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DESIGN AND CONSTRUCTION OF A 53-METER-TALL TIMBER BUILDING AT THE UNIVERSITY OF BRITISH COLUMBIA

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ABSTRACT: The paper discusses the challenges during the design of a tall timber building: The University of British Columbia Brock Commons Phase I project, known as UBC Tall Wood Building (TWB). Once completed, TWB will be the tallest mass-timber building in the world standing at 18 stories with a height of 53 m. The discussion includes the technical, financial, supply chain and regulatory challenges, as well as the social, economic and environmental benefits that result from the building. The TWB will house 404 student beds laid out in single and quad occupancy rooms. The structural system is viewed as being very simple by the project stakeholders, simplicity and ease of erection being one of the key drivers for this project. The structural system is designed as a hybrid configuration: the foundations, ground floor and first level, as well as the building cores, are cast-in-place concrete. Levels 2 to 18 are mass-timber columns (standard Glulam with some parallel strand lumber columns on the lower levels for increased compression strength) and floors made of cross-laminated timber panels and a non-structural concrete topping.

KEYWORDS: Tall Wood Construction, Hybrid Structure, Site Specific Regulations, Building Monitoring

1 BACKGROUND

In the early 20th century, the construction of tall wood buildings based on post and beam systems with un-reinforced brick as exterior walls was common in North America. Some of them were nine storeys tall with ceiling heights of up to 6.9 meters [1]. Later, changes to the National Building Code of Canada (NBCC) [2]. limited the height of wood buildings first to three and then to four stories. After a comprehensive consultation process, the code was changed to permit six-storey wood frame residential buildings [3].

The emergence of new engineered wood products and advanced structural, mostly hybrid, systems have prompted a resurgence in the use of timber in buildings more than 6 storeys tall. One of the main external drivers for giving timber products more consideration in non-residential construction is Bill 9-2009 ("Wood First Act"), passed by the Province of British Columbia in 2009, which aims to promote a culture of living and building with wood by requiring its use as a principal material in any provincially funded building [4].

Over the last decade, buildings using mass-timber products such as cross-laminated timber (CLT) have been constructed around world. The "Stadthaus", a 9-storey residential building completed in 2009 in London, was one of first tall wood buildings in which CLT was used as main structural material [5]. The LifeCycle Tower ONE, an 8 storey building with concrete foundations and a concrete central core with glulam columns and hybrid slabs which span up to 9 meters, is an example for a timber based hybrid building [6]. "Forte", the first tall mass-timber residential building in Australia, is 32-meter-tall and has 10 stories with only the first floor and foundation made of concrete [7]. "TREET", a 14-storey building in Bergen, Norway, is currently the tallest contemporary timber building in world with a height of 45 meters above concrete foundation level. It consists of glulam trusses with prefabricated building modules whereas CLT is used for elevator shaft, internal walls and staircases. The singularity of this building is introduction of a "power story" after every four levels that carries a prefabricated concrete slab on top and acts as a base for the three levels above [8].

Currently, the tallest modern timber building in Canada is the 29m-tall Wood Innovation and Design Center located in Prince-George, British Columbia, which consists of six stories including a mezzanine. The structural concept was dry construction which eliminated the use of concrete above the foundation level except the mechanical pent-house [9]. The building is home to a new Master's program on Integrated Wood Design [10].

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2 PROJECT CONTEXT

2.1 CANADA TALL WOOD DEMO PROJECTS

In 2013, Natural Resource Canada (NRCan) launched the Tall Wood Building Demonstration initiative "To test the use of wood in larger and taller wood buildings". Subsequently, the Canadian Wood Council issued a request for an Expression of Interest (EOI) for developers, institutions, and design teams who were willing to undertake an innovative approach to design and build high-rise wood demonstration projects. "The aim of this initiative was to link new scientific advances and data with technical expertise to showcase the application, practicality and environmental benefits of innovative wood based structural solutions" [11].

These projects were expected to bring together researchers, building code officials, fire safety professionals, designers, engineers and construction industry experts to foster innovation in the timber building sector. The requirements were a building height of at least 10 storeys and the use of mass-timber products in an innovative way. Proposals were evaluated by the CWC/NRCan panel that included professionals from the fields of design, engineering, fire safety, building code, research and building industry professionals.

The University of British Columbia (UBC) has been at the forefront of the movement towards the use of timber in construction, adopting ambitious sustainability criteria for building projects and development initiatives [12]. New institutional buildings must achieve a minimum Gold certification under LEED®. In addition, UBC has adopted the "Living Laboratory Challenge" for its Vancouver as "a kind of giant sandbox in which there is the freedom to explore the technological, environmental, economic and societal aspects of sustainability" [13].

The now defunct Strategy Partnership Office at UBC submitted the proposal following the call for EOI for the Tall Wood Building Demonstration Initiative. The UBC projects was selected as one of three Canadian demo projects. As of the time of writing, only the UBC project is underway. The project context in which the UBC Tall Wood Building (TWB) is being developed comprises the business, regulatory, industry, and site specific contexts.

2.2 UNIVERSITY CONTEXT

As part of the *UBC Vancouver Campus Plan* adopted in 2010, the Brock Commons were designated to be developed to address UBC's increasing need to house its growing student population. SHHS (Student Housing & Hospitality Services) has developed the Student Housing Growth Strategy to "add more than 2,000 beds by 2017 [14]. The development of the UBC Brock Commons phase I is part of this strategy. The need to provide additional housing and space on campus is the project's principal driver. In this sense, given the residential occupancy of the proposed building, the most important consideration for UBC is fire and life safety, regardless of structural solution. The designed solution, a residential tower with public amenities, would traditionally be built with a concrete structure.

The NRCan Tall Wood initiative offered a key business incentive to support the use of mass timber in the project. The available funding was the key driver for the use of wood as a structural element in the TWB. Without this funding, the building would have been built with traditional materials, in this case concrete [15].

The opportunity to implement a mass timber structure introduced a second objective in the project: to design, build, evaluate and monitor a tall building utilizing advanced wood-based building systems, physically demonstrating the applicability of wood in the tall-building market. The decision to go with mass timber had repercussions on the business context as the use of wood in the project introduced new issues relating to insurance and liability. Furthermore, and perhaps more importantly, the question of marketing a tall wood building to students and their parents due to the perceived increased risk of fire associated to wood construction was a significant challenge. Potential tenants would have to rest assured that this building would be as safe, if not safer than traditional buildings.

2.3 REGULATORY CONTEXT

Brock Commons has been identified as one of six *Hubs* on campus as defined in the *UBC Vancouver Campus Plan*. This plan defines that "Hub buildings may reach 53 m height exclusive of rooftop appurtenances, and will consider visual impact analyses regarding sightlines." With regards to site location, the proposed building footprint is located in close proximity of an existing multi story parkade. The site is relatively narrow, measuring approximately 26 m wide. According to the geotechnical report: "the site qualifies as a "Site Class C" defined as very dense soil sites". The soil conditions are thus deemed adequate for a tall building and do not require any special foundation work to be undertaken.

UBC operates within following regulatory framework for development on its campus:

- The British Columbia Building Code 2012 (BCBC)
- The British Columbia Fire Code (BCFC)
- UBC Policy#92 (Land Use and Permitting)
- The BC Building Act

All projects undertaken on the UBC Vancouver Campus must meet the requirements laid out in these documents.

The principal use for the project will be a student residence; the building will be Group C (residential) major occupancy and Group A-2 (assembly) subsidiary occupancy. BCBC article 3.2.2.50 states that buildings with Group C occupancy can be of combustible construction if they are no more than 6 storeys and/or 18m high and have a max. building area of 1,200 m^2 [16].

For buildings to surpass these constraints, they must be of non-combustible construction, sprinklered throughout, have floor assemblies with a fire-resistance rating (FRR) no less than 2hr and loadbearing elements that have a FRR no less than the supported assembly. In the case of the TWB, the building does not conform to the current requirements of the BCBC.

Given this noncompliance with the BCBC, the project must propose a performance based approach to achieve compliance. This is captured in the form of a proposed Site Specific Regulation (SSR) to be developed by the Authorities Having Jurisdiction (AHJ), in this case the Province of British Columbia's Building Standards and Safety Branch (BSSB), authorized under the Building Standards and Safety Act and authorized by the Minister as well as UBC [15].

2.4 INDUSTRY CONTEXT

The industry context is defined by the local Architecture, Engineering and Construction practices. The preferred construction type for high rise buildings is cast-in-place reinforced concrete. The use of wood in construction is mainly limited to residential construction for buildings up to 6 stories and is commonly referred to as light-frame wood construction. Though some expertise exists throughout the design and construction supply chain although, mass timber construction remains relatively marginal and is mainly used in cases where there is a desire to develop a certain aesthetic. Mass timber is not seen as a "go-to" material for routine projects, such as low or mid-rise commercial, institutional and residential construction. Given the regulatory constraints outlined above, mass timber is not seen as a "go-to" material for high rise residential construction either. In North America, there are a limited number of suppliers of mass-timber producers which translates into a limited supply network and thus a challenge in procuring products on a large scale.

2.5 ASSEMBLING THE TEAM

The design and pre-construction process officially began in November 2014 and was completed in September 2015. During this period, the building was designed and approvals were obtained on the part of the UBC Board of Directors (for budget), the Owner (for design) and the Authorities Having Jurisdiction (AHJ) (for code and building permit). The total project duration is 593 days (including tender), beginning in October 2015 and slated for occupancy in May 2017.

UBC Properties Trust, UBC's property management subsidiary, was mandated to manage the project. The Owner was seeking companies and individuals to form, what they termed, an "Integrated Design Team". The request for proposals (RFP) for design services was issued in summer 2014 and the RFP for the pre-construction services was issued in October 2014. By November 2014, the team comprised of the architects, structural, mechanical and electrical engineers, construction manager and fire engineer was assembled. The prime consultant for the initiation of the project was the structural engineering company, Fast+Epp, who was selected by the owner and project manager amongst a small group of local structural companies.

In a parallel process, the Architect of record was chosen. The owner received more than 20 initial submissions from local and international firms out of which three submissions were invited to present their proposal in front of a UBC selection committee. Conscious of the current limitations with the level of expertise on Tall Wood Construction in the North American market, the winning proponent for architects of record consisted of the team Acton+Ostry from Vancouver and Hermann Kauffman Architects from Austria.

The other design consultants, the mechanical and electrical engineers, Stantec, as well as the code consultant, GHL Consultants Ltd., were selected based on past experience working for UBC. UBC PT also hired a virtual design & construction integrator, CAD Makers Inc., to assist the team by providing virtual design and construction services. The pre-construction managers, Urban One, were selected following a public RFP.

Specialty trades that were deemed critical to the project, in this case mass timber supplier, Structurlam, and erector, Seagate, as well as concrete forming and placement, Whitewater, were brought on board early on in a design-assist role, although not formally bound by contract to the project team. Instead, the specialty contractors provided pre-construction services, yet still had to bid on the job during the tender process.

2.6 DESIGNING THE PROJECT

The project's timeline for design was very compressed. The team had 8 months to design and get approval for the entire project. An integrated design workshop was held in January 2015 to discuss several options for, and then develop and refine the various building systems. The use of a virtual mock-up and its development in real time, provided rapid feed back to the project team which was beneficial in the decision making process. At the end of the workshop, the team had settled on the structural solution, mechanical and electrical systems to be provided and how they would be integrated into the building and an understanding of the guiding principle for the pre-fabricated envelope panels. Furthermore, the project team developed a comprehensive cost model of the proposed building and were able to rapidly estimate alternative design solutions.

In developing the project, the team used an approach akin to set-based design, a process through which all project stakeholders share a range of acceptable solutions for a particular scope of work and look for an overlap. The process is continued until a final solution is found. Principally, the team focused on two major elements of the project to perform this light form of set-based design: the structural system and the prefabricated envelope panel system.

UBC retained the services of a VDC integrator, who was involved early on and was tasked with collecting all relevant project information from the different team members to create a singular model of the building that would be developed to a very high level of detail. One of the key elements in this process was removing any burden on the design consultants to produce a 3D model that could be used throughout the project's lifecycle.

2.7 PRE-CONSTRUCTION

UBC typically involves a construction manager (CM) in its major projects. The CM is principally responsible for estimating the work, developing a plan and a schedule and sourcing and procuring the work necessary. In this case, one of the project's objectives, aside from providing housing for students, was to demonstrate the financial viability of tall wood construction and that it could compete with traditional construction.

The construction estimate was developed by the construction manager and included a concrete equivalent to act as a project baseline. The target construction budget set by UBC was $78,000/bed and $192/sf. The cost of mass timber was tracked throughout the development of the project as there was considerable risk. The team was assuming a cost of $1,100/m^3 for wood compared to a $900/m^3 for concrete [15]. Furthermore, the team included allowances for the premium for the tall wood component. The difference in price between concrete and wood was absorbed by funding from the Tall Wood Demonstration Initiative. However, the project team did believe that speed of erection and ease of assembly could help close the gap between concrete and wood. The other cost item that they were tracking was the price for the pre-fabricated envelope panel. The team had set aside a $60/sf of façade.

The foremost constraint in planning the work sequence was to mitigate any possibility of water damage during construction. This prompted the team to develop two strategies: first is to erect the mass timber structure during the "dry months", and second is to enclose the building as quick as possible behind the structure. The first constraint involves building the entire concrete structure prior to the erecting the mass timber structure. As a consequence, this would also allow the team to potentially use one of the elevators during construction as a material and man lift, thus eliminating the need for a construction elevator. The second constraint led to choosing a prefabricated envelop panel.

2.8 MOCK-UP

A full scale mock-up was built (see Figure 1) to test the viability and constructability of the designed solutions. The mock-up consisted of a core wall and measured 3 x 3 bays 2 stories high. It was built by the design-assist trades and helped them further refine both their product and the installing process. It was also used to validate the speed of erection for the structure. The mock-up helped the project team validate a number of decisions such as: connection details with column and slab, connection with the slab and concrete core and confirmed the choice of steel assembly for the structural columns. It also allowed the team to make a decision regarding which prefabricated envelope panel they would use on the project [15]. The project team also tested some options for materials and assembly, namely the type of concrete topping as well as the wood sealer to be used during construction. Finally, it allowed the VDC integrator to test the exchange of data with the mass timber supplier.

Figure 1: Mock-up

2.9 GETTING APPROVAL

Along with economic viability, obtaining approval from the AHJs was the biggest challenge for this project, specifically when considering the time-line. Indeed, many design decisions were made to keep the project simple and ensure its approval. A key consideration was to get the AHJ involved and communicate the intent of the project team regarding design solutions. In order to respect the project schedule, the project had to obtain the BSSB's approval by September 2015.

The building is residential major occupancy assembly subsidiary occupancy. Given the noncompliance with the BCBC regarding building height, non-combustible materials and the FRR required for structural assemblies, the project had to provide a performance based approach and prove that the proposed solution achieves regulatory requirements of Division B, Part 3 of the 2012 BCBC. This was captured in the form of a Site Specific Regulation (SSR) which was developed by the AHJs, in this case the UBC Chief Building Official and the Province of British Columbia's BSSB, authorized under the Building Standards and Safety Act.

The SSR process is a rigorous procedure which entails a thorough peer review process. The outcome of a SSR is a regulation that is only applicable to the site that is concerned by the project. Therefore, while setting an important precedent for future Tall Wood Building, the SSR of the UBC TWB does not allow for future tall wood building of similar design to be approved without a new alternative solutions approval process.

The project was subject to two peer reviews of the proposed structural system conducted by two structural engineering firms, one local, Read Jones Christoffersen consulting engineers, with expertise in local building codes and one international, Merz Kley Partner AG (MKP), with expertise in tall wood construction [15]. Both reports highlighted elements that were believed to require further consideration by the design team. The RJC report concluded that "in general, the concept appeared to be reasonable and the member sizing appropriate". The MKP report was based on Eurocodes and focused primarily on the structural capacity of the mass timber under on gravity loads. The report found them to be acceptable in all cases.

To assist the team in ensuring the proposed building perform sufficiently to meet the intent of the prescriptive requirements of the BCBC as well as help it develop the application for the SSR and other alternative solutions for items unrelated to the tall wood component of the building, a 3rd party code consultant, GHL Consultants Ltd., was brought on early in the project. The company played an important role in changing the BCBC requirement regarding mid-rise building from allowing six storeys combustible construction in BCBC 2012.

The SSR process involved a panel of experts which focused on two specific elements of the building: the structural review expert panel and the fire safety expert panel. The expert panels met on two occasions with the final presentation being made by the design team in June 2015 to get approval by September. In both cases the objectives of the review panels were to identify that:

- All areas of uncertainty regarding the project have been identified and adequately addressed
- There was no need for more robust administrative requirements
- All items relating to the project be clearly outlined and brought to the attention of the BSSB.

During the final structural review panel session, the structural design team was looking for feedback from the expert panels on whether the proposed design was too conservative, thus adding unnecessary cost to the project, and whether or not it would be more appropriate to use the NBCC 2015 rather than the BCBC 2012. Furthermore, the structural panel discussed issues pertaining to the following items:

- Type of glue to be used in the manufacturing of CLT
- Charring of mass timber elements in case of fire
- Use of other materials, e.g. steel, for major elements
- Design of structural connections
- Differential settlement and its impact on the building
- Type of concrete
- Behavior of building in case of progressive failure
- Obtaining consensus on design loads
- Risk of wood getting wet (construction, operation)
- Using the latest seismic codes (NBCC 2015)

During the fire safety review panel session, the design team was looking to get feedback on several items including the proposal to use a combustible exterior wall, exposing timber on the 18th floor, and reducing the amount of encapsulation or backup water supply.

Furthermore, the fire safety review panel discussed issues pertaining to:

- Behavior of building elements in case of failure such as gypsum wall board falling off
- Presenting a conservative approach to fire protection to facilitate approval, e.g. no reliance on charring for fire resistance of structural elements
- Facilitating the approval process by providing a highly detailed design
- Providing different material options such as increasing quantity of mineral wool in the assembly or using Magnesium Oxide boards
- Discussion of past events of fire during construction of a tall wood building in the UK
- Questions around the contribution of mass timber to fire spread once all fire protection has disappeared
- Encapsulation of structural connections, noting that no steel will be left apparent
- Presentation of the multi-compartment nature
- Fire load used (790 MJ/m^3)
- The question of life safety versus property protection in designing the encapsulation of the structural elements and the automatic sprinkler system
- Concerns about service penetrations added during the building's operations
- Accounting for earthquake events and providing life safety measures for extreme cases
- Overall design, testing and decision making process regarding strategies to offer acceptable performance.

The fire safety review panel ended with a roundtable discussion on whether the direction that the design team had taken was acceptable. The panel was in favor of the design presented, which included encapsulation and sprinklered throughout with water back-up supply [15].

The BSSB accepted the proposed design and issued the SSR in September 2015.

3 THE BUILDING

3.1 OVERVIEW

The building is designed to provide 404 student residence beds distributed in single-bed studio or four-bed units. The building will surpass the maximum allowable height of 53m as defined by the UBC Campus Plan and attain 54.8m and 58.5m at the top of elevator core parapet. The building will be 18 storeys with a typical floor to floor height of 2.8m. The ground level will have a 5.0m floor height. Residences will be located on floors 2 to 18. The typical floor plan is approximately 15m x 56m for a typical gross floor area of $840m^2$. The total building gross floor area will be approximately 15,000 m^2. Table 1 summarizes the project statistics.

3.2 STRUCTURAL SYSTEM

A key driver in developing and detailing the design was to stick to tried and tested solutions, which were code compliant and certified by product standards. In other words, while the whole of the project was innovative, its parts were simple and as standard as possible.

The building's structural system is designed as a hybrid configuration, see Figure 2. The foundations, ground floor and the building cores, which house stairwells, elevators and risers, are cast-in-place concrete. The floor on level 2 acts as a transfer slab. The building is supported by 2.8m x 2.8m x 0.7m thick reinforced spread footings. Each core is supported by a 1.5m thick raft slab that include soil anchors with 1250 kN tension force capacity. A 250mm thick wall on a 600 x 300mm strip footing is designed at the perimeter of the building's foundation [15].

The choice of a mass timber superstructure is estimated to result in a building that is 7,648 tonnes lighter than a concrete building. This lighter building requires smaller footings which results in lower costs for the project. However, Vancouver being a high seismic zone, the decrease in mass results in less inertia and thus leads to a lower resistance to overturning than compared to a concrete structure. The use of a hybrid structural solution has also required to ensure that all lateral forces are adequately transferred to the building cores and subsequently to the raft slabs.

The building's superstructure comprises the concrete podium and cores, the mass timber columns and floors as well as the steel roof structure. The decision to go to a hybrid structural solution was taken early on in the project by the owner and was key in setting the direction for the project to get it approved. The concrete podium houses the ground level amenity and service spaces. The decision to build a concrete podium was driven by many things, namely the need for high clearances in public spaces as well as large spans.

Other issues, such as resistance to impact and as well as the need to house large mechanical and electrical services in non-combustible spaces while providing room for large equipment were also taken into consideration during the design. The 2nd floor acts as a transfer slab and accepts the full gravity load of the 17 storeys above it. The slab is 600mm thick. This allows the ground level structural grid to be independent from the grid for the wood structure.

The concrete cores form the "backbone" of the UBC TWB. They provide the rigidity that is required to support any lateral forces exerted on the building. They also provide the vertical circulation, housing both the stairs and the elevator shafts, as is common with high rise construction. The core walls are 450 mm thick cast-in-place reinforced concrete. They form a continuous element from the foundation to the roof to which each level of the building is attached. As mentioned, the decision to use a concrete core was taken early on in the design process. This early decision had a significant impact on the project team due to it eliminating the need to design and get approval for an alternative approach such as a steel or mass timber core.

Table 1: Project overview

Project costs	
Building Location	49°16'10.7"N 123°15'05.4"W
Building Address	6088 Walter Gage Road
Building type	Residential (Group C) with assembly spaces (Group A-2)
Sustainability target	LEED Gold / ASHRAE 90.1-2010
Gross Floor Area	15,120 m^2
Building Footprint	840 m^2
Number of stories	18 (17 in mass timber)
Building height	54.81m (T.O.P.)
Typical floor height	2.81m
Project costs	
Design	$2,411,000 160$/m^2
Construction	$39,437,000 2,608$/m^2
Estimated premium for mass timber	$4,452,000 294$/m^2
Total project cost	$51,525,000 3,390$/m^2
Project Schedule	
Start Date	October 15, 2015
Finish Date	May 30, 2017
Duration	593 days
Building elements	
CLT Panels - volume	1973 m^3
CLT Panels - quantity	464 panels
CLT Panels - weight	954 tonnes
Columns - volume	260 m^3
Columns - quantity	1,298 columns
Volume concrete saved	2,650 m^3
Reduction in CO2 emission (over similar concrete building)	500 tonnes

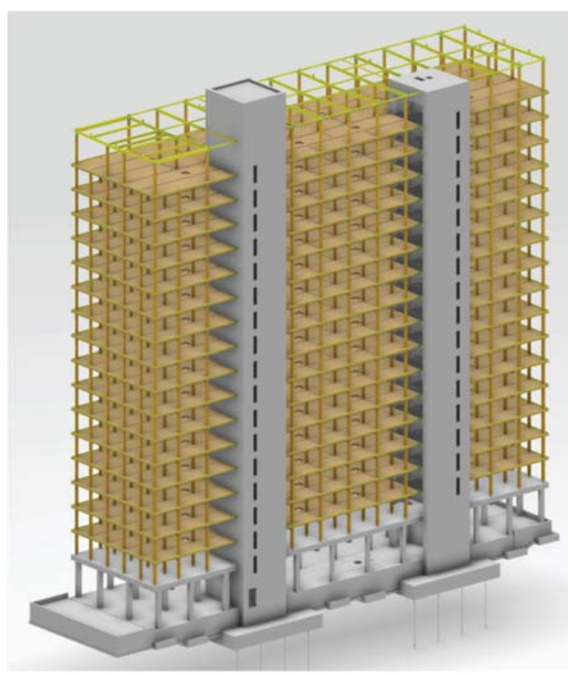

Figure 2: Hybrid structural system (Courtesy Fast + Epp)

3.3 GENERAL DESIGN CONSIDERATIONS

In developing the design, the structural team considered over 60 different options. Using cost, constructability and availability of products as filters, the number of options was reduced to 15. Of those, the structural team had earmarked two options to be developed. The first involved a primary framing oriented on the long axis of the building and consisting of a glulam post and beam configuration and a secondary framing oriented in the short axis of the building consisting of single span, prefabricated hybrid concrete timber panels. The advantage of this option is the added rigidity provided by the hybrid concrete-timber panels, acting as a diaphragm for the building. The disadvantage is the considerable weight that these panels added to the building.

The second option, which was finally chosen, involved a primary framing consisting of Glulam columns and a perimeter beam to support the building envelope. The secondary framing consisted in three span continuous CLT panels oriented on the long axis. The advantages of this option are the elimination of the need for beams, the relatively light weight of the CLT panels and the speed of erection. The disadvantages were mainly related to supply as there is currently only one local supplier who can produce CLT panels up to 3m wide, other capable suppliers are located in Europe and have to contend with shipping constraints. Another consideration is that the columns must be braced during construction as they are free standing until the top panel is in place.

3.4 FLOOR AND COLUMN DESIGN

The gravity load system of levels 2 to 18 consists mass timber columns and floor panels. The team opted for a 5-ply CLT panel system point supported on Glulam columns. The Some PSL columns are used on the lower levels for added compression strength. The typical column cross sections are 265mm x 265mm and 265mm x 215mm on the upper levels.

As previously mentioned the typical structural bay measures 4m x 2.85m. The choice of using a 4 m bay on the long axis was partly influenced by the fact that the CLT panel manufacturers that were being considered fabricate the panels in lengths of 12m (Canada) and 16m (Europe). Thus, a desire to minimize waste was considered in establishing the structural layout. The other driver was the typical floor plan. The CLT panels will be oriented on the long axis of the building and installed in a staggered configuration.

The CLT panels are joined together using 140 x 25mm plywood splines nailed or screwed to each panel. Although there are only four different panel lengths in the project, most panels on a single floor are unique due to the configuration of the mechanical, plumbing and electrical openings to be provided. This requires a very high level of collaboration between the designers and the fabricators to ensure that each panel is properly coordinated.

Based on the chosen suppliers (Structurlam) production, the CLT panels will be 169mm thick. The panels will be constructed of two outer layers of machine stressed lumber (MSR - 1650f-1.5E MSR specified) and three inner layers of SPF lumber (No. 1/2 or better specified) or equivalent. The maximum allowable moisture content is 12% +/- 3% at the time of fabrication. The final design of the floors calls for a 2hr FRR between levels and to achieve an acoustic performance of 54 STC. Both are achieved with three layers of Type 'X' GWB and 40mm concrete topping, 32mm air space, hat track and resilient bars. The floors and roof are supported by glulam and PSL columns.

3.5 CONNECTION DESIGN

Amongst the key challenges in designing the level 2 slab are the different reaction to lateral loads between the concrete and the wood structures, the precise layout and placement of the anchor bolts for the columns during construction, and the coordination of the mechanical and electrical sleeving through the slab. The connections between the concrete slab and the wood columns are shown in Figure 3.

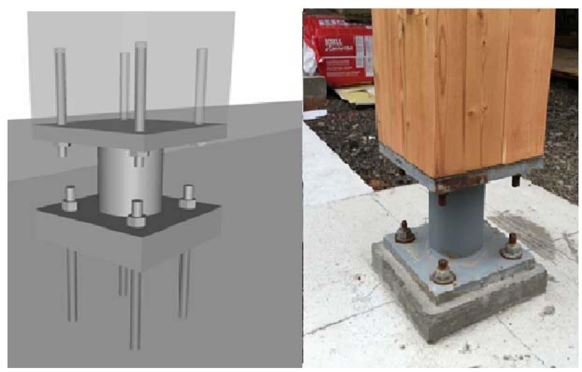

Figure 3: Typical connection ground floor; Left: 3D model (Courtesy CADMakers), Right: Picture from mock-up

The connections between the core and the CLT floor panels form one of the most important interfaces in the building due to its structural importance. There are three critical details for this interface. The first connection supports the CLT panel at the cores. In designing this connection, the differential settlement between the wood and the concrete structure and the vertical shear transfer had to be accounted for. The retained solution is a steel ledger angle (L203x152x13 LLH) welded to a 300mm wide embed plate cast in the core at every 1500mm, see Figure 4. The original solution called for the ledger to be bolted in vertical Halfen channels cast in the core. This would have eliminated the need to weld the ledger and also provide more flexibility during installation. However, due to the high concentration of steel reinforcement at the corners of the core, the installation of the Halfen channel would have been compromised [15]. The ledger will be screwed to the CLT panels. Installation of the ledgers during construction will be a critical item and require high levels of precision.

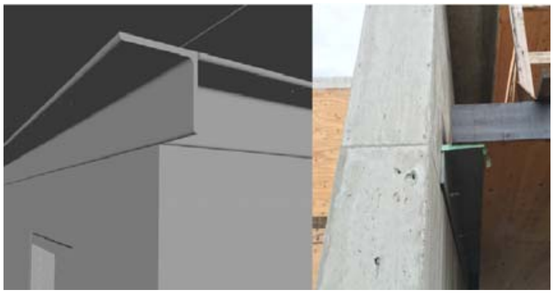

Figure 4: Typical connection between core and CLT floor; Left: 3D model (Courtesy CADMakers), Right: Picture

The next connection is the drag strap to core connection which are a critical part of the structural system in that they ensure that any lateral loads exerted on the building are transferred to the core. The presence of the drag straps means that no penetrations can be made through the floor in those areas. Four different types of drag straps are called for in the design. The drag straps are 100mm wide steel plates which vary between 6.4mm and 12.5mm depending on location in the building (the thicker plates are located on levels 17 and 18). Depending on orientation, the straps vary between 1.5m and 7.2m in length and the distance between the screws vary between 50mm and 250 mm. The drag straps are welded to faceplates that are anchored to the core using DYWIDAG anchors [15]. To ensure that the anchors do not conflict within the core wall, the face plates are flipped for each face of the core. Figure 5 shows a typical connection between the drag-strap and the core. The “slab edge” connection to the core is a drag strap connection similar to the one described above but is located on the periphery of the building (chord). There is also a chord strap installed between each panel at the perimeter of the building.

Figure 5: Typical drag-strap connection; Left: 3D model (Courtesy CADMakers), Right: Picture from mock-up

The connections between columns and panels represented a significant challenge as two interfaces have to be managed: column to column and column to panel. The connection has to effectively transfer both the vertical loads as well as support the panel shear loads. The connection must include a 2hr FRR and minimize the transmission of vibrations throughout the building. The connection must also allow the panels to act as a diaphragm to transfer lateral loads to the building cores. Constructability issues that were taken into consideration in the design of the connection were related to ease and speed of installation of the columns and panels, fabrication and installation tolerances and cost of the assembly, among others. Operational issues that were considered in the design were to mitigate any water infiltration. Four different connection designs were considered and analyzed taking into account the criteria mentioned above.

A welded HSS and steel plate assembly, as illustrated in Figure 6, was chosen since it was seen as the simplest solution which fulfilled the design, constructability and operational constraints. Notably, the ease of installation as well as the full transfer of the vertical load to the column below (as opposed to some compression being exerted on the panels as in the wood to wood connection) while providing adequate vertical shear load support was key in making the decision. The solution, consists of a round HSS welded to a steel plate that are embedded at the top and the bottom of each column using threaded rods that are epoxied into the column. The bottom connection assemblies have a smaller HSS which fits into the top connection assemblies that are installed on the columns below [15]. These top connection assemblies have four threaded rods to which the CLT Panels are bolted. In effect, this ‘suspends’ the column from the floor above and allows all the vertical load to be transferred through the columns only. Shims are provided as needed to level the assembly and account for differential settlement of the structure. A 40mm concrete topping will fill the space between the bottom of the columns and the top of the CLT panels.

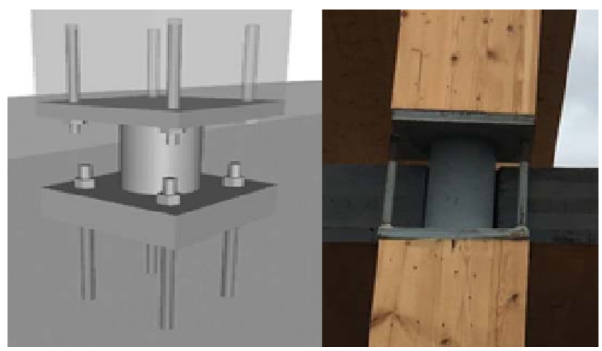

Figure 6: Typical column detail; Left: 3D model (Courtesy CADMakers), Right: Picture from mock-up

3.6 BUILDING ENVELOPE

The building will be enclosed with a curtain wall system on the ground floor. A three layered CLT canopy will be provided with double folded standing seam metal roofing system attached to the concrete columns at the base will provide rain coverage for pedestrians. On the upper floors, a prefabricated exterior panel system will be used. The panel system will comprise of 8.0 m long (corresponding to two structural bays) by one story (2.8m) high panels.

Beyond the floor layout discussed above, interior construction for the UBC TWB project is principally driven by the need to encapsulate all wood elements to provide a 2hr FRR rating for all the structural assemblies including providing 2hr FRR between floors, the need to provide 2hr FRR between suits and 1hr FRR between the units and the corridor.

Encapsulation was chosen as a passive fire protection and life safety measure in the alternative solution report [16]. Two requirements within the building code are addressed by these measures: the requirement for non-combustible construction and the requirement for 2hr. FRR floors and supports. The requirement for non-combustible construction has the objective "to limit the probability that combustible construction materials within a story of a building will be involved in a fire, which could lead to the growth of fire, which could lead to spread of fire within the story during the time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm to person or damage to the building." To achieve this goal, all structural elements will be encapsulated.

3.7 CONSTRUCTION RISKS

The risks and mitigation strategies were categorized into water events, fire events and schedule extensions:

1) Water Event

- Erection of mass timber structure scheduled for Spring/Summer seasons
- Water resistant coatings on wood elements to minimize water absorption during construction
- Prefabricated temporary rain protection potentially erected during wet weather conditions
- Prefabricated building envelope installed approximately 1 level behind erection of structure
- Man-hoist connection to building to allow for control of rain shedding
- Water flow alarm used at main water entry room after hours; main water shut off at night
- Fire standpipes not charged during construction; standpipe valve caps wrench tightened
- Site security presence to commence at start of wood structure erection; personnel to receive training regarding water damage prevention and mitigation
- Concrete topping covering wood slab structure may be sloped to direct drainage
- Envelope consultant involved in moisture content assessment of wood structure prior to encapsulation

2) Fire Event

- Fire safety plan to be reviewed and approved by Vancouver Fire Department
- Detail wood structure to minimize or eliminate welding; hot work permit process in effect for hot work activities; firewatch personnel as required
- Temporary heat to be used will avoid open flame heat within the structure
- Fire standpipes to be constructed no less than 4 levels below active structure deck and to be available for use by Fire Department
- CLT floor structure to be encapsulated with 1-layer Type X gypsum board with no more than 4 levels of unprotected wood structure exposed at any one time
- Site security begins at wood structure erection; training in fire prevention and fire response

3) Schedule Extension

- Construction schedule prepared with involvement through buy-in process from major trade contractors; specialized methods required to achieve structure erection timeline will likely involve 6-day work week
- Proactive procurement process of major materials, systems, and equipment; tracked for availability of items in advance of construction timing requirements
- Wood structure and building envelope materials prefabricated and stored offsite;
- Computerized design models and physical mock-ups analyzed in advance of mass production to ensure correctness and approval
- Concrete work scheduled for winter; wood structure erection to take place in Spring/Summer for reduced weather-related stoppages
- Erection of wood structure after concrete structure will ensure sufficient tower crane time for prefabricated building envelope

3.8 MONITORING

Monitoring of initial and in-service performance is crucial to refine designs to be more cost effective in future buildings. Tall wood buildings are a new form of construction. It is therefore prudent to design demonstration buildings conservatively. Monitoring these buildings aids in learning lessons and in designing future buildings more efficiently. While it is common industry practice to monitor the building physics performance, specifically the energy usage, in the TWB, three aspects that pose specific challenges to Tall Wood buildings will be monitored:

- Moisture content of CLT panels
- Vertical settlement including elastic shortening, moisture related shrinkage and creep
- Horizontal vibrations due to wind (and earthquake)

The moisture content of CLT floor panels and not of façade elements will be monitored. While the latter is important, it is not a challenge specific to Tall Wood buildings. Whereas, there is little data available on moisture fluctuations of CLT panels from the moment of fabrication over the time of storage, transport, installation, building completion and building use.

Differential movement between parts of a building is an important consideration due to the cumulative effect of vertical settlement. Detailing to reduce and accommodate differential movement is required to prevent its potential adverse impact on structural integrity, serviceability, and building enclosure. Downward movement is typically predominant in wood structures resulting from shrinkage due to change in moisture, elastic instantaneous compression shortening due to the applied loads and viscoelastic delayed compression shortening due to the applied loads (creep).

The accelerations of a building, at both the top and the ground levels, in both building directions, can be recorded by installing accelerometers. The system will allow monitoring the serviceability performance during regular and extreme wind events and potentially, the ultimate limit state performance during an earthquake.

4 CONCLUSIONS

The principal drivers that led to mass timber being used on the UBC TWB project was the Tall Wood Building Initiative being steered by Natural Resources Canada, the Canadian Wood Council, the National Research Council Forestry Innovation Investment, the Binational Softwood Lumber Council, and FPInnovations with the aim to demonstrate that wood is a viable option for most construction applications.

UBC's TWB was retained as one of three demonstration projects in Canada and. Safety issues were the top priority for the owner and design team. From a public relations perspective, the housing of residences in a mass timber building brought up concerns relating to fire safety. To mitigate this concern, a dual fire protection strategy was designed. First, the building will be fully equipped with sprinklers and includes a reserve tank to ensure sprinklers function even in case the main water line was breached. Secondly, all wood elements are encapsulated in gypsum wall board to a 2hr FRR.

The building design was submitted to the province for a Site Specific Regulation given that it does not comply with the prescriptive elements of the Provincial Building Code. To facilitate the approval process with the Province's Building Standards and Safety Branch, a panel of experts was put in place to review the project and submit recommendations to the design team. The expert panel reviewed design considerations and approved the project in September 2015. The documentation of the design phase of the TWB allowed drawing following conclusions:

- A strong commitment to a wood solution on the part of the owner was highly beneficial to the project team in providing a strong direction;
- A clarity of goals amongst the project team: safety, simplicity and viability;
- Engaging the AHJs early in the process was key to managing expectations on both the part of the project team and the part of the regulatory agencies;
- Engaging key suppliers early in the process was key to ensuring project viability;
- Use of 3D modeling and virtual design and construction was critical in providing a digital "mock-up" to visualize and coordinate the design as it progressed. The model was developed with pre-fabrication of the structural components in mind;
- Construction of a mock-up was crucial for testing and developing design choices

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REFERENCES

[1] K. Koo, "Study on Historical Tall Wood Buildings in Toronto and Vancouver," FPInnovations, 2013.

[2] NRC Canada, "National Building Code of Canada 2010," National Research Council of Canada, Ottawa, Canada.

[3] E. Karacabeyli, "Technical Guide for the Design and Construction of Tall Wood Buildings in Canada (90% draft)," FPInnovations, 2013.

[4] "WOOD FIRST ACT "2009 Legislative Session: 1st Session, 39th Parliament"," Victoria, British Columbia, Canada, 2009.

[5] TRADA Technology, "Stadthaus, 24 Murray Grove, London," 2009.

[6] M. Zangerl and N. Tahan, "LCT ONE," Wood design & building, Vols. Winter 2012-13, 2012.

[7] Lend Lease, "Forté– Building Australia's first timber Highrise," in Wood Solutions Presentation, Atlanta, February 6, 2013.

[8] R. B. Abrahamsen, "14 Story TREET project under construction in Norway," in Toward taller wood buildings, Chicago, November 2014.

[9] Rethink Wood, "Tall Wood Takes a Stand," Architectural Record, December 2014.

[10] University of Northern British Columbia (UNBC), "Engineering Graduate Program," [Online]. Available: http://www.unbc.ca/engineering-graduate-program/master-engineering-integrated-wood-design-program-details. [Accessed 15 April 2016].

[11] Natural Resources Canada, "Tall Wood Structure Demonstration Projects," Canadian Wood Council, 2013. [Online]. Available: http://www.cwcdemoproject.ca/en/faqs.php. [Accessed 14 April 2016].

[12] E. Gonzales, I. MacDonald and T. Tannert, "Exploring our campus: A showcase of innovative timber construction," branchlines, vol. 25, no. 4, pp. 10-11, Winter 2014.

[13] University of British Columbia, "CAMPUS AS A LIVING LABORATORY," UBC Sustainability, [Online]. Available: https://sustain.ubc.ca/our-commitment/campus-living-lab. [Accessed 13 April 2016].

[14] Campus+Community Planning, "UBC Housing Plans & Policy," Vancouver, 2015.

[15] E. A. Poirier, A. Fallahi, M. Moudgil, T. Tannert and S. Staub-French, "UBC Tall Wood Building Case Study (Design and Pre-Construction Phase)," Forestry Innovation Investment, Vancouver, 2016.

[16] GHL Code Consultants, "Approach to Building Code Compliance for student residence at Brock Commons at University of British Columbia," Vancouver, 2015.