The TallWood House at Brock Commons, Vancouver

Paul Fast
PEng, StructEng, PE, FIstructE, BK Berlin/Hessen
Partner, Fast + Epp

Robert Jackson
PEng, PE
Associate, Fast + Epp

Synopsis
The TallWood House at Brock Commons is an 18-storey, 400-bed student residence at the University of British Columbia in Vancouver, Canada. Reaching 53m, the building is among the tallest mass-timber hybrids in the world. The building features an innovative ‘post and panel’ system, with cross-laminated timber panels, point-supported on glulam columns. The project highlights mass timber’s increasing viability as a cost-effective building material for high-rise construction.

Introduction
The University of British Columbia (UBC) has gone through significant growth in recent years, which has resulted in a need for more student housing on campus. In response, it set out to build multiple residences across the University grounds, one of which was the TallWood House at Brock Commons (Figure 1). UBC’s key goals for the TallWood House project were to create a safe, functional, sustainable and cost-effective residence for its students.

UBC has made a sustainability commitment to a campus that acts as a ‘living laboratory’; where innovation in building and infrastructure is encouraged – particularly when it comes to pioneering cost-efficient solutions that will be embraced by the industry and policy makers at large. Building off this commitment, UBC’s question to the design team was not, ‘Is it possible to go 18 storeys with timber?’
but rather, ‘Can this be built at a price competitive with concrete construction?’

The design intent was firmly established in response to the budget demands: keep the structure simple and sensible – develop a prefabricated ‘kit-of-parts’ that could be quickly and easily installed, with minimal labour on site. Materials were used where they made the most sense, rather than maintaining a strict timber-only approach.

The TallWood House at Brock Commons was part of Natural Resources Canada’s Tall Wood Building Demonstration Initiative, which had a goal to foster commercial and regulatory uptake of tall timber buildings in Canada. The initiative’s aim was to link scientific advances with technical expertise, to showcase the application, feasibility and environmental benefits of innovative structural solutions with timber. Funding supported the planning and design of both the TallWood House at Brock Commons in Vancouver, as well as Quebec City’s Origine Ecocondos. Government support for taller timber buildings continues in Canada, with a recent announcement of an additional CAD$39.8M (approx. £23M) in funding to be awarded during the next four years.

Superstructure

UBC’s TallWood House comprises 17 storeys of 169mm thick, five-ply cross-laminated timber (CLT) floor panels, point-supported by glued-laminated (glulam) timber columns that rest on a concrete transfer slab at Level 2. Two full-height concrete cores provide the lateral stability. The building envelope consists of prefabricated top-hung wall panels (Figure 2). A layer of 50mm non-structural concrete topping was placed directly on top of the CLT panels to increase the acoustic performance.

Structural concept development initially focused on more traditional approaches, such as timber post-and-beam construction with timber floor panels, as well as wall-and-panel systems using CLT wall and floor panels, as has been used on mid-rise timber buildings in the UK. However, the point-supported CLT concept quickly became the preferred option as it interfaced best with other disciplines. From a cost perspective, it was determined that the post-and-panel system paired with back-framed non-loadbearing steel stud walls was more efficient compared with a CLT floor-and-wall system.

Gravity system

CLT is often used as a one-way decking system, largely ignoring its spanning capability afforded by its cross laminations. By using CLT to span in both directions, the beams of a classic post-and-beam system were eliminated, along with labour-intensive connections. This dramatically reduced the costs associated with fabrication and erection, and significantly reduced the structural depth. The result was a clean, flat, point-supported surface for unobstructed service distribution (Figure 3).

Finite-element analysis of the CLT panels was carried out with Dlubal RFEM software with an add-on module to analyse laminated shell elements. Approximations and hand calculations using first principles validated results from the software. Based on an initial analysis, the moment and deflection demands exceeded the capacities of standard five-ply panels available in Western Canada. To achieve the required performance, Fast + Epp designed a custom layup using machine stress-rated spruce laminations on the outer layers, with an elastic modulus of $E = 10$ GPa and a specified bending stress capacity of $f_b = 23.9$ MPa. The inner layers typically comprise No. 1/No. 2 spruce-pine-fir (SPF).
lumber with $E = 9500$MPa and $f_t = 11.8$MPa. In addition to stiffness and bending requirements, rolling shear stresses at supports have typically been a controlling factor in two-way, point-supported CLT floor plates. A rolling shear failure is one in which the fibres ‘roll over’ each other, due to shear forces perpendicular to the grain. This rolling shear failure typically governs in CLT design when compared with longitudinal shear behaviour. The only North American code or material standard that addresses this rolling shear issue is the CLT fabrication standard ANSI/APA PRG-320, which specifies rolling shear resistance values, $f_r$, for CLT panels at approximately one-third of longitudinal shear resistance values, $f_c$. However, recent research by Mestek and Dietsch indicates that rolling shear capacities could be slightly higher in point-supported panels, due to added restraint from the high compressive forces near the supports.

The design included 78 columns per floor, resulting in 1248 CLT panel nodes in the building where rolling shear stresses could be the controlling design factor. However, reinforcing the panel points with inclined, fully threaded screws was not a desired solution, due to the significant increase in material cost and prefabrication labour.

After designing the custom layup to suit the rolling shear and flexural demands, the design team completed 18 full-scale load tests on panels from three prospective CLT suppliers at FPInnovations laboratory in Vancouver.

A testing apparatus (Figure 4) was set up for two-span continuous panels on six-point supports, loaded along their centrelines at quarter points.

Testing confirmed rolling shear values were slightly higher in point-supported CLT floor plates, providing higher resistances than originally anticipated. The team anticipates that this was due to the high perpendicular-to-grain compression forces near the supports. During testing, the CLT appeared to have some capability to redistribute forces, as internal shear cracks propagated through the panel before the critical failure mode occurred. Multiple types of shear/bending failures were observed near the supports (Figure 5). While perpendicular-to-grain compression was not the governing failure mode, the panels did begin to significantly crush near the ultimate test load.

In addition to the ultimate load testing, full-scale vibration tests were also conducted. Ultimately, it was determined that vibration was not a concern with this system due to the tight column spacing and the high fundamental frequency.

Lateral system
The structure's primary lateral support for earthquake and wind loading consists of two concrete cores. Although timber-based lateral force-resisting systems (such as CLT walls/cores, timber-braced frames, or post-tensioned/self-centring systems) were feasible design options for this project, the testing and time required to obtain regulatory approvals would have negatively impacted the client's completion date. In addition, the cost of such systems was of significant concern, due their application in such a severe seismic zone.

The cores were designed as ductile concrete shear walls in the shorter, north–south direction and partially coupled ductile concrete shear walls in the longer, east–west direction. Building fundamental periods are $T_{East-West} = 2.0s$ east–west and $T_{North-South} = 1.65s$ north–south; the design base shear correlates to 4.5% of the building weight.

In addition to the cores, the floor diaphragms are a critical part of the lateral system and needed to be designed to remain elastic when the cores yield in flexure. This requirement resulted in significant diaphragm forces in the CLT panels. The CLT panel-to-panel connection consists of continuous Douglas fir plywood strips, nailed into CLT recesses with ring shank nails to transfer in-plane diaphragm shear forces. Additional
The SSR also specified the two-hour fire rating requirements of this unique building system. While allowing glulam columns and CLT panels to char in a fire event is considered a feasible engineering solution to achieve two-hour fire ratings, for this project, three layers of type X drywall cladding was selected as the fire protection strategy to expedite the approvals process and to raise the acoustic performance of the units. In addition, a backup water supply tank was required in the basement, such that the sprinkler system could be independent from the municipal water supply. With this sprinkler-encapsulation strategy, a two-hour fire rating was achieved.

**Prefabrication**

Prefabrication should be regarded as an essential consideration when designing large-scale timber structures. Well-planned erection and shop drawings were key to ensuring smooth production and installation of the timber elements at the TallWood House. These drawings ensured fewer errors on site, less remedial work and a shorter overall construction schedule. All CLT and glulam elements were CNC (computer numerical control) machined with quality control protocols to allow for seamless erection of the timber superstructure.

To achieve this high level of prefabrication, CadMakers (a third-party consultant) modelled the building and helped coordinate design documents prior to, and during, construction. Its 3D model, created with CATIA software, included fully detailed structural elements and connections, as well as mechanical/electrical systems and architectural fitouts (Figure 6). The model allowed all CLT penetrations for mechanical and electrical sleeves to be fully coordinated during the design process and to be converted into the fabrication files (CAD/CAM) needed for CNC machining.

Additionally, quality control measures were critical with this level of prefabrication; there was far more upfront information and documentation required than for a typical project.

**Column-to-column connections**

A key challenge on the design of the TallWood House was to develop a column-to-column connection that would avoid transfer of large axial loads through the CLT floor panels (which have weak perpendicular-to-grain compression capacity). A further concern was the accumulation of panel shrinkage, resulting in large vertical deformation if the columns were to pass load through the panels.

The solution was a simple spigot-type connection using circular hollow sections (CHS), fastened to base plates that were, in turn, connected to the timber columns with epoxy anchors (Figure 7). The timber columns arrived on site complete with end connections pre-installed; thus, on-site erection consisted of setting CLT panels on the columns, installing nuts on the threaded rods, and then slipping the next column lift onto the sleeve of the lower column.

**Progressive collapse**

Although progressive collapse/robustness is not addressed in detail in the National Building Code of Canada, it is a concern for taller buildings. Progressive collapse can be described as the sequential spread of local damage from an initial event, from element to element, resulting in the ultimate collapse of the building or a portion thereof. The mitigation strategy for this project was the column tie method, as outlined in EN 1991-1-7. By installing a bolt and cotter pin through the steel hollow structural sections (HSS) and epoxying the threaded vertical rods from the plates into the column ends, an effective tension tie was created (Fig. 7). The solution was a simple spigot-type connection using circular hollow sections (CHS), fastened to base plates that were, in turn, connected to the timber columns with epoxy anchors (Figure 7). The timber columns arrived on site complete with end connections pre-installed; thus, on-site erection consisted of setting CLT panels on the columns, installing nuts on the threaded rods, and then slipping the next column lift onto the sleeve of the lower column.
 Axial column shortening
In tall timber buildings, axial column shortening must be considered during design. When properly accounted for, the shortening should not negatively affect the construction, use or long-term performance of the building.

Several factors affect glulam column shortening, including:
- dead load elastic axial shortening ($\Delta = PL/AE$)
- live load elastic axial shortening ($\Delta = PL/AE$)
- shrinkage parallel to the grain
- joint settlement
- column length tolerances
- creep.

The main concern surrounding these shortening effects is the impact of deformations on vertical mechanical services, and elevation tolerances between the timber superstructure and the stiff concrete cores. The effects of these factors culminate at the roof level, where all columns below contribute to the shortening. Nearly 45mm of deformation was expected at the roof if no
mitigation strategy was put in place (Figure 8). To offset these expected deformations, a series of 1.6mm thick steel shim plates was added at the column-to-column connections on three strategic levels.

Dynamic wind-induced vibrations
The NBCC 2015 requires a dynamic wind load analysis for structures more than 120m tall, with a height-to-width ratio of greater than 4.0, or with natural frequencies of less than 1.0Hz. As this structure's first mode has a frequency of 0.5Hz, a dynamic wind load analysis was undertaken. The building's vibration behaviour was studied using a finite-element model with a 10-year return period for wind loading. To ensure occupant comfort, the building was designed to limit wind-induced accelerations at Level 18 to 1.5% of gravity (15milli-g).

Based on this information, a sensitivity analysis was performed with damping values between 1% and 3%. Accelerations at Level 18 fell within the design limits with a damping value of at least 1.5%. For a student residence building with multiple full-height partitions on every floor, this damping value seemed reasonable. These damping assumptions will be monitored with building sensors, as discussed further below.

Construction
Mock-up
To help improve the constructability of the proposed design, the construction team completed a full-scale mock-up of a portion of the building, 8m × 12m in plan and two storeys tall (Figure 9). The mock-up included several connection types, to determine which to use in the final design and how best to optimise them. In addition to the structural lessons learned, the mock-up was also used to develop and evaluate various building envelope systems considered for the project. The mock-up proved to be an invaluable component to the design development.

Sequencing
In order to facilitate the use of one crane, and provide sufficient time for manufacturing and shipping of the timber components, the construction team erected all 18 storeys of the concrete cores before the timber arrived on site. Once the cores were fully erected, the crane switched over and began to install the timber and envelope (Figure 10).

The timber and envelope installation sequence was completed in four phases. The first involved erecting all columns on one level, diagonally bracing them and using horizontal spreader bars at the column caps to set the grid. The columns were installed by hand from bundles on the active deck (Figure 11), freeing up the crane for envelope panel installation. The second phase was the installation of the CLT panels and plywood strips, stitching them together as each one was placed, to maintain
Project focus
TallWood House, Vancouver

TallWood House, Vancouver

"MORE THAN 2000m³ OF TIMBER WAS USED IN THE BUILDING"

lateral stability (Figure 12). The third phase was the installation of the steel plates at the concrete cores, as well as perimeter angles to support the curtain wall system (Figure 13). The fourth phase was the installation of the prefabricated envelope panels, two floors below the active deck (Figure 14). By repeating this erection process, the installation of the timber and envelope components was completed in just nine weeks with a crew of less than 10.

Weather protection strategies
Considerable effort was made to complete the concrete work to Level 18 during the winter and spring months, to facilitate a summer installation schedule for the timber and envelope elements. The timber arrived on site in early June 2016, which is typically a dry summer month in Vancouver. However, there was a significant amount of rainfall in June, impacting the installation of the first six levels. A weather protection strategy was implemented by the construction manager and changed throughout the construction process as the team learned what worked and what didn’t.

The first strategy was to erect the timber elements with speed, in tandem with the envelope panels. This worked well to protect against the driving rain. A second strategy provided a temporary coating on the exposed face of the CLT panels to repel moisture when it rained. In general, the sealer itself performed well and stopped moisture from penetrating the timber directly through the surface. However, as the CLT panels were not edge-glued, the lamination lines often opened up as the material shrank in the summer heat (ultimately providing a pathway for the water to get to the panel edges when the rain did come). This resulted in water leaking through the floors at the plywood strip locations.

The third strategy was to install peel-and-stick tape over all machined mechanical penetrations and along the plywood strips, to stop water from penetrating to the floor below. However, this was not an effective
strategy – the lamination lines opened up and drove water to the plywood strips, under the tape, and to the floors below. In the end, the concrete topping that trailed the active deck by four levels was taped at its crack lines and this proved to be the most formidable barrier to the rainwater.

The main concern regarding water ingress into the panels was that it could be trapped between the concrete topping and panel itself – leading to mould and ultimately rot. It was determined that if the panels were appropriately dried out and coated prior to pouring the concrete topping, this risk would be reduced.

The design team considered temporary cover solutions, but they were found to be too costly and restrictive for the erection sequencing.

Other attributes
Monitoring
In an effort to better understand the unique behaviours of the building, it was fitted with accelerometers, moisture meters and vertical shortening string pots. UBC research teams and SMT Research Ltd are undertaking the data allocation and analysis.

Accelerometers will allow the research teams to determine in situ damping values from ambient vibration testing (wind). These values will help determine a baseline damping ratio for future hybrid buildings of this type, which will be useful for dynamic wind acceleration calculations in particular. Additionally, sensors have been placed on the concrete cores to record the building’s angle of inclination during a seismic event. The data collected from the accelerometers and inclination gauges will help verify the building’s performance.

String pots will measure the floor-to-floor axial column shortening at strategic levels, to provide more insight into axial column shortening in highly loaded glulam columns. Lastly, moisture meters and data loggers have been installed in the CLT panels, collecting data from the manufacturing plant to the final installed condition. These meters will continue to measure moisture content throughout the service life of the building. In a few years’ time, it is expected that these data will provide an effective moisture content timeline from fabrication to moisture equilibrium.

Sustainability
The prefabricated strategy resulted in fewer errors on site, less remedial work, and a shorter overall construction schedule. Prefabrication reduced the negative social impacts associated with construction, such as noise or vehicle traffic, and pollution. It also meant less site labour in the rain, and more labour in a controlled shop environment.

Every material has its place, yet the best science seems to suggest timber is hitting all the sustainability markers. It is a rapidly renewable resource with low-embodied energy and carbon sequestering capabilities. More than 2000m² of timber was used in the building, sequestering upwards of 1700t of carbon dioxide. The project awaits LEED Gold certification10.

Value
With a hard construction cost of CAD$2570 (approx. £1500) per square metre, this timber solution has proven competitive with its cast-in-place concrete alternative. This demonstrates that timber can be economically viable in the local market – even at this height.

The approvals process and building code amendments permitted by the local government are already being used as a precedent for prospective tall timber projects in Canada.

This will help to drive change in future building codes and material standards, allowing the structural properties of timber to be harnessed in new ways.

Summary
The unique, clutter-free, post-and-panel concept with easy-to-install connections allowed the timber components of the building to be erected in just nine weeks. The project has proven cost-competitive with concrete towers in the local marketplace, successfully meeting the university’s objective, and bolstering its reputation as an incubator for innovation – a true testament to fresh thinking and holistic design (Figures 15 and 16).

PROJECT TEAM
Owner and client: UBC Student Housing and Hospitality Services & UBC Properties Trust
Structural engineer: Fast + Epp
Architect: Acton Ostry Architects & Hermann Kaufmann Architekten
Mechanical and electrical engineer: Stantec
Fire and code consultant: GHL Consultants
Construction manager: Urban One Builders
3D coordination consultant: CadMakers
Virtual Construction
Timber manufacturer: Structurlam Products
Timber installer: Seagate Structures

REFERENCES
2) Canadian Standards Association (2016) CSA O86-14: Engineering design in wood, Mississauga, ON: Canadian Standards Association
5) Canadian Standards Association (2014) CSA A23.3-14: Design of concrete structures. Mississauga, ON: Canadian Standards Association