International Journal of High-Rise Buildings
September 2020, Vol 9, No 3, 261-271
https://doi.org/10.21022/IJHRB.2020.9.3.261

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Pushing the Boundaries of Mass Timber Construction and Building Codes

Jean-Marc Dubois, Julie Frappier, Simon Gallagher, and Nordic Structures

Simon Gallagher, P. Eng., M. Sc. A. Team Leader
Nordic Structures Montreal (Quebec) Canada

Abstract

The 2020 National Building Code of Canada (NBC) and the 2021 International Building Code (IBC) both include Tall Wood Buildings (TWB) and are hailed as documents responsible for the proliferation of Mass Timber construction. Mass Timber construction is critical to reducing the carbon footprint of the construction industry; a sector acknowledged as being one of the greatest contributors of global annual CO_2 emissions. Origine, a 13-storey multi-residential building erected in 2017 in a previously unsuitable site, is currently the tallest all-wood building in North America. This article describes the challenges overcome by the designers and client as they engaged with code officials, building authorities, and fire-service representatives to demonstrate the life-safety performance of this innovative building. It also traces the development of the "Guide for Mass Timber Buildings of up to 12 Storeys" published in Quebec and how it has enabled other significant Tall Wood projects across North America.

Keywords: Construction, Mass Timber, Low Carbon

1. Brief History of Wood Construction

"In the early 1900s, heavy timber, up to ten storeys in height, and light-frame wood construction were commonplace in major cities throughout Canada. The longevity and continued appeal of these building types is apparent in the fact that many of them are still in use today."[1]

The first National Building Code of Canada (NBC), published in 1941, contained height and area limits for different occupancies and construction types that were based on foreign building codes responding to historic city-destroying fires. Building height was limited to four storeys for heavy timber construction and three storeys for light-frame construction. The significant change in the 1965 NBC was the introduction of two primary types of construction: 'combustible' and 'non-combustible'. Provisions for 'heavy timber construction' were also detailed as a subset of 'combustible construction' however, Mass Timber construction was absent.

In 2005, National Research Council of Canada (NRC) published the world's first objective-based codes. "Converting the national model codes to an objective-based format made them more accommodating to innovation by clarifying their scope as well as the intent behind their requirements. Each code provision is supplemented by clearly stated objectives, functional statements and intents. This additional information helps proponents and regulators determine the minimum performance that must be achieved, thereby facilitating the code conformance of new products and construction techniques."[2]

Following the work of the Joint Task Group on Combustible Construction, six-storey buildings using traditional combustible construction materials were permitted in the 2015 NBC.

Of note, CSN-Fondaction: a six-storey glued-laminated timber (glulam) post-and-beam commercial building and District 03: two cross-laminated timber (CLT) multi-residential buildings of four and six-storeys were erected prior to the 2015 NBC publication. These projects made it possible to develop alternative solutions and fostered discussions with the Authorities Having Jurisdiction (AHJ); these works set the stage for Origine, a multi-residential, 13-storey Mass Timber building.

2. Tall Wood Building Demonstration Initiative

In 2013, National Resources Canada (NRCan), in collaboration with the Canadian Wood Council (CWC), launched the Tall Wood Building Demonstration Initiative to

†Corresponding author: Simon Gallagher
D 514-871-5621
E-mail: simon.gallagher@nordic.ca

[1]CWC, https://cwc.ca/how-to-build-with-wood/building-systems/mid-rise-buildings/

[2]NRC, https://nrc.canada.ca/en/certifications-evaluations-standards/codes-canada/codes-development-process/canadas-national-model-codes-development-system

support the development of new scientific data and technical expertise for the design and construction of buildings over 10 storeys in Canada.

The architect, Mass Timber engineer/supplier/installer, and the general contractor (Gestion Yvan Blouin, Nordic Structures and EBC, respectively) created the NEB consortium to develop Origine. This group, motivated by NRCan's initiative, formed a perfect trifecta to answer the challenge. Subsequently, the Quebec Ministry responsible for forests, wildlife, and parks (*Ministère des forêts, de la faune et des parcs:* MFFP) announced their financial support of a technical demonstration program for wood buildings and innovative solutions (*Programme de vitrine technologique pour les bâtiments et les solutions innovantes en bois)*, whose goal was the reduction of greenhouse gas emissions through wood construction.

3. Mass Timber Skyscraper

It took years of research to bring Origine (Fig. 1) from concept to reality; a fair question to ask is: why use Mass Timber if a more conventional construction material would not have imposed as many hurdles? A look at its unique location provides some initial answers.

Situated on the once empty banks of the Rivière St-Charles, between nature and the city center, Quebec City Council was looking to transform this area into a model 'Eco-District' by showcasing sustainable construction. To that end, Mass Timber was an obvious choice. Roughly 3200 cubic meters of Mass Timber used to create the structural frame represents 2300 tons of sequestered equivalent carbon dioxide (CO_2 eq.), in addition to 1000 tons of CO_2 eq. avoided by not using steel or concrete as the main structure.



Figure 1. Origine.

Wood's density is another factor that explains the choice of Mass Timber, as volumetrically, wood is roughly one fifth the weight of concrete. Due to the site's proximity to the river, the saturated soils exhibit low bearing capacities. Surprisingly, despite its lower density, Mass Timber's compressive resistance is on par with standard concrete; by extension, a wood structure is orders of magnitude lighter. Had Origine been a concrete structure it would have been limited to roughly six levels, and to attain the same height with concrete, expensive piles would have been required.

4. Origine Research

4.1. Building Code

When the project started, the Quebec Construction Code, Chapter 1 ("CCQ-c.1") – Building, and National Building Code – Canada 2005 (amended) was in force. In this version, combustible construction was limited to four storeys, while the proposed 13-storey building required non-combustible construction. Alternative solutions needed to limit the probability that a fire or explosion would create an unacceptable risk of personal injury or structural damage. These areas of performance are drawn from code-based objectives and functional statements.

Although Mass Timber has proven its superior performance and its crucial place in the future of construction, significant work was required to change the stakeholders' ambivalence to tall wood projects. Before starting the project, the design team met with the AHJ: the Quebec Housing Authority (*Régie du bâtiment du Québec:* RBQ), and subsequently with fire services to present the project. Nordic Structures and Yvan Blouin Architect demonstrated that the performance of the proposed alternative solution was equivalent or superior to prescriptive requirements through a comprehensive methodology that included code studies, fire modeling and testing, peer reviews, and structural and architectural performance testing.

It goes without saying that such a major and innovative project requires significant collaboration. Amongst others, the team consulted with designers of tall wood buildings from Australia, the United States, Italy, the United Kingdom, and Norway. Collaboration subsequently expanded with code consultants, research centers, and laboratories around the globe.

4.2. Fire Safety

Concerns from fire services regarding Mass Timber shafts led to the development of a large-scale fire demonstration (https://www.nordic.ca/en/documentation/publications/large-scale-fire-demo) whose objective was to evaluate the shaft's fire safety performance (Fig. 2). Results show that CLT is an appropriate and safe material for building construction when exposed to severe fire conditions.



Figure 2. Large-scale fire demonstration.

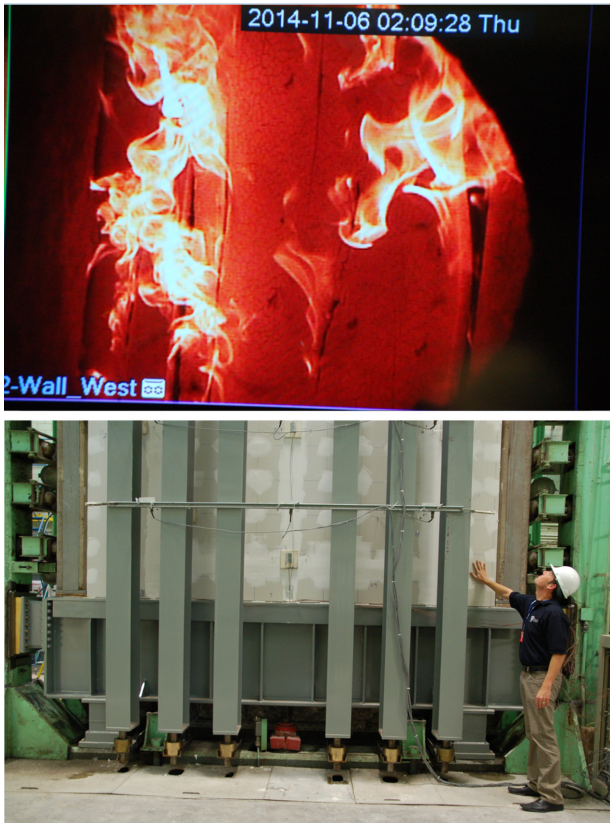


Figure 3. Fire resistance test of a CLT wall.

The fire resistance tests validated the anticipated fire resistance when calculated using Annex B of CSA O86 which was subsequently published in 2017. The excellent thermal properties of wood can be seen in fire tests (Fig. 3), when after a period of 2 hours, the temperature on the exposed side of the CLT wall was 1007ºC, in contrast to the unexposed side that measured 20ºC and was smoke free.

4.3. Structure and Architecture

Numerous tests were necessary to validate the structural and architectural hypotheses central to the success of Origine, the first 12-storey building over a concrete podium designed and built entirely of Mass Timber. Although some of these tests would not normally have been required, it was of the utmost importance for the design and research teams to demonstrate a high level of per-formance. The battery of structural tests undertaken validated or increased CLT mechanical properties and supported proposed connections and construction systems.

Given the scale of the project, competing architectural Mass Timber detailing solutions were compared, examined, and tested. The results ensured a design with optimal acoustic, thermal, and building physics performance, exceeding code requirements.

5. Guide for Mass Timber Buildings

The Technical Guide for the Design and Construction of Tall Wood Buildings in Canada, published by FPInnovations, was used as the basis for evaluating alternative solutions. A working group consisting of government departments, code consultants, and fire services operating under the RBQ was formed in March of 2013. As a result of the working groups' efforts and the acceptance of Origine, the "Directives and Explanatory Guide for Mass Timber Buildings of up to 12 Storeys" superscript guide was published by the RBQ, allowing combustible construction of taller buildings. This guide was modeled on the principles that governed the design and implemen tation of Origine.

Although the guide now allows 12-storey Mass Timber construction, it includes additional requirements. For instance, sprinkler pipes must be non-combustible, increased mechanical pressurization in the exit stair shafts is required, a fire-resistance rating of one hour is mandated for the roof, and all wood must be encapsulated with non-combustible material.

It is important to recognize that one benefit of Mass Timber construction is the warmth and physiological human response to biophilia created by the expression of exposed wood. This guide, and by extension Origine, opened the door to many new projects that do just that. Located in the heart of Montreal, Quebec, Arbora is comprised of three eight-storey buildings. Boasting the greatest volume of Mass Timber in the world, this 434-unit multifamily complex would not have been possible without Origine and yet was still able to have exposed beams and columns in every apartment.

6. Origine from Theory to Reality

Origine is a 12-storey Mass Timber structure with 1600 m^2 per level built on a one-story raft foundation concrete podium. The building counts a total of 92 residential units and 87 underground parking spaces. At over 41 m tall, Origine is currently the tallest all-wood

[3]RBQ, https://www.rbq.gouv.qc.ca/en/areas-of-intervention/building/different-and-equivalent-measures/guide-for-mass-timber-buildings.html

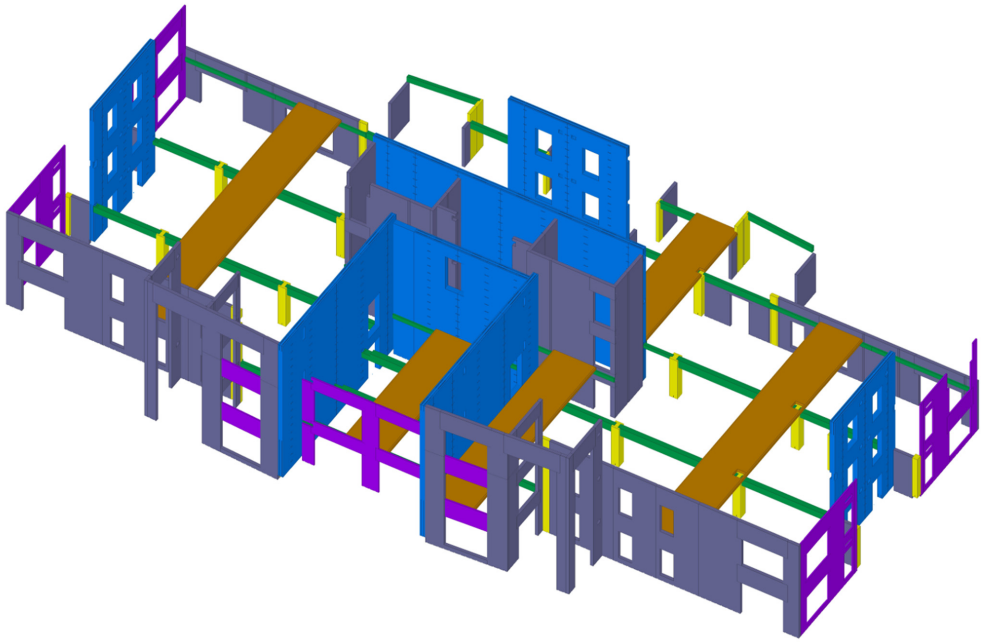


Figure 4. Structural System.

building and the second tallest Mass Timber building in North America.

Origine has a unique Mass Timber structural system (Fig. 4). It is made up of CLT floor slabs (brown) supported by a combination of glulam posts (yellow) and beams (green) as well as CLT walls. The elevator and stair shafts and exterior walls are composed of CLT panels. North and south walls, 5-ply 175 mm thick (purple), serve as load-bearing elements while east and west walls, 3-ply 78 mm thick (pink), serve as a support for exterior cladding and transfer wind loads to the diaphragm. Seven shear walls (blue) comprise its seismic force resisting system.

6.1. Gravity System

The floors are composed of 5-ply 175 mm thick CLT slabs. These multiple-span panels are supported by glulam beams, typically 327 mm × 502 mm, and CLT walls. The beams are in turn supported by single storey glulam columns measuring 456 mm × 456 mm at the foundation and shrink to 279 mm × 279 mm by the top.

It is important that Mass Timber construction avoids applying load perpendicular to wood grain. For this reason, great care was taken detailing the column-to-column joints. Beams rest on notched columns that extend beyond the slab to support columns above (Fig. 5). To ensure that no load is transferred through a beam, the detail calls for a small gap between the top of the beam and the underside of the column.

This same principle can be seen in the CLT slab-to-wall connection (Fig. 6). Balloon framing was selected over platform framing to avoid compression perpendicular to grain generated by wall loads transferring through floor slabs. CLT floor slabs lie on Glulam ledgers screwed to the CLT walls.

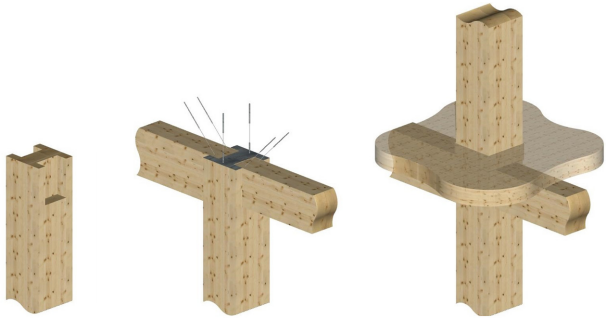


Figure 5. Beam-to-Column Connection.

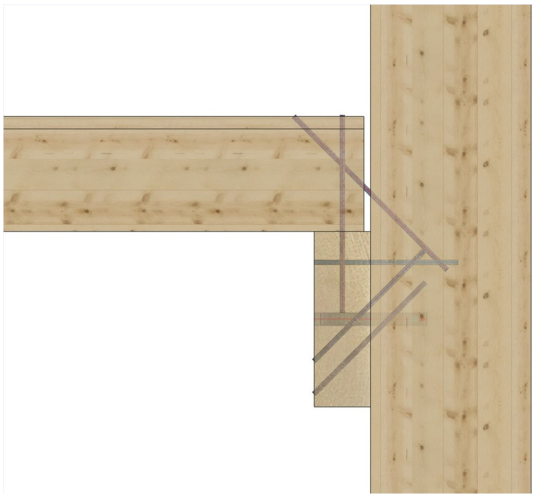


Figure 6. CLT Slab-to-Wall.

CLT gravity walls are typically composed of 5-ply 175 mm, two-storey panels. Notches cut into CLT walls support glulam beams.

Steel angles anchor the CLT walls to the concrete foundations. Mechanical anchors fasten these angles to the foundation while screws are used to secure the wall in place (Fig. 7). Columns attached to the foundation feature cast-in-place anchor rods, two-storey base plates, and a knife plate with dowels (Fig. 8).

6.2. Lateral System

A significant achievement for this project is its pre-eminent position as the tallest building in North-America relying exclusively on Mass Timber for its lateral-force resisting system. This system is composed of the seven shear walls performing the dual function of supporting lateral and gravity loads. The walls are three-storey tall and are 291 mm thick at the foundation, narrowing to 175 mm over its height. The wall's central portion is composed of CLT and is flanked on either side by glulam 'column' elements (Fig. 9). The central CLT portions and the glulam side sections resist shear forces and compression/tension forces, respectively.

Given the paucity of guidance on CLT diaphragms and shear walls, designers opted to create two finite element

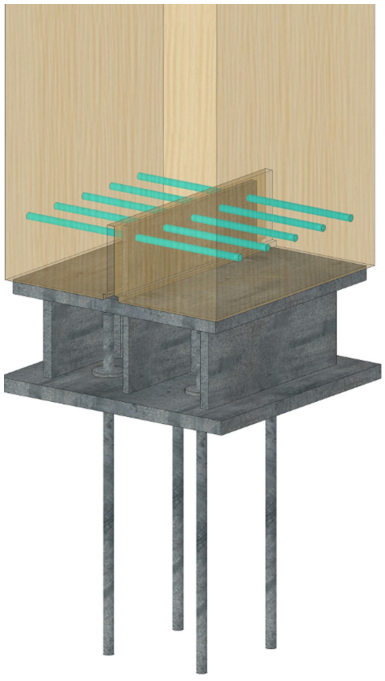


Figure 8. Column-to-Foundation Connection



Figure 9. CLT Shear Wall.

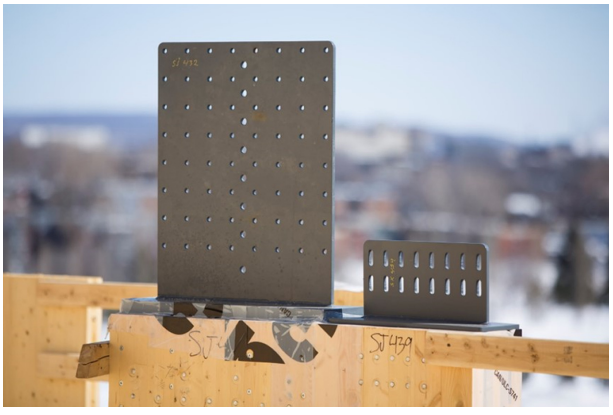


Figure 10. Shear Wall Connector.

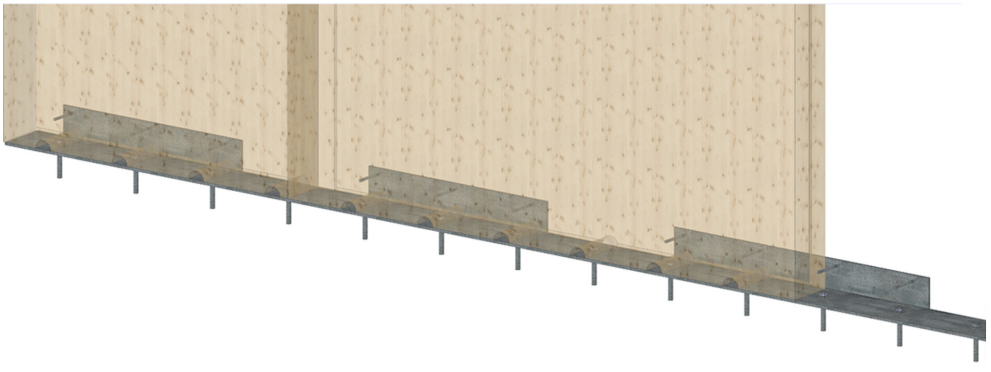


Figure 7. CLT-to-Concrete Connection, Gravity Wall.



Figure 11. Shear Wall Connection, Tension/Compression Portion.

models: one rigid and one flexible. A conservative design of these elements was carried out using the envelope of the two models, although in reality, the truth lies somewhere between.

To ensure continuity of the CLT diaphragm, individual panels were stitched together with nailed plywood splines, steel straps, and where appropriate, using beams or ledgers as drag struts. Lateral load transfer between the CLT slab and CLT shear walls was achieved with custom bent nailed plates. Large steel beams with W-section shear keys embedded into the concrete are located at the base of the shear walls to transfer shear forces from CLT walls to the foundation (Fig. 12). Pre-existing pockets facilitated installation of the steel shear keys and were subsequently back-filled. Tension and compression forces from the glulam side elements were transferred to the foundation via cast-in-place anchor rods attached to a

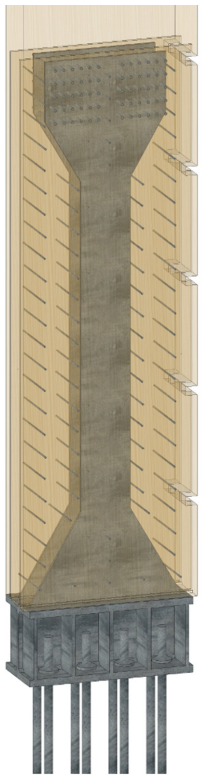


Figure 13. Shear Wall-to-Foundation Connection, Tension/Compression Portion.

steel base plate connected to the glulam element with dowels (Fig. 13). To improve building performance, the knife plates were elongated increasing ductility.

Similar doweled knife plates were used every three floors to splice shear walls together (Fig. 14).

6.3. Attention to Detail

When a detail is well thought out and easy to install, it generally goes unnoticed and receives little attention or comment. Time and energy went into making sure that this was the case with Origine, whose gravity wall-to-wall horizontal connection detail (Fig. 15) exemplifies

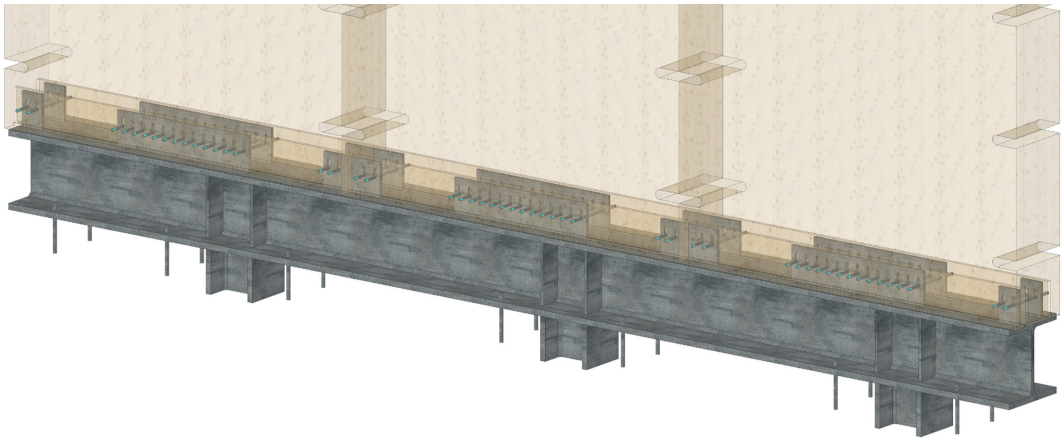


Figure 12. Shear Wall-to-Foundation Connection, Shear Portion.

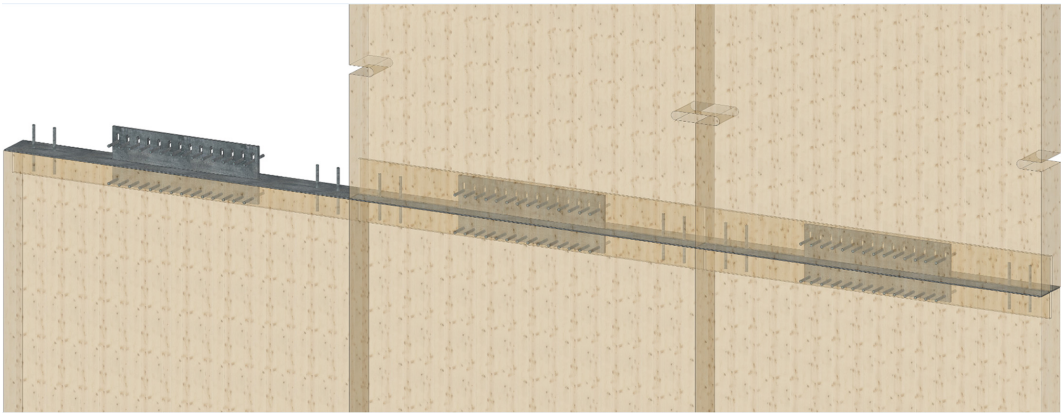


Figure 14. Shear Wall Connection, Shear Portion.



Figure 15. Screw Installation at Gravity Wall-to-Wall Connection Detail.

this philosophy. Although the chosen detail was a simple butt joint with screws at 45 degrees, a great deal of thought went into locating this joint 1.2 m above the slab, the minimum height for a construction guardrail in Quebec. Sealing window and door openings was the only step required to secure each level after the placement of the final floor panel. This saves not only on fall protection, but also on schedule by allowing other trades to access floors more quickly. Another benefit of locating the joint further from the floor is that the install crew was able to fix screws at a comfortable level, while standing instead of crouching.

The most prevalent CLT wall-to-wall splice is a half-lap joint (Fig. 17), ideal since each panel creates a bearing surface to abut the subsequent panel. On Origine, a different direction was chosen as there are approximately 1476 linear meters of vertical joint on the building. The use of a half-lap joint would have meant significant wood waste and more panels, resulting in additional manipulations and longer install times. Designers chose the spline detail typically reserved for CLT floor slab connections instead (Fig. 18). To always provide an abutting surface, panels were shipped to site with routings face-side up, allowing pre-installation of plywood spline on wall panels prior to hoisting. These splines mimic the half-lap while saving a significant volume of Mass Timber (Fig. 19).



Figure 16. Spline Installation.

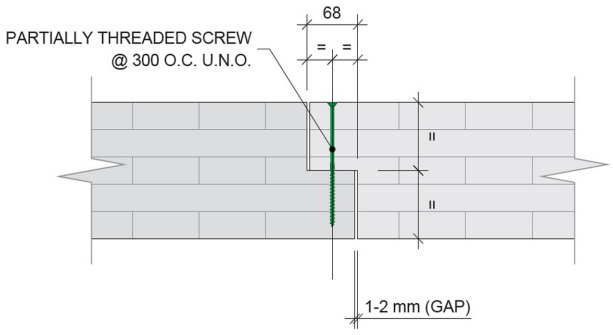


Figure 17. CLT Half-Lap.

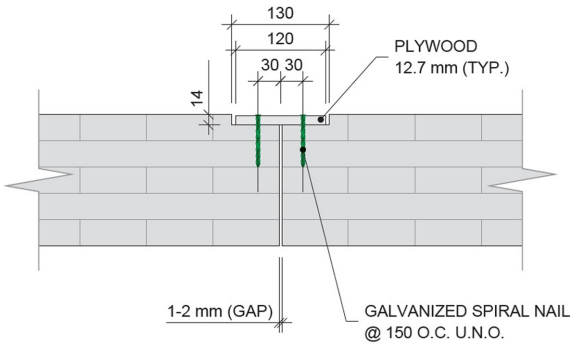


Figure 18. CLT Spline.

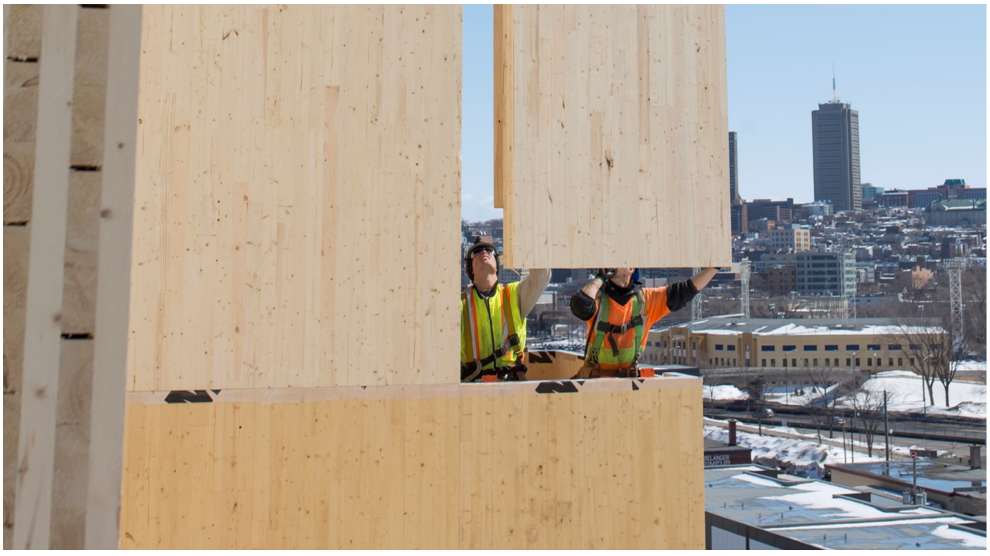


Figure 19. CLT Wall Panel Installation.

The horizontal splices in the shear walls also required some ingenuity. To ensure that tension and compression loads are resisted by side glulam elements, at each horizontal splice in the shear wall, knife plates in the CLT feature vertical oblong holes (Fig. 14). Tension screws passing through additional holes in the center of knife plates prevent buckling of the residual glulam sections that result from machining the knife plate slots (Fig. 10).

Another piece of the puzzle required to make the CLT shear walls feasible was an efficient horizontal shear connection. Nailed plates are the typical solution; however with the large forces found in such a tall building, the immense quantity of nails would have made this impractical. Many alternates were examined, but ultimately, although previously untried, steel shear keys provided the ideal solution (Fig. 20). Precise factory-cut slots (Fig. 21)



Figure 20. Shear Key Being Inserted.



Figure 21. Shear Key Slot.



Figure 22. Shear Key Test Setup.



Figure 23. Shear Key Test.

line up in adjacent panels. These allow steel keys to be inserted without drilling or measuring. The advantage of these shear keys is ease of installation, a job that can be done quickly and efficiently even by the uninitiated, with the further bonus of facilitating post-install inspection. The resulting time impact is easy to imagine when considering the 400 nails that each key replaces. Shear keys engage the full thickness of CLT walls, providing a much more efficient connection than nailed plates that otherwise lead to stress concentrations in the outermost layers of CLT. The theoretical capacities and behaviors of this novel design concept were validated by significant testing prior to inclusion (Fig. 22 and 23).

6.4. Installation Sequence:

The first elements installed were the 3-storey CLT shear walls, comprising elevator and stair cores, lobby walls, and single walls on the north, east, and west side of the building. Columns and beams were next, followed by the first set of gravity walls. With the exception of the north wall on the first level, gravity walls are all two storeys high. This first wall section was intentionally kept

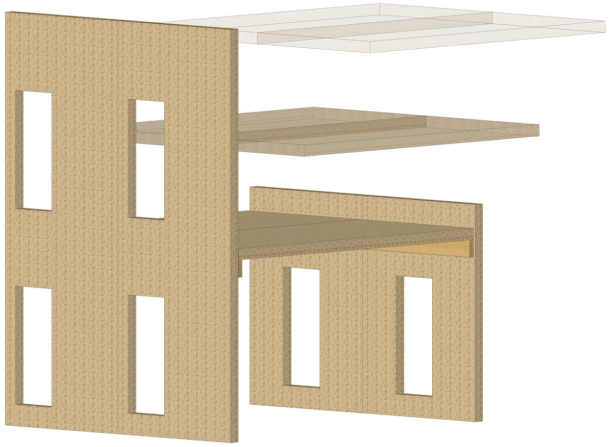


Figure 24. North wall; south wall

to one level to create a stagger between the north and south walls, meaning one of the walls always extends past the other. This was done to facilitate the installation of floor panels, the last element on every level before blocking off openings for fall protection. Had the walls not been staggered, and with such tight tolerances, the installation of full depth, 60-ft, 10 000 lb CLT floor panels would have been extremely difficult, and risked jamming the elements (Fig 24). Crane time and number of picks drives the speed of Mass Timber installation; keeping the number of pieces to a minimum reduces the number of picks. Staggering enables the use of the longest possible panel, effectively reducing piece count while ensuring ease of installation.

This process of installing columns, beams, walls, and slabs, followed by shear walls every three floors was repeated until the final roof panel was raised (Fig. 25).

Where possible, the designers optimized connection details to facilitate installation and reduce crane time. Column-to-column and beam-to-column connections were easily installed via readymade pockets in the CLT slabs and column tops, respectively. Pre-drilled dowel holes provided temporary anchorage for glulam ledgers, eliminating onsite measurements and the need for crane support during permanent attachment of the ledgers via fully-threaded screws. The result was a structure that went up like a Lego set, erected in record time.

6.5. Installation schedule:

The wooden structure was erected during difficult winter conditions in only 16 weeks. Early difficulties resulted from the interface between the tight tolerances of Mass Timber and the less precise foundations. Given the need for onsite adjustment, it is important to provide tolerance to connection details between Mass Timber and other building materials.

Remarkably, the last six storeys took only five weeks to erect, more than one level per week.

In an effort to minimize schedule, the general contractor

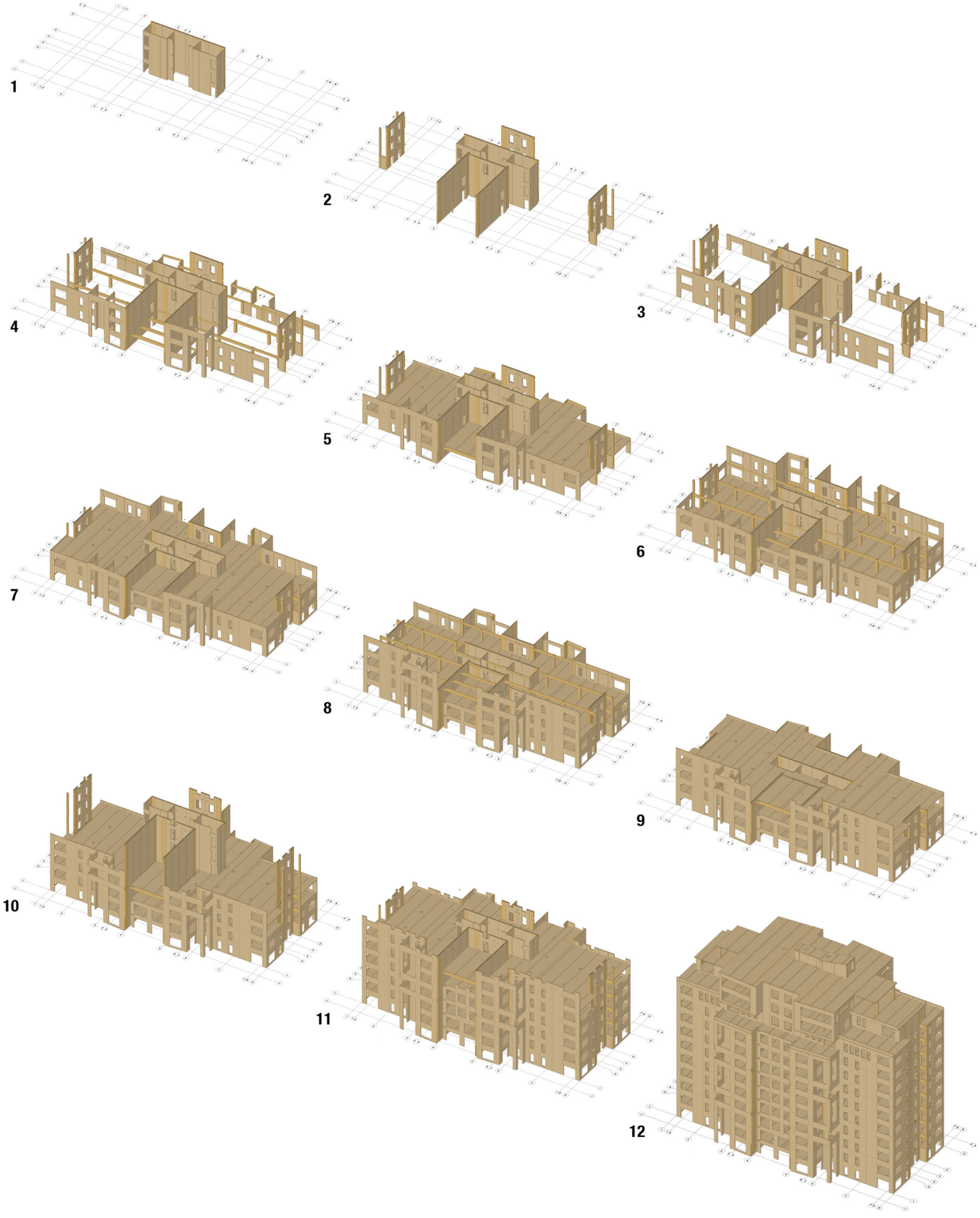


Figure 25. Installation Sequence

activated multiple subcontractors simultaneously, requiring signi-ficant coordination between the Mass Timber team and other trades. It was not uncommon to have windows and exterior cladding crews operating minutes after wall panel erection. As Mass Timber managed to outpace other trades, the additional elbow room allowed timber framers to greatly accelerate their installation speed. The departure of exceedingly bad winter conditions which

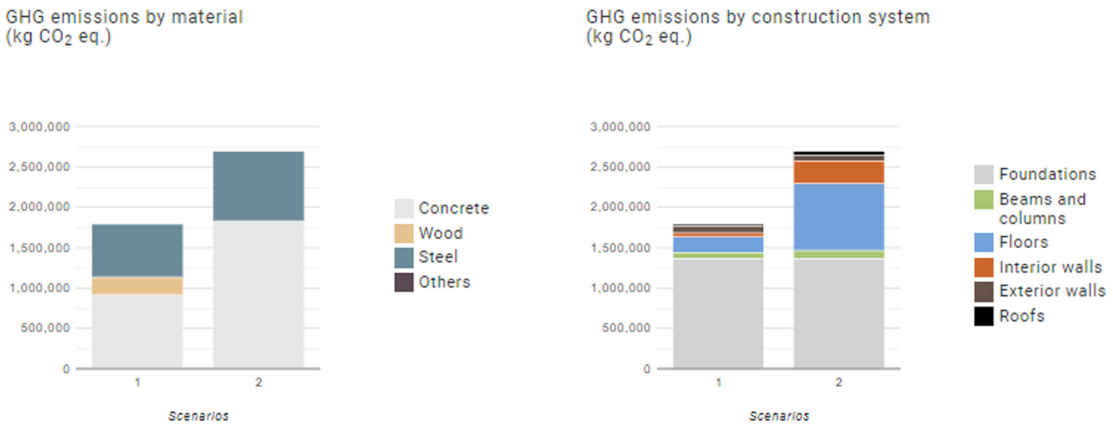


Figure 26. Comparison of GHG emissions attributable to the structure of Origine (1) and the reference scenario (2).

prevented crane use on multiple occasions early in the schedule was also an important factor.

6.6. Sustainable Development

The environmental footprint of Origine was minimized to ensure its LEED-NC Silver accreditation - from building construction to thermal insulation of the units, including energy consumption.

As part of the MFFP's demonstration projects program, Cecobois was mandated to quantify the reduction in greenhouse gas (GHG) emissions attributable to Origine as compared to a reference concrete building using Gestimat, a proprietary software program developed for these purposes.

Origine's material GHG emissions are estimated at 155 kg of CO_2 eq./m^2, compared with 233 kg of CO_2 eq./m^2 in the reference scenario, 50% more than Mass Timber, or 907,640 kg of CO_2 eq. (Fig. 26). For the purposes of this exercise, the larger foundation required for the concrete reference model was not taken into account.

6.7. The Outcomes

Interest in Mass Timber construction is soaring globally as developers race to meet demand for sustainable, biophilic buildings. Today's design and manufacturing technology makes Mass Timber, with its excellent properties, light weight, and intrinsic fire resistance, an ideal candidate for building taller structures. The 2020 edition of the NBC contains requirements for Encapsulated Mass Timber Construction (EMTC) up to 12 storeys in height. EMTC refers to buildings where Mass Timber components are surrounded or encapsulated with fire-resistant material. This allows for equivalent or better fire protection when compared to other construction types currently permitted by the code.

In December 2015, the International Code Council (ICC) chartered the ICC Ad Hoc Committee on Tall Wood Buildings (TWB) in response to growing interest in this area. Its purpose was to "explore the building science of tall wood buildings and investigate the feasibility of and take action on developing code changes for tall wood buildings". The committee reviewed voluminous documentation regarding tall wood buildings, including the previously mentioned RBQ guide. Approved provisions allowing for the construction of tall Mass Timber buildings up to 18 stories will be published in the 2021 edition of the IBC.

The evidence of Mass Timber's suitability for Tall Wood Buildings can be seen with the announcement of a significant number of projects such as The Arbour, a 10-story Mass Timber building that will be Ontario's first institutional building to use the material and T3 Bayside, also in Toronto, the tallest Mass Timber office building in the world at its completion.

7. CONCLUSION

It would be remiss to overlook the contributions of our colleagues at CWC, FPInnovations, GHL Consultants, MFFP, NRC, NRCan, Technorm without whom this project would not have been possible. With their hard work and encourage-ment, they provided an authoritative voice of support, vetting this endeavour to advance the code and the pursuit of Tall Wood Buildings.

Despite myriad challenges faced by the designers and client to prove the validity of the design solution that is Origine, alternative solutions provided a viable means to demonstrate its performance to the AHJ and code-writing authorities. This approach facilitates communication with the public, owners, and stakeholders alike. Origine is an excellent demonstration of group dynamics and engaged stakeholders collectively delivering a successful ground-breaking project. Rather than a prescriptive code based on the construction typology of the past, one can now imagine a future that holds performance-based design as the paragon of sustainable building innovation.