to protect wood components from long exposure to inclement weather. Many of these projects include wood and non-wood based structural and building enclosure components based on economic and technical factors, thereby creating truly hybrid wood building structures and building enclosures.

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