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CASE STUDY ON A LARGE-SCALE TIMBER ACADEMIC BUILDING DESIGNED TO ADDRESS CURRENT INDUSTRY CHALLENGES

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ABSTRACT: The need for more sustainable construction has led to the desire to increase the use of wood materials in our buildings. However, challenges in terms of larger column grids, future design flexibility, and fire resistance have occurred in institutional, commercial, and industrial building types that have hindered mass timber's adoption. This study reviews these challenges and provides insight into the design of a mass timber academic building as a viable design solution. The building creates open-concept and future flexible spaces by taking advantage of several novel structural solutions, while achieving fire resistance requirements. The structural solutions include the long span hollowcore mass timber floor panels for large amenity areas, two flat plate "service towers", and a combination of timber braced frames and CLT shear walls for the lateral system, in order to meet the challenges faced.

KEYWORDS: Academic building, hollowcore mass timber, flat plate, design challenges, design precedents

1 INTRODUCTION

1.1 BACKGROUND

The Intergovernmental Panel on Climate Change has emphasized that global warming needs to be limited in order to avoid the worst effects of climate change and prevent long-lasting changes to our planet [1]. One approach to tackle this global issue is the way in which we build our structures. As per the United Nations Global Status Report 2017, the buildings and construction industry accounted for 39% of global energy-related CO_2 emissions, with 11% embodied in the construction processes and materials [2]. This, combined with the wider availability of mass timber products, has led to a desire to use more sustainable materials, such as wood, in our buildings.

Still, challenges remain in some building types that are hindering mass timber's adoption, in particular, in high-end residential as well as institutional, commercial, and industrial (ICI) buildings[3,4]. Key features of these building types that are challenging and limiting the use of mass timber include:

1. Larger column grids – these buildings often require large, open floor plan spaces;
2. Future design flexibility – the use of these spaces often changes over the building's lifetime;
3. Fire resistance – codes often require non-combustible materials and/or increased fire resistance ratings in these spaces.

1.2 LITERATURE REVIEW

Currently, a limited number of mass timber projects have been able to solve the design challenges faced in ICI and high-end residential structures. These solutions have often involved the use of novel structural systems pioneered or innovated to overcome a specific challenge on a project. Despite the additional analysis and engineering required at the time, these novel systems now serve as precedents to those looking to build ICI and high-end residential structures using mass timber as opposed to conventional materials such as concrete or steel. To illustrate the potential and capabilities of mass timber in ICI and high-end residential structures, a handful of these projects and their innovative solutions are presented.

The four-storey Edward J. Ray Hall at Oregon State University uses a post-and-beam system to meet the owners' requirements for adaptability and the large open classroom spaces [5]. To optimize the CLT thickness, while maintaining the required 9m clear span, the main grid has columns spaced at 3.05m, with glulam beams spanning 9.75m over the classrooms. A 3.05m wide grid with shallower beams is run down the middle of the building to act as a service corridor. This allows services to access any of the spaces between the deeper 9.75m-long beams without having to drill holes through beams, or jog beneath them. The underside of the wood slab is left fully exposed while a 100mm concrete topping is used for lateral design and to limit floor vibration [5]. The post-

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and-beam system used in the Oregon State project is depicted in Figure 1.

The four-storey John W. Olver Design Building at the University of Massachusetts (UMass) also consists of a post-and-beam glulam system; however, the slab spans are longer (i.e., up to 8m distance over the open spaces) [6]. The latter was achieved by using a timber-concrete composite (TCC) floor supported by shallower beams spanning the shorter distance between columns.

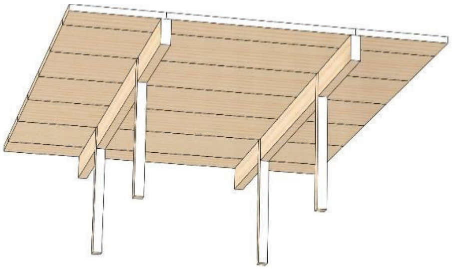

Figure 1. *Post-and-beam system* [7]

Brock Commons, which is located at the University of British Columbia, uses a flat plate system to frame an 18-storey (53m) hybrid mass timber and concrete student residence (Figure 2). The structure includes CLT floor panels that are point-supported on glulam columns; eliminating the use of beams which is highly efficient in framing tall buildings with a smaller, regular grid. The column grid of 4m x 2.85m was chosen to match the maximum available CLT panel size as each panel had to be supported in the corners by columns [8]. Eliminating the dropped beams maximized the future adaptability; however, the column grids are limited by the largest available width of CLT panels, as well as the two-way spanning capabilities of the CLT slabs.

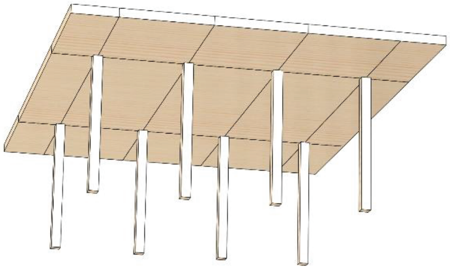

Figure 2. *Flat plate system* [7]

The Limberlost project at George Brown College, also known as The Arbour, uses an advanced structural system aiming to eliminate the use of deep glulam beams. Large flat beams consisting of 2.4m wide TCC slabs are used to support thinner CLT slabs spanning in the opposite direction in a similar fashion to systems employed in concrete parking garages. These wide beams require large "wall-column" supports, of similar width, to prevent the slabs from toppling due to unbalanced loads [9]. This system is shown in Figure 3. Here the wide flat beams consist of a 7-ply (245mm) CLT slab with 150mm of concrete compositely connected to span 9.2m over the open areas to provide flexibility for space planning [9].

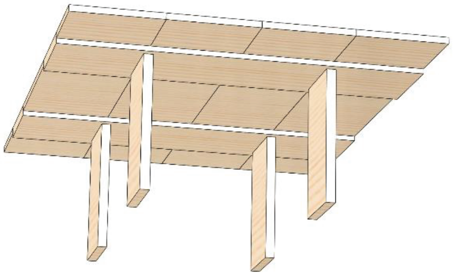

Figure 3. *Wide flat beam system* [7]

With regards to lateral systems, a number of approaches are observed in these projects. Brock Commons and the Oregon State project make use of concrete shear walls for the lateral load resisting system [5,10]. This was attributed to the lack of perimeter beams in the gravity systems, the ongoing development of code guidance on the use of mass timber lateral systems, and the relative familiarity of concrete shear wall systems. The Limberlost project uses steel braced frames, and again, this choice was attributed to the developing code provisions and lack of precedents using mass timber lateral systems as well as the designers' familiarity with steel braced frames. The UMass project was one of the first to make use of a mass timber lateral system. This system incorporates a combination of CLT shear walls and glulam braces [11]. The combination works well together due to their similar relative stiffnesses, and the ability to use shear walls in the vertical circulation core areas while braces are used around the perimeter to allow for openings [11]. In terms of tall structures, the 51m Mjøstårnet building in Norway showcases the use of glulam braced frame trusses along the exterior of the structure to resist wind-dominant lateral loads, thereby eliminating the need for shear walls [12]. With a growing list of building precedents using mass timber lateral systems, as well as ever-growing knowledge and code guidance around these systems, more projects are able to employ mass timber lateral systems including the Origine building in Quebec, Canada, the Candlewood Suites in Alabama, USA, and the Fast and Epp Home Office building in Vancouver, Canada [13–15].

1.3 OBJECTIVES

This case study focuses on a review of the main challenges faced by using mass timber in ICI and high-end residential building types, as well as provides an overview of a large-scale mass timber academic building design in the context of an international design contest. The building design was completed as part of Rothoblaas Build the (Im)possible design challenge, where it was selected as the winner in the academic category [16]. The design approach, along with design solutions to the identified three main challenges, is discussed with the intention of providing architects, engineers, and decision-makers with novel solutions to the design of mass timber ICI and high-end residential buildings, adding to the growing precedent list of these types of buildings.

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2 CHALLENGES TO MASS TIMBER IN ICI BUILDINGS

2.1 LARGER COLUMN GRIDS

ICI and high-end residential building types often require large, open floor plan spaces that can challenge the efficient use of mass timber building products. For example, commercial office space frequently demands at least a 9m (~30ft) column grid [17], which is challenging to efficiently achieve using conventional mass timber slab products such as CLT or nail laminated timber (NLT) on glulam beams (e.g., Figure 4). This is primarily due to strict serviceability limits and poor vibration performance limiting the achievable slab spans [3]. To overcome these shortcomings, a common solution consists of using a concrete topping on top of the wood, thereby contributing to a greater slab depth as well as increased total weight of the building. While a beam and purlin system can be implemented to limit the spans of slab products, this leads to deep purlins which can negatively impact the clear floor-to-ceiling height and the ease of running services, as well as causing more "beam shadowing" [7]. For these reasons, a flat slab post and beam system is preferable, if an efficient structural system allows for the long slab spans. Furthermore, in the principal girder span direction, large column grids can also lead to deeper beams that can affect the overall floor-to-floor height and impact the running of building services.

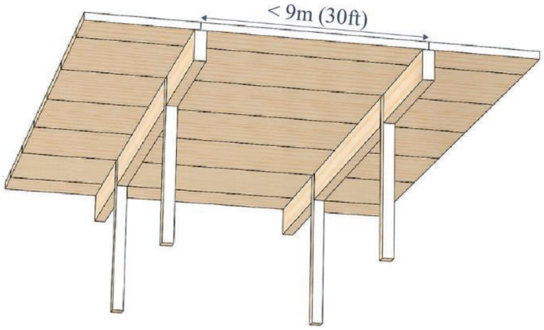


Figure 4. *Flat slab post and beam system [6]*

2.2 FUTURE DESIGN FLEXIBILITY

ICI buildings generally have a longer design life which means that the building, or individual spaces, will likely change occupancy over the lifespan of the building. The need for future-flexible spaces is thus tremendously important in these types of buildings. When combined with larger column grids to create more open-flexible spaces, this often requires limitations on the number of large load-bearing walls and deep beams. An open floor plate thus allows for building services and partition walls to be placed almost anywhere within the space (Figure 5). Therefore, selecting a structural system that allows future flexibility in design plays a key role in the design of ICI buildings.

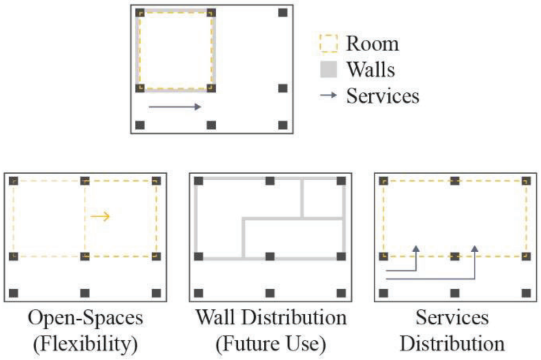


Figure 5. *Design flexibility in ICI buildings*

2.3 FIRE RESISTANCE

Structural members that are exposed to view are not uncommon in ICI buildings, as leaving structural elements exposed often optimizes costs by limiting the number of finishes. Mass timber also has the added aesthetic and biophilic benefits associated with natural materials [18], which often means mass timber building owners want the structure left exposed. However, wood is a combustible material and if desired to be left exposed requires compliance with prescriptive design code provisions, engineering analysis using known charring rates, or more time-consuming "alternative solution" pathways to justify the structure's fire resistance. These extra steps can hinder mass timber's use as prescriptive design codes typically limit how much wood-based materials can be exposed, often varying from jurisdiction to jurisdiction. These exposure restrictions limit the aesthetic and biophilic benefits of using wood-based materials. It is possible to expose nearly all of the mass timber in a structure using the reduced cross-section method (i.e., charring) in the Canadian *Engineering design in wood* standard (CSA 086) [19], as shown in Figure 6. However, this approach can be much more complex and time consuming than simply achieving the required fire resistance through encapsulation of the timber structure in non-combustible materials.

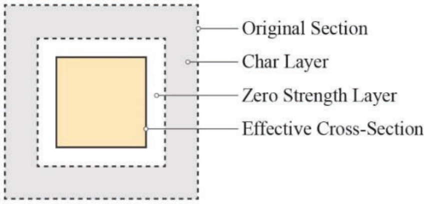


Figure 6. *Effective cross-section for fire design (CSA 086)*

3 CASE STUDY OF ALL-WOOD MASS TIMBER ACADEMIC BUILDING

3.1 OVERVIEW OF DESIGN APPROACH

The proposed design solution is a 7-storey state-of-the-art Mass Timber Engineering Building (MTEB), as shown in Figure 7, that is proposed for the University of Waterloo main campus in Waterloo, Ontario, Canada.

Figure 7. *Exterior render of METB*

The MTEB aims to provide academic and research spaces to nurture research in timber and sustainable construction at the University of Waterloo, promote the adoption of mass timber in ICI buildings and confront the changing climate with innovative new solutions. The building creates 28 000m^2 of multifunctional and future-flexible spaces by taking advantage of several novel structural solutions (Figure 8Figure 7).

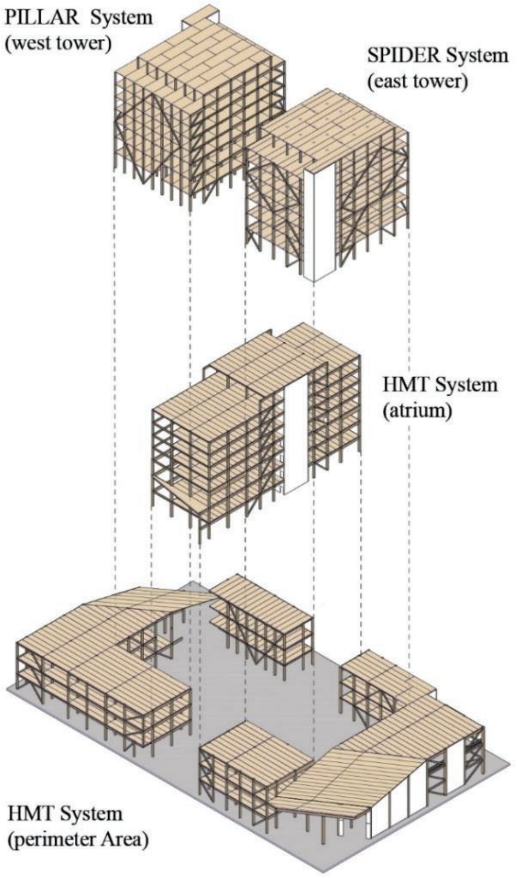


Figure 8. The *MTEB structural system*

Hollowcore mass timber (HMT) panels [20] are used at the perimeter areas and to connect the two towers through a multilevel atrium. Large open space areas, with clear spans ranging from 7-15m are created with the HMT panels. The perimeter structure accommodates lecture halls, workshops, testing laboratories, classrooms, computer laboratories, and a library. The atrium provides a connection between the two towers at each level of the structure and creates gathering areas, event spaces, and access points at the ground level.

Rothoblaas' SPIDER and PILLAR connectors [21] are used to create a flat plate structure in the two towers adjacent to the atrium. The flat plate system, traditionally only achievable with reinforced concrete, takes advantage of the two-way spanning capabilities of CLT to create spaces with tremendous flexibility, where building services do not conflict with beams or load-bearing walls, and partition walls can be placed as desired. For this reason, the towers accommodate spaces that can be distributed in a smaller and consistently repeating grid (5m x 5m and 3.5m x 5m) for small laboratories, meeting rooms, office spaces, etc. The system also allows the two flat plate regions to act as "service towers" bringing services from the centre of the building into the perimeter zone without conflict.

The lateral system uses a combination of braced timber frames, supplemented by CLT shear walls that are used for the elevator and stair cores. The Waterloo lateral design loads are wind-governed, allowing for braced timber frames to be selected for their material efficiency compared to a shear wall system, and to free up the perimeter of the structure of large load-bearing walls, allowing for windows and other openings in the current and future layouts of the space.

The design of the structural system aims to serve the growing demand for space with a flexible design to serve multiple functions, with adaptability considerations for future use. The building form is the result of an optimization of the HMT, flat plate, and bracing systems to obtain an efficient structural design.

3.2 GRAVITY SYSTEM

The structural gravity framing was designed as per the Ontario Building Code (OBC) 2012 [22]. The loading consists of the structure's self weight, superimposed dead loads, live loads, as well as snow and rain loads (Table 1).

Table 1. *Loading summary*

Dead Loads		
HMT Panel (420-740mm)	1.10-1.50	kPa
CLT Panel	0.8	kPa
Live Loads		
Lecture Hall/Mechanical	3.6	kPa
Library*	7.2	kPa
Corridor/Gathering Areas	4.8	kPa
Flexible Space	4.8	kPa
Labs/Other Spaces	2.4	kPa
Snow + Rain Load		
Base	2.0	kPa

*50% considered as long-term loading

Table 2 provides information regarding the material properties for the main structural members from the CSA

086 to provide designers a reference against other international wood design codes.

Table 2. *Material information* [19]

Beams and Slabs			
Material	Grade	F_b (MPa)	E (MPa)
Glulam	SPF 20f-E	25.6	10,300
CLT	E1	28.2	11,700
Columns			
Material	Grade	Fc (MPa)	E (MPa)
Glulam	SPF 12c	25.2	9,700

3.2.1 Hollowcore Mass Timber (HMT) System

The requirements for long-span spaces at the perimeter of the building and atrium area are met using an HMT system. This is a one-way floor system with a fully assembled depth varying from 420mm to 740mm for the 7m to 15m spans achieved. The HMT panel utilizes 3-ply CLT panels for the top and bottom flanges, with glulam beams acting as web members as shown in Figure 9.

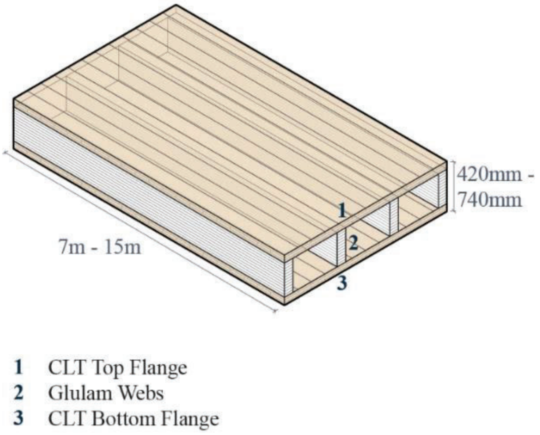
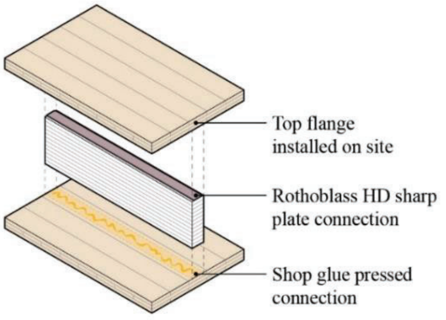
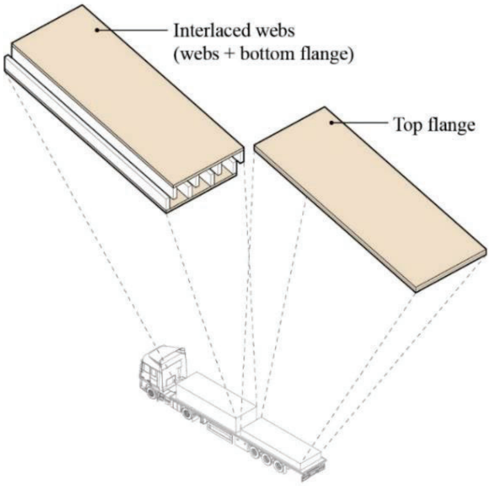


Figure 9. *Hollowcore mass timber panel*

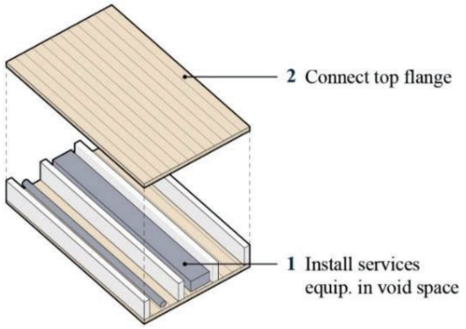
The CLT and glulam can be fastened together using mechanical or adhesive shear connectors in order to provide a partially- or fully-composite section. For this project, the HMT panels utilize shop-glued connections for the bottom flanges and Rothoblaas HD sharp plates for the top flanges (Figure 10a). This allows for the ribbed sections to be interlaced during long-distance shipping, thereby decreasing the amount of "void air" shipped as shown in Figure 10b. The top flanges are attached using sharp plates on site where some services and acoustic treatments can be installed in the void space of the panels (Figure 10c). For shorter shipping distances, the top flanges can also be shop-glued to limit the work required on site. The shear connections play an important role in the degree of composite action achieved between the flanges and the webs. As such, the glued connection and HD sharp plates were deemed optimal as both were able to provide near-fully composite shear transfer.



(a) Assembly



(b) Transport



(c) Installation

Figure 10. *HMT construction sequence*

The HTM panels are supported by a post-and-beam glulam structure by face-mounting the glulam webs to main beams or columns using flush hangers. Beams typically span seven meters in order to have a depth that is similar to the HMT panel depth, providing relatively continuous headroom clearance. Building services are integrated within a raised access floor system to maximize the overhead visibility of exposed mass timber slabs providing biophilic benefits. A cement board layer is installed between the mass timber slabs and raised floor to meet concealed space requirements and aid with acoustics. The post-and-beam structure using the HMT panels is shown in Figure 11.

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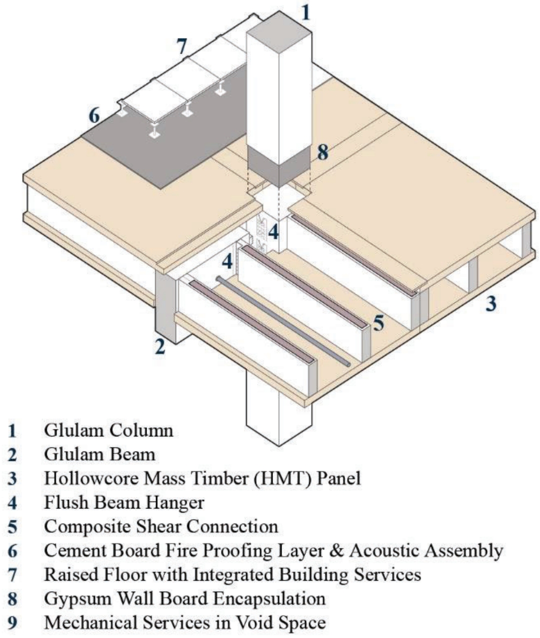


Figure 11. *HMT system*

3.2.2 Mass Timber Flat Plate Floor System

The seven-storey central towers are designed to engage the two-way spanning capabilities of CLT panels by point-supporting them on glulam columns using the Rothoblaas SPIDER and PILLAR connectors [21]. The flat-plate system eliminates beams which reduces the structural depth, thereby creating a clear ceiling space that allows for easy distribution of building services in addition to the possibility of installing large exterior windows. However, flat plate systems create areas of high shear and bending stresses, as well as compression perpendicular-to-grain, at the support locations. This can lead to high rolling shear stresses in the CLT panel [23]; similar to the punching shear behaviour seen in flat plate concrete structures. The east and west towers use the SPIDER and PILLAR connectors, respectively, to provide adequate reinforcement for punching shear stresses and to bypass compression perpendicular-to-grain caused by bearing on the CLT slabs.

Rothoblaas SPIDER System

For the east tower, a 5m x 5m column grid is created using a 220mm 7-ply CLT, with dimensions of 3m x 15m (width x length), for panels centred over the columns, and 2m x 15m for intermediate panels connected to the column bands using a metal plate and epoxy moment connection as seen in Figure 12.

The SPIDER connector consists of three main components: a cylinder and bottom plate fixed to the column below, the top plate attached to the column above, and the coupling disk and cone to engage the six arms connected to the panel to the steel core (Figure 13) [24]. For aesthetic and fire resistance purposes, the bottom plate is concealed by grooving the column below and the segment of the connector above the CLT panel can be covered with the finished floor.

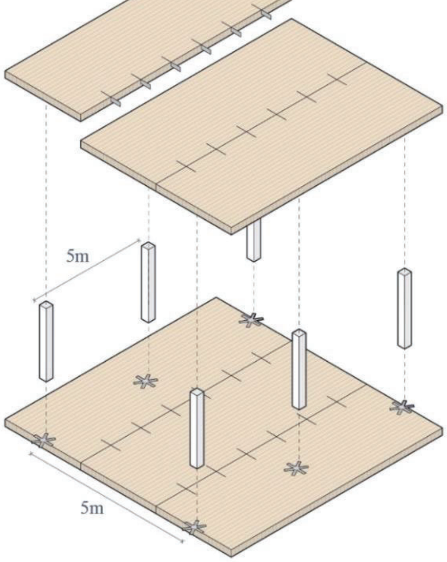


Figure 12. *5m x 5m flat plate grid with spider connector*

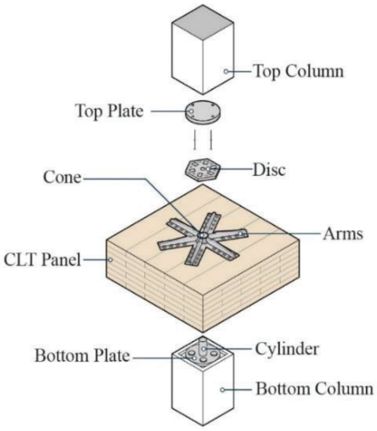


Figure 13. *SPIDER connector components*

To connect the glulam columns to the CLT, the connector (1) transfers the axial load from the column above to the column below through the steel core, (2) resists rolling shear with 45-degree fully-threaded screw reinforcement in its arms, and (3) reduces the concentrated stress at the column below by transferring the slab loads directly to the steel core (Figure 14). Further information can be found in the extensive research performed by Maurer and Maderebner [23] on the mechanical methods and numerical simulations of the SPIDER system to provide engineers with an insightful understanding of the structural response of the connector.

Due to the imposed limit on the width of CLT panels to around 3.5m during transportation, for column grids greater than 3.5m, a moment connection is necessary between CLT panels. In the design, these connections are placed 1.5m from the centre line of the column (Figure 10) to avoid the zones of maximum bending and shear stresses over the column, and the large bending stresses found at midspan. The manufacturer recommended that the moment connection consist of steel plates that are epoxy-glued into vertical grooves in the top of the CLT panel [24]. The grooves are cut deep enough to ensure positive and negative bending strength while leaving enough wood material beneath to protect the connection from the fire below. Moment connections between panels can also be created using other systems such as TS3's high performance glued butt-joint [25] or metal tension straps.

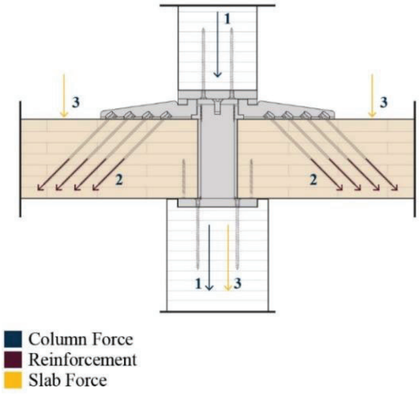


Figure 14. *SPIDER connector mechanics*

Rothoblaas PILLAR System

For the west tower, a 3.5m x 5m column grid is created using a 200mm 7-ply CLT panel with dimensions of 3.5m x 10m (width x length) that are edge- and corner-supported by the PILLAR system (Figure 15).

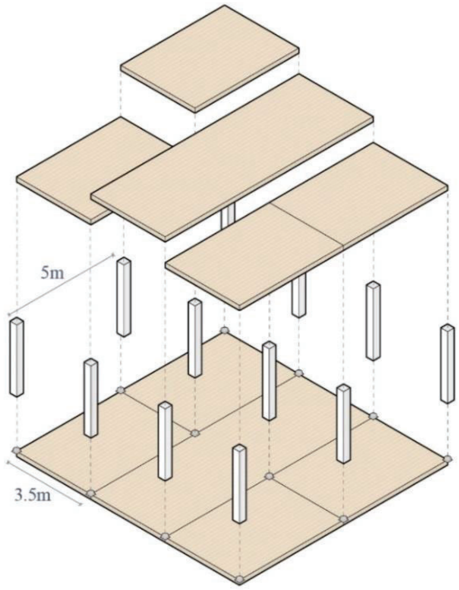


Figure 15. *3.5m x 5m flat plate grid with PILLAR connector*

This connector is a simpler alternative for the smaller column spacing of the west tower, where stresses at the columns are lower. The PILLAR connector also has three main components; the cylinder, bottom plate, and top plate (Figure 16) [24].

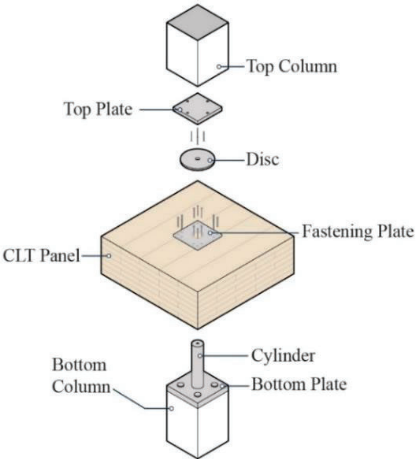


Figure 16. *PILLAR connector components*

The mechanics of the PILLAR connector are similar to that of the SPIDER connector; however, the absence of the arms diminishes the rolling shear and punching shear resistance. The rolling shear and bending resistance, as well as the bearing resistance, are provided by the CLT panel itself, and therefore this limits the maximum column spacing due to the absence of additional reinforcement seen in the SPIDER connector (Figure 17).

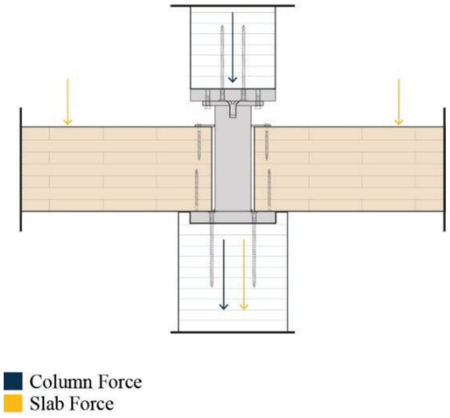


Figure 17. *PILLAR connector mechanics*

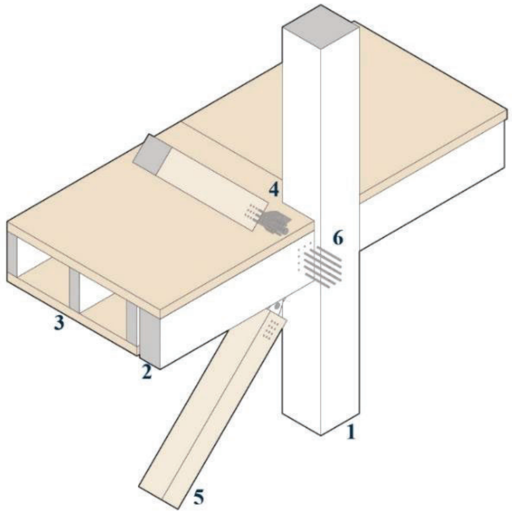
3.3 LATERAL SYSTEM

Mass timber buildings are fortunate in having a lower overall weight, and thus reduced seismic demands, but are more susceptible to vibrations induced by wind or occupant loading. Currently, design provisions in the CSA O86 [19] focus solely on the use of CLT as shear walls in platform construction for mass timber lateral load resisting systems (LLRS). Despite not being included in CSA O86 [19], code provisions for braced timber frames (BTFs) are provided for use in low- to mid-rise buildings [26]. The lack of guidance for the design and detailing of BTFs and their connection on the overall system ductility and stiffness has contributed to the limited use on projects. However, ongoing research has contributed to design guides being developed and future iteration of the wood design code to incorporate BTF design [27]. Many international design codes are similarly limiting with explicit guidance lacking, or novel guidance having recently been added as a result of on-going research efforts [28]. With limited explicit guidance, or designers lacking the most current knowledge base, many opt to fall back to more familiar steel bracing and concrete shear wall LLRS in lieu of pursuing more complex, and possibly ‘alternative solution’-based paths with mass timber LLRS. With the goal of demonstrating the viability of mass timber LLRS, the design of the MTEB makes use of CLT shear walls and BTFs. However, these systems can easily be substituted with concrete shear walls (e.g., Brock Commons) or steel braced frames (e.g., Limberlost).

3.3.1 Braced Timber Frames

Despite including provisions on the design of panel-based LLRS (e.g., CLT and light frame shear walls), the current CSA O86 [19] does not provide explicit guidance for BTFs. However, it is a generally accepted practice that connections can be designed for highly ductile yielding failure modes in order to achieve moderately ductile performance for seismic design [29]. This has allowed BTFs to be successfully deployed in several past projects, such as the Mjorstarnet [12].

In Waterloo, a city located in a low seismic hazard zone, the proposed LLRS for the MTEB consists of braced frames fastened to beams and columns by two internal knife plates and 7.5mm SBD self-drilling dowels (Figure 18). The BTFs are located around the perimeter of the building in order to counteract wind-induced vibration and are left exposed to contribute to the architectural expression of the entire building.



1 Glulam Column
2 Glulam Beam
3 Hollowcore Mass Timber (HMT) Panel
4 Lateral Brace Knife Plate Connection
5 Lateral Brace
6 Steel Dowel Fasteners

Figure 18. *Lateral brace system*

3.3.2 Shear Walls

Similar to BTFs, CLT shear walls heavily rely on the yielding of connections to dissipate energy [29]. The high relative stiffness of CLT can prove to be an efficient LLRS in low- to mid-rise buildings if careful attention is given to achieve the necessary detailing required by code for “rocking” to occur [29]. This mechanism is heavily reliant on a combination of elastic and plastic connectors acting upon wall segments of appropriate aspect ratio, a challenging feat in high-rise timber construction. Given that the MTEB already employs a CLT-based gravity system for the elevator and stair cores, these walls can be effectively utilized as shear walls to counteract the governing wind loads, all while using the same CLT suppliers and trades.

The CSA O86 [19], like many other international standards, includes discussion on the design and detailing of platform-type CLT shear walls. However, design provisions for balloon-framed CLT shear walls (e.g., John W. Olver Building, UMass) are still under development, and often require alternative approval and reference material outside the design codes [29]. The Canadian CLT Handbook is a prominent reference that provides guidance on the design of CLT balloon-framed LLRS [30].

3.4 FIRE DESIGN

An acceptable level of fire performance of mass timber structures can be achieved through the encapsulation of some or all wood elements. While straight-forward in achieving the desired fire performance rating, full encapsulation of the structural elements in fire resistant finishes, such as gypsum drywall, severely discounts the biophilic benefits of using timber. It was desired to expose a large portion of the mass timber structure in the MTEB, including nearly 100% of ceilings to maximize these benefits for the greater university community. This was done through calculations of the charring and residual cross-section of mass timber elements, including around connections. While the acceptable code solutions in many jurisdictions lag behind the level of exposure and design solutions prosed for the MTEB, the goal was to design to the approved requirements for the 2024 International Building Code (IBC) in the United States as an easier justification for the alternative solution being proposed. The 2024 IBC has been approved to allow mass timber buildings up to 12 storeys to fully exposed ceilings and exposed up to 40% of walls and columns based on testing from the Research Institute of Sweden [24].

Overall, the main fire performance solutions of the MTEB include; 1. Beams and columns designed to have residual capacity after 2 hours of charring to support the required loading, 2. The bottom flange of the HMT panels insulate the webs and top flange which have sufficient capacity as a ribbed panel given that the HMT panels are governed by vibration, rather than strength as in a fire scenario, and 3. The concealed space under the raised access floor contains a non-combustible cement board layer to meet code requirements for concealed spaces.

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4 ADDITIONAL CONSIDERATIONS

Other considerations regarding the design of the MTEB include the sustainability, building envelope opportunities, and benefits of mass timber structures.

4.1 NON-STRUCTURAL BENEFITS

4.1.1 Sustainability

The MTEB is a sustainable timber building that depicts the possibilities of mass timber innovative systems to serve multipurpose academic buildings. Wood as a building material, when harvested from sustainably managed forests, has a smaller carbon footprint than traditional construction materials. Wood also has the added benefit of absorbing and storing carbon over its life, storing approximately one tonne of carbon per 1m^3 of wood building product [31]. As a result, mass timber structures can play a crucial role in reducing a building's material and construction environmental impact and in achieving a design team's green building goals. From the carbon analysis of the MTEB it was found that when compared to an equivalent steel or concrete building, the MTEB would contribute an estimated four times less carbon emissions in terms of building materials for the primary structure (Fig. 19). Foundations were not designed for the MTEB case study and therefore were excluded from the analysis. However, it should be noted that mass timber structures are often much lighter, thus requiring smaller foundations than their concrete or steel alternatives thereby resulting in less carbon emissions. Overall, it is estimated the MTEB would also store 9800 tonnes of carbon in the wood structural materials [32]. This analysis further validates the fundamental need for the use of mass timber in net-zero carbon construction of ICI buildings.

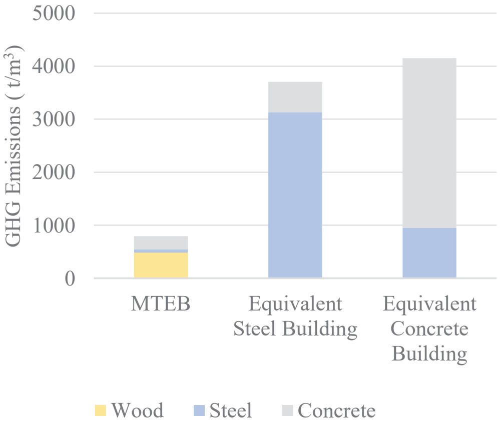

Fig. 19: *Carbon impact of the MTEB and alternative designs*

4.1.2 Occupant Impact

Wood buildings have also shown learning and happiness benefits in their occupants, a phenomenon known as biophilia. Studies have found that students benefit from being surrounded by natural materials. Demattè et al. [18] stated that wooden environments make users feel comfortable, generate a greater level of positive feelings, and even encourage sensory stimuli. Determan et al. [33] found that biophilic learning spaces result in students with higher academic performance and reduced stress levels. The biophilic appeal of wood spaces can also lead to increased design longevity, reducing long-term costs of upgrades, renovations, and re-designs.

4.1.3 Construction Efficiency

Projects that use mass panel systems are completed faster and more efficiently. Brock Commons Tallwood House, an 18-story student residence at the University of British Columbia, took just 2.5 months for timber erection [10] – four months faster than a comparable reinforced concrete building. Prefabrication also leads to fewer site errors, remedial work, and material waste. At one-fifth the density of concrete, wood projects have smaller foundation requirements, thereby decreasing project costs. All this translates to less time on site, fewer disruptions on campus, and long-term beneficial space for the campus community.

5 CONCLUSIONS

This paper outlines challenges facing the adoption of mass timber in institutional, commercial, industrial, and high-end residential buildings including; larger column grids, future design flexibility, and fire resistance. Design strategies previously used to overcome them are presented, along with a detailed description of those implemented in this case study, in order to give designers an additional precedent exhibiting the capabilities of mass timber for types of structures typically reserved for concrete and steel. The project has shown:

- The importance of selecting efficient structural systems based on the needs of the intended building use early in the project;
- Mass timber composite panels, specifically hollowcore mass timber panels, can be an efficient system for achieving the long spans in a simple post-and-beam system;
- Flat plate systems are viable with mass timber products, including column grids larger than the typical maximum panel width of 3.5m;
- With a focus on future design flexibility, mass timber can be designed to accommodate future use changes of these building types;
- In wind-governed lateral system design, the use of CLT shear walls as vertical circulation cores, in combination with glulam braced frames in perimeter walls provides an efficient structural and architectural solution.

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