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Todd Snapp brings versatile expertise and dynamic knowledge as a practice leader and design principal at Perkins+Will. His work spans from mixed-use master planning of high-rise residential and office developments to cultural and higher education facilities. Todd was recently selected as one of *Fifty Under Fifty: Innovators of the 21st Century*.

Alejandro Fernandez is a structural engineer in Thornton Tomasetti's Chicago office. Alejandro brings a holistic approach to the design of tall buildings with master's degrees in both architecture and engineering from the Illinois Institute of Technology and the Ecole Nationale des Ponts et Chaussées in Paris.

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Abstract

The Chicago River Beech Tower is a collaborative research effort with the goal of identifying challenges and opportunities associated with designing increasingly tall mass timber structures. This paper represents the team's findings to date on these topics, their implications for tall building design, and suggests possible pathways that may inform and engage the design community. A key objective of the project is to explore new design potential with timber buildings, rather than substituting timber in the familiar forms of conventional construction in steel and concrete. Refer also to Tall Buildings in Numbers on page 47.

Keywords: Timber, Construction, Low Carbon, Code Compliance, Prefabrication

Introduction

While the reasons for considering mass timber will vary by project, client, and region, the building industry is experiencing an increase in the use of mass timber products for tall buildings. In 2008 there was one mass timber building over eight stories tall; by 2014, a survey of tall wood buildings identified nearly 30 buildings over eight stories that were either complete, under construction, or in late-phase design (Perkins+Will 2014).

This research began with acknowledging how wood behaves as a material. Its properties were compared to steel and concrete in terms of structural behavior, fire resistance, construction methods, environmental impact, and architectural expression. This fundamental understanding was then applied to the challenge of designing a building with real world design constraints.

Designed by the Chicago offices of Perkins+Will and Thornton Tomasetti in collaboration with researchers at the University of Cambridge's Centre for Natural Material Innovation, the River Beech Tower follows the program of an 80-story, 244-meter-tall timber residential tower situated along the South Branch of the Chicago River (see Figure 1). Exposed mass timber would offer a unique experience within the residential market by connecting occupants with natural materials. The program includes 300 units, a development density in keeping with current

construction along the Chicago River (see Figure 2). The 80-story program of the tower forces the design team to consider many of the issues typical to designing tall buildings, while staying within the established 70- to 80-story height range for tall residential towers in Chicago.

Design Strategies

The overarching goal of this study is to identify areas of mass timber research that could help advance the use of timber in tall building structures. Approaching this from a practitioner's perspective, the team placed focus on developing an all-timber superstructure and allowed the planning and architecture to adapt in response. Using a residential floor plate as a planning framework, the team set out to examine how design professionals could use current timber technology to make the design of a tall timber tower feasible.

The material properties of mass timber drive the design of a tall tower in unique ways. Timber's elastic stiffness and material density vary notably from those of structural steel and reinforced concrete. Both natural and engineered timber have lower strength than steel and concrete, with steel supporting up to 460 MPa (fy), concrete up to 95 MPa (f'c), and timber around 25 MPa (Axial ADS); new engineered hybrid materials record higher strengths. However, it is the softer elastic stiffness that will most directly influence the design of tall towers, which must resist large lateral loads. In this case, steel comes in at

200 GPa, concrete at 25–44 GPa, and timber at 7–17 GPa (see Figure 3). Using this data, the team developed several strategies to guide the design when using mass timber.

Proportion the tower footprint to make a timber superstructure feasible.

The design of River Beech Tower interconnects two separate towers, with each tower having a narrow profile. This slenderness is ideal for residential planning, but too narrow for each tower to be stable when subjected to lateral loading. Separating the two towers on each side of a multi-story atrium creates a wider combined footprint and increases stability by performing as a single, larger superstructure. The two individual towers are structurally connected across the atrium using glued laminated timber (GLT) cross-bracing (see Figures 4 and 5). This connection couples the structure together to act as one, maximizing the superstructure’s performance and minimizing member stresses.

Maximize the participation of all vertical members of the tower’s lateral system.

River Beech Tower’s lateral system connects all the vertical structural members together. Cross-laminated timber (CLT) shear walls, GLT bracing, and laminated veneer lumber (LVL) diaphragms effectively engage the vertical elements for resisting the tower’s lateral loads, making full use of gravity-carrying members (see Figure 6).

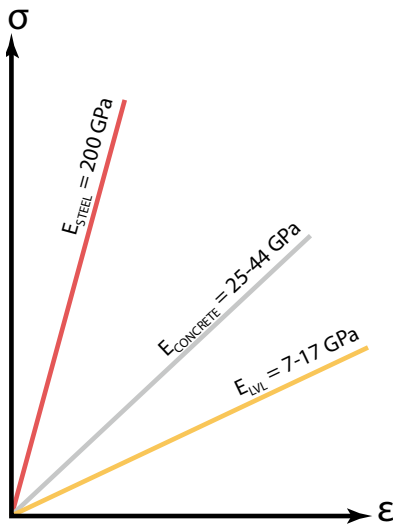


Figure 3. Relative elasticity of steel, concrete, and LVL timber. © Thornton Tomasetti



Figure 1. River Beech Tower, Chicago. © Perkins+Will



Figure 2. The proposed tower in context of its site at the southwest edge of the Chicago Loop CBD. © Perkins+Will

“Establishing timber as ‘non-combustible’ is a challenge. A wood sample would need to be genetically modified, treated, or engineered as a composite material to pass the ASTM E136 test for combustibility.”



Figure 4, Atrium cross-bracing is key to both the stability and the architectural expression of the design. © Perkins+Will

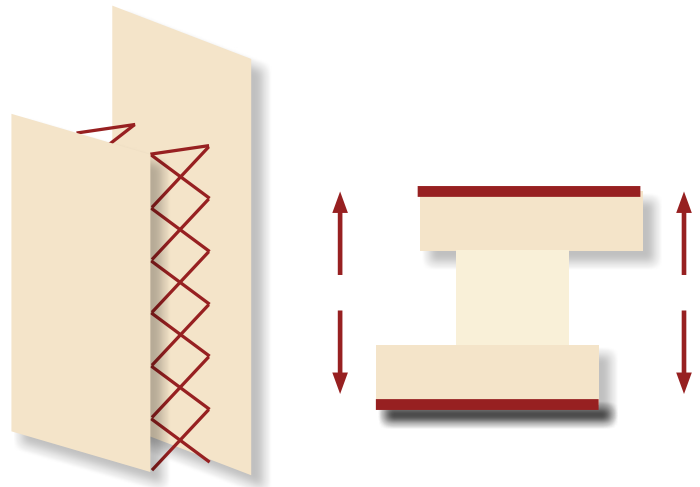


Figure 5. Cross bracing is used to engage the entire structure (left). Reduced material stiffness is balanced by material concentration on outer edges (right). © Thornton Tomasetti

Arrange the timber material in plan for maximum effectiveness.

Timber supports are located along the floor plate edges where the material is most effective. This balances the loading among the supports, improving the consistency of vertical member sizes and helping to equalize member stresses. Balancing of these member stresses helps reduce the risk of differential shortening across the vertical load-carrying members of the superstructure.

Use the material in its most naturally effective way.

Based on their specific demands, structural components are matched to the mass timber product that is best suited to the job. This includes GLT, CLT, and LVL.

River Beech Tower uses a signature LVL diagrid on the wider tower façades to make best use of timber's strong compression load-carrying capacity. The LVL diagrid creates a network of many members, emulating the performance of a largely perforated solid wall at the façades of each tower. This unique structural system echoes the performance of perimeter tube towers, but without having to overcome the limitations of timber moment connections. LVL, being axially strong, is an ideal engineered timber diagrid member. The dimensions of the LVL diagrid reflect the magnitude of the loads, typically thin at the upper floors and expanding in thickness to the base of the tower.

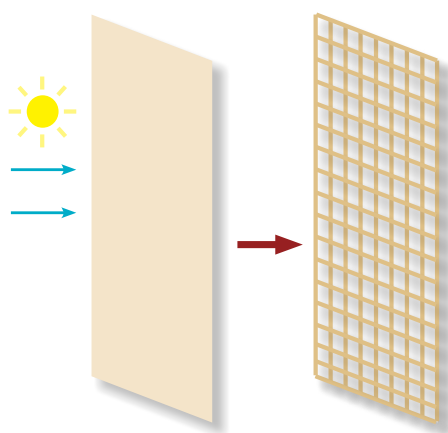
The atrium brace beams are constructed of GLT to achieve the 18.3-meter-span design. While in the façade, the aim is to minimize the size of the beams to limit the impact on views and light, in the atriums, the objective is to express the connection between the buildings.

Use CLT for walls and Nail Laminated Timber (NLT) for slabs.

Mass timber panels are used for both the core walls and the floor slabs. Both NLT, made of pieces of dimensional lumber stacked and tied together with nails, and CLT, consisting of

multiple layers of lumber boards rotated 90 degrees and glued together, have been investigated. The core walls take advantage of the two-way behavior of the CLT, while the floor slabs could potentially make use of CLT or NLT (see Figure 7). However, the design goal of avoiding intermediate columns and the structural strategy of concentrating the load in the façades most strongly suggests the use of NLT slabs, since they are more efficient for one-way behavior. With spans nearing the limits of current technology, these slabs require further research.

DIAGRID TO PROVIDE FENESTRATION AND AVOID LOCALIZED BEAM/COLUMN MOMENT CONNECTIONS



TRIANGULATION ACTIVATES TIMBER AXIAL STIFFNESS MAXIMIZING THE SYSTEM EFFICIENCY

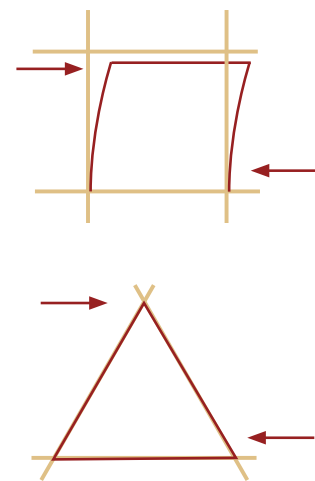


Figure 6, The diagrid maximizes openings for daylight and views while avoiding localized beam-to-column moment connections. Triangulation activates timber's axial stiffness, maximizing the system's efficiency and creating a rigid truss, instead of a more flexible frame. © Thornton Tomasetti

Expect to use more material with timber than if using steel or concrete.

River Beech Tower's structure greatly benefits from good proportioning, but an increase in material volume was anticipated as the design developed. More timber material volume is needed than if using steel or concrete, reflecting the uniqueness of timber. The LVL diagrids allow additional timber material to be well-distributed across the network of diagrid members, rather than requiring localized columns of special size.

Prefabrication can leverage the adjacent Chicago River for large off-site assembly and shipment to the site.

The tower structure is modular, making the most of repetitive connections between system components. The LVL diagrids will be connected using repetitive prefabricated steel or concrete nodes. The CLT floors connect in the factory to a horizontal member of the LVL diagrids. Along the outer façades, vertical CLT shear wall panels join to the diagrid at specific nodes. At the inner edges of the shear walls, GLT bracing connects at the intersection of vertical and horizontal boundary elements, which helps transition the concentrated bracing force gradually into the shear wall system.

Prefabrication plays a major role in the benefit of mass timber construction. Lightweight panels, the use of CNC milling, and integrated fabrication create major potential to reduce construction schedules. River Beech takes advantage of a site on the Chicago River, allowing for the delivery of large modules to the site by barge. Duplex units, envisioned as two-story modules, are sized to weigh within the capacity that a typical crane can pick up off a barge and set into place on the tower. As two-story units are stacked into six-story blocks, they are bound together by the atrium trusses to maintain stiffness (see Figures 8 and 9). The modules are designed as standardized elements in two configurations, one with a void to accommodate the shear wall and core elements, and the other without (see Figure 10).

Analysis

The timber superstructure performs in a similar way to residential towers of similar heights and size constructed using concrete or steel. The tower was structurally analyzed, from which a number of observations can be made:

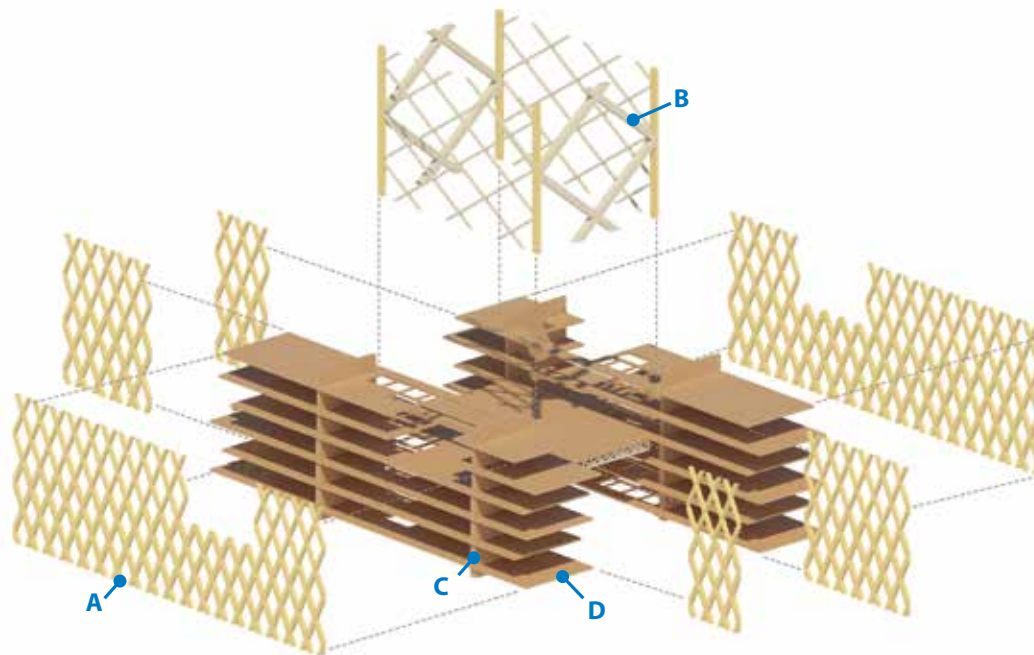


Figure 7. Exploded axonometric section of tower floor plates showing mass-timber products used in their optimal configuration. The result is a composite mass timber structural system. © Thornton Tomasetti
Laminated veneer lumber honeycomb diagrid (A). Glue-laminated timber atrium cross bracing (B). Cross-laminated timber planks for shear core (C). Cross-laminated timber or nail-laminated timber planks for floor slabs (D).

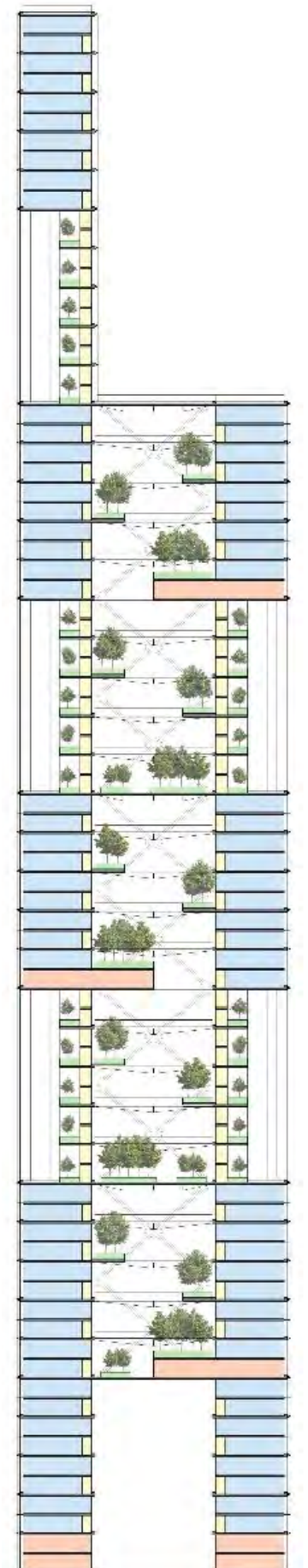


Figure 8. River Beech Tower – section.
© Perkins+Will



Figure 9. The braced area between the two towers required for stiffness is activated as an atrium amenity space. Exposed wood surfaces emphasize mass timber's expressive potential. © Perkins+Will

- The interconnection of the structure using cross-bracing, shear walls, and diagrids successfully activates the vertical members for resisting lateral loads.
- Under gravity load, there is good load balance across the diagrid system.
- The towers coupled together with cross-bracing show good lateral load distribution across the system.
- The diagrid network is highly engaged for load resistance, without dependence on moment connections (see Figure 11).
- Timber material proportions are larger than if using steel or concrete. However, because of the above design strategies, the added timber material is minimized.

This research supports the feasibility of using timber as a tower's primary superstructure material. In addition, it has also successfully identified next-step topics of research for advancing the use of timber in tall building structures incorporate:

- Wind engineering to assess unique responses of a tower with low-mass density and low-dynamic periods.
- Further develop connection details in the diagrid, shear walls, and atrium braces.
- Establish vibration control criteria for CLT floor planks.
- Conduct performance testing for rationalization of seismic loading (Note: this study used Chicago Building Code wind loading for lateral system development).
- Coordinate fire engineering solutions and structural design.
- Research material modifications that may improve member stiffness including genetic improvements and hybrid composites with steel and carbon fiber.

Each module would be glazed with unitized curtain walls to the extent possible. Pieces between modules

would be glazed in the field (see Figure 12). Fireproofing between floor panel and curtain wall follows a conventional two-hour UL-rated solution.

The skin of the atrium façades is a lightweight Ethylene tetrafluoroethylene (ETFE) system (see Figure 13). In all tower areas, the timber is protected within the exterior skin. On balconies, where sealant can be easily accessed for maintenance, the timber is exposed to the elements.

Life Safety and Building Code

Construction of an 80-story timber tower is not currently permissible by major building codes. Chicago Building Code prohibits wood construction within the city's downtown area, referred to as the Central Business District. Looking to the 2012 edition of the International Building Code, heavy timber or Type IV construction is limited to five stories. The team considered three scenarios that may allow the material to achieve the height and area needed to make a high-rise tower feasible.

The first possibility is to meet the requirements for IBC Type 1A construction. To do this, the structure must be protected and non-combustible. Timber meets protected criteria by virtue of charring, and standard charring rates and fire resistance is now noted in IBC. However, establishing timber as "non-combustible" is a greater challenge. A wood sample would need to be genetically modified, treated, or engineered as a composite material to pass the ASTM E136 test for combustibility.

A second option is to encapsulate the timber in fire-resistant material to achieve a fire rating. This is the method used for Brock Commons dormitory at University of British Columbia, one of the world's tallest timber buildings. According to the project's architect, "Since the mass wood structure is significantly higher than the six stories currently permitted by the code for wood buildings, the project required a Site Specific Regulation (SSR) from the British

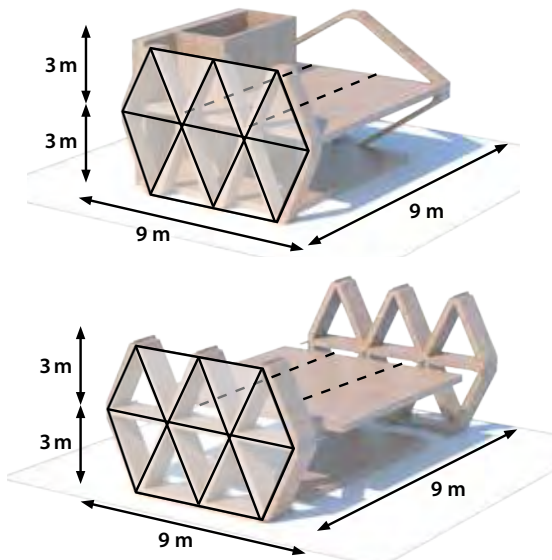


Figure 10. The tower is designed to be constructed out of two prefabricated module types: one with shear cores (top) and one without (bottom). © Thornton Tomasetti

Columbia Building Safety & Standards Branch. The SSR process included peer reviews involving panels of leading structural engineers, fire safety experts, scientists, authorities, and firefighters” (Acton Ostry Architects 2016).

The third, most likely scenario for wide adoption is the evolution of building codes to recognize multiple categories of height and area within the heavy timber category. The International Code Council has created the Ad Hoc Committee on Tall Wood Buildings to “explore the building science of tall wood buildings with the scope being to investigate the feasibility of and take action on developing code changes for tall wood buildings” (ICC 2017). The group is looking to introduce expanded sections of the code for IBC 2018 and 2021.

Environmental Considerations

Environmental, social, and economic sustainability is fundamental to every stage of this project – both in terms of the designs

produced and in terms of this integrated model of research-led design. It is critical to look deeper into mass timber than its carbon entraining properties.

It is incumbent on our industry to understand the life cycle process of a material from farming, harvesting, manufacturing, fabrication, construction, and ultimately reuse at the end of its usable life as a building material. A further objective of this study is to work with industry partners to design habitats for growing renewable timber, working with members of the US Forest Service and other land-management authorities to understand the capacity of the land over time.

Furthermore, the increased value of timber that is expected to result from its use as an engineered construction product is likely to confer increased value on well-managed forestry. This is less critical in Europe and North America, where there is a long tradition of responsible forest management – but in many parts of the developing world, this may be a key driver towards better long-term forestry practice. What is critical in Europe and

“The LVL diagrids allow additional timber material to be well-distributed across the network of diagrid members, rather than requiring localized columns of special size.”

North America, however, is that the development of new, large-scale and large-volume markets for timber will have a profound positive effect on areas where forest cover is expanding due to the relative decline in the use of trees for paper pulp. These stands of managed forest can now go toward higher value-chain use in urban construction. A

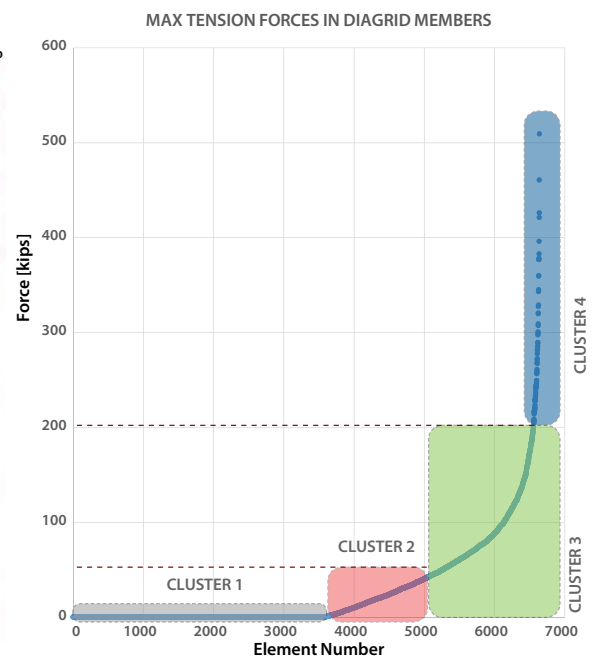
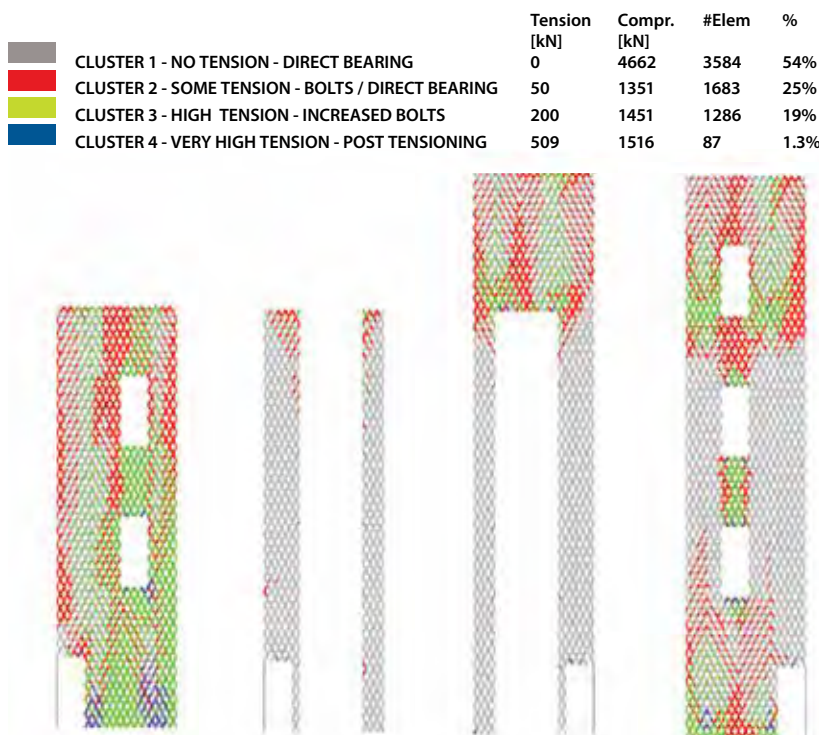


Figure 11. Measurements of structural stresses of several connection systems. © Thornton Tomasetti

“The two individual towers are structurally connected across the atrium using glued laminated timber (GLT) cross-bracing. This connection couples the structure together to act as one, maximizing the superstructure’s performance and minimizing member stresses.”

relevant trend in relation to economic and environmental sustainability in densely urbanized areas is the demolition of buildings long before the end of their design lives. This suggests that renewable, perhaps cyclic, materials such as timber are particularly well suited to use in the modern built environment.

Conclusion

This study only begins to address the substantial questions surrounding the design and construction of very tall mass timber

buildings. The team continues to develop the next steps of the study. Through a partnership with Jensen Hughes, a more thorough understanding of fire analysis is being developed, culminating in full-size mockups that will be fire-tested in laboratory conditions. Full-scale mockups are currently under design through a partnership with Autodesk’s BUILD Space and Pollmeier, a European LVL manufacturer. The research has also made headway with the City of Chicago Permit Office, which has approved the construction of a single tower module, perhaps becoming the first permanent wood structure in the city’s downtown area

in over a century. By continuing to provide provocative, thoughtful solutions, our industry will advance the potential that these materials have to offer. ■

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Figure 12. Duplex module connection configuration. © Perkins+Will



Figure 13. Sky gardens would be enclosed in lightweight ETFE. © Perkins+Will