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# Structural Design of Tall Mass Timber Buildings

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*Following the Industrial Revolution, the construction of tall buildings has surged as a means of utilizing dense urban lands more efficiently. Previously, iron/steel and reinforced concrete were the primary structural materials used in tall buildings. However, the use of engineered mass timber as a structural material for tall buildings is steadily increasing due to its numerous benefits compared to its steel or reinforced concrete counterparts. These benefits include a lower carbon footprint, biophilic effects on occupant well-being, high-quality products due to reduced on-site manufacturing and labor, and shorter construction periods. Nevertheless, there are structural design considerations for tall mass timber buildings. This study first briefly examines the development of industrialized mass timber and investigates mass timber products. Mass timber encompasses a range of timber products, including glued laminated timber (GLT), cross-laminated timber (CLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), laminated strand lumber (LSL), laminated veneer lumber (LVL), parallel strand lumber (PSL), and mass ply panel (MPP). It then explores the types of framing systems created with mass timber. These framing systems can be categorized according to their material usage as all-timber or hybrid systems and, according to load-bearing element usage, as post and beam, point-supported panels, wall and panel, and modular. Later, structural design considerations for tall mass timber structures are explained. After conducting case studies for the five tallest mass timber buildings worldwide, current approaches and research areas were identified for tall mass timber building structures.*

**Keywords:** *tall buildings, mass timber, structural system, framing system*

## Introduction

Wood is a natural and environmentally friendly material that humans have used as a building material for thousands of years. Traditionally preferred for smaller structures, advancements in technology and sustainability efforts have made wood an increasingly attractive option for high-rise construction. This rediscovery of wood has sparked excitement among architects and engineers, opening new horizons in the construction sector.

There are several reasons why wood is chosen for high-rise buildings. Firstly, its high strength and durability make it ideal for constructing long-lasting and safe buildings. Additionally, wood's natural beauty and aesthetic value provide aesthetic richness and warmth in modern architectural designs. Wood also stands out as an environmentally friendly option; it reduces carbon emissions and is easily recyclable. These features make it particularly desirable for sustainability-focused projects.

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However, using wood for high-rise buildings comes with challenges. The risk of fire and wood's susceptibility to external factors such as moisture and insects require careful design and maintenance. Moreover, the technical complexity and cost of large-scale wood structures are among other factors that need attention during the design process.

Impressive high-rise buildings constructed using wood can be found worldwide. These structures represent significant achievements both technically and architecturally.

This article will examine the development and usage of mass timber in high-rise buildings, supported by examples from around the world. It will explore how wood could play a role in the future construction industry and discuss its potential.

## Industrialized Mass Timber Products

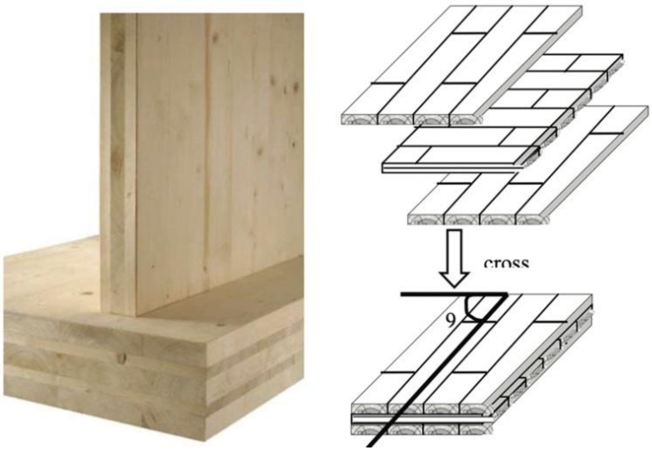
The development of the engineered mass timber began with the discovery of the cross-laminated timber (CLT) in the mid-1990s. While multi-layered wood products like plywood had been used before, they did not play a primary role in the load-bearing systems of structures. In 1994, a doctoral thesis titled "Elastic Analysis of Flexibly Jointed Laminated Timber Plates" was completed at Graz University of Technology in Austria. Existing mechanical theories were applied to multi-layered wood. Following this, collaboration with industry leaders led to the development of marketable structural panels. Initially produced as three-layer panels, they later evolved into five-layer panels and more (Wood et al. 2023).

Today, a variety of laminated timber products are manufactured in the construction industry. The main types of mass timber used in construction industry are Cross-Laminated Timber (CLT), Glued Laminated Timber (Glulam), Nail Laminated Timber (NLT), Dowel Laminated Timber (DLT), and Structural Composite Lumber (SCL) (Abed et al. 2022).

### *Cross-Laminated Timber (CLT)*

CLT panels are created by stacking timber boards perpendicular to each other and bonding them together with a structural adhesive (see Figure 1). The moisture content of the timber used is reduced to around 12% through a kiln-drying process. Any knots or other defects in the panels are removed or cleaned. Once the dimensions of the panel are determined, they are pressed together under pressure using a press machine. After coming out of the press, the panels are cut to their full dimensions, edge profiles are applied using Computer Numerical Control (CNC) machines, and they are prepared for assembly.

**Figure 1.** *Picture and Lay-up of Cross Laminated Timber*



*Source:* Kulien et al. 2011.

These panels are typically produced with an odd number of layers, with three, five, and seven layers being the most common. CLT panels can vary in size depending on the manufacturer, but they can be as large as 18 meters in length, 5 meters in width, and up to 500 mm in thickness. They are ideal for use in floors, walls, and roofs (Harte 2017, Kuilen et al. 2011).

### *Glued Laminated Timber (Glulam)*

Glued Laminated Timber (GLT) is created by bonding shaped timber pieces together with the grain directions parallel to each other using adhesive. Glulam elements can vary in size from manufacturer to manufacturer, but they are typically produced in thicknesses ranging from 180 to 630 mm, widths from 66 to 200 mm, and lengths up to 50 meters. This makes them suitable for use as beams and columns. The length of the element is generally limited due to transportation and handling constraints.

One of the significant advantages of GLT is its ability to be produced in large sizes and complex shapes, thereby meeting both architectural and structural design requirements (Abed et al. 2022).

### *Nail Laminated Timber (NLT)*

Nail Laminated Timber (NLT) involves bonding shaped timber pieces together with their long edges placed side by side using nails. This engineered wood material, created through mechanical lamination, is suitable for use in floors, roofs, and walls of buildings.

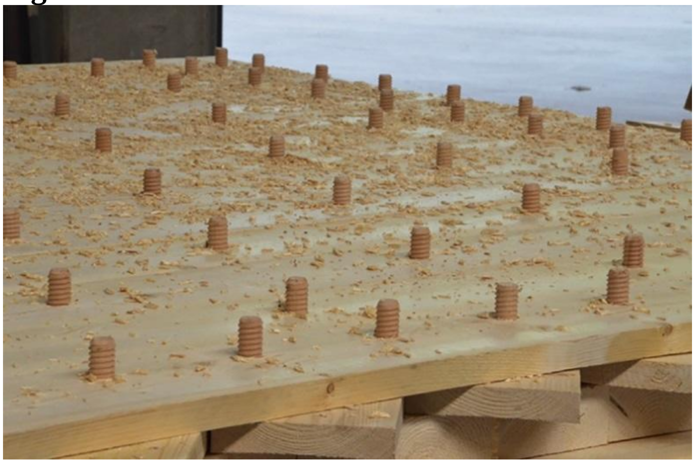
One significant advantage of NLT, compared to other types of laminated wood, is that it does not require specialized production facilities or equipment. NLT systems can be assembled on-site using basic carpentry techniques and locally sourced wood species. Another advantage of NLT is its long history of use in buildings for over a century, which means that engineering requirements and details are well supported by building codes and standards (Abed et al. 2022).

NLT offers a versatile and accessible solution for structural applications, leveraging traditional carpentry skills and readily available wood types to meet construction needs effectively.

### *Dowel Laminated Timber (DLT)*

Dowel Laminated Timber (DLT) is a layered wood product that is widely used in Europe but is slowly gaining acceptance in North America and other countries. The manufacturing of DLT employs a concept similar to NLT, but instead of nails or screws, wooden dowels are used (see Figure 2). In the production of DLT panels, multiple boards of softwood lumber are placed edge-to-edge and joined together using hardwood dowels. These hardwood dowels expand into the surrounding lumber to achieve moisture equilibrium, creating a tight friction fit that enhances the dimensional stability of the panel.

**Figure 2.** *Dowel Laminated Timber Panels*



*Source:* Soyato et al. 2020.

DLT panels are typically manufactured using CNC machines, automating the process and producing a highly consistent product that is safer than traditional manufacturing methods (Sotayo et al. 2020).

Unlike layered wood products such as CLT and GLT that use adhesives, which can emit toxic gases like formaldehyde and Volatile Organic Compounds (VOCs), DLT products do not use these chemical compounds. This absence of chemicals improves indoor air quality, reduces the risk of allergic reactions, and creates a healthier indoor environment. Furthermore, by eliminating adhesives and metal connectors, DLT facilitates easier recycling and reuse of wood materials (Sotayo et al. 2020).

### *Structural Composite Lumber (SCL)*

Structural Composite Lumber (SCL) is obtained by combining small wood pieces to create a single structural member. The two main types of SCL products widely used in construction projects are Laminated Veneer Lumber (LVL) and Laminated Strand Lumber (LSL) (Stark et al. 2010).

LVL was developed in the 1970s and is manufactured by bonding thin sliced wood veneers under high heat and pressure. Before lamination, the wood is dried and the grains are oriented parallel to the member's length. LSL is very similar to LVL but uses timber strands instead of veneers (Stark et al. 2010).

These SCL products are suitable for residential construction and can be used in various structural applications including beams, columns, and roof joists. However, they are not suitable for tall buildings and are generally more appropriate for low-rise construction projects.

## Mass Timber Structures & Design Considerations

Buildings constructed with mass timber can be categorized based on the types of structural materials (timber, concrete and steel). According to the structural material, mass timber structures are classified under four headings:

- All-timber structures.
- Concrete-timber hybrid structures.
- Steel-timber hybrid structures.
- Concrete-steel-timber hybrid structures.

In all-timber structures, all horizontal and vertical structural elements are made of wood. Non-wooden connection elements can be used at the joints of these wooden load-bearing elements.

A single-material tall building, whether made of steel, concrete, or timber, primarily uses one material for its main structural components. Secondary flooring materials do not affect this primary structural classification. This approach aligns with current guidelines for defining tall buildings, such as those with concrete floors on steel beams in steel structures (Foster et al. 2017). Alternatively, concrete floor slabs can be used in an all-timber structure. One of the most well-known examples of this type of structure is the Treet Building in Bergen, Norway (see Figure 3) (Safarik et al. 2022).

**Figure 3.** *Treet building, Bergen-Norway*

*Source:* Foster et al. 2017.

In Concrete-Timber Hybrid Structures, building structure combine concrete and timber elements to form the primary structural framework. Typically consisting of a wooden frame and a reinforced concrete core. Another type of these structures involves concrete slabs being constructed as wood. Currently, the tallest concrete-timber hybrid building is the 84-meter tall, 24-story HoHo Building located in Vienna, Austria.

In Steel-Timber Hybrid Structures, the vertical and horizontal load-bearing elements are steel. These steel elements are typically combined with steel-frame cores or perimeter frames, complemented by wooden floor and wall systems. Currently, the tallest steel-wood hybrid building is the Sara Kulturhus mixed-use building located in Skelleftea, Sweden (Safarik et al. 2022).

Concrete-Steel-Timber Hybrid Structures, utilize a blend of all three materials for primary load-bearing purposes. A common configuration includes a concrete core supported by steel beams and columns, along with timber flooring and partition walls, although numerous variations are possible. The tallest known concrete-steel-timber hybrid building is De Karel Doorman in Rotterdam, Netherlands, standing at 71 meters and 22 floors. This structure predominantly comprises a lightweight hybrid tower erected atop an existing department store from 1951 (see Figure 4) (Safarik et al. 2022).

**Figure 4.** *De Karel Doorman Building in Rotterdam, Netherlands*

*Source:* Safarik et al. 2022.

Using mass timber structural elements, different framing systems can be created. The typical timber framing options are post and beam, point-supported panels, wall and panel, and preassembled/modular systems. Each system has its own strengths and weaknesses. Therefore, designers need to thoroughly evaluate the specific requirements and limitations of their project to decide on the most advantageous framing system for their application (see Table 1).

**Table 1.** *Each Framing System is Suitable for Various Building Types. Pros and Cons are Outlined to Highlight Crucial Design Considerations.*

| **Framing Systems** | | | |
|---|---|---|---|
| **Post and Beam** | **Point-Supported Panels** | **Wall and Panel** | **Modular** |
| **Applications** | | | |
| High-end, multi-unit residential<br>Commercial office<br>Amenity floors, conference rooms, lobbies | Cellular, multi-unit residential<br>(student residences, hotels, small apartments) | Multi-unit residential | Small room, multi-unit residential (student residences, hotels, small apartments) |
| **Examples** | | | |
| 2150 Keith Drive, Vancouver<br>25 King, Brisbane<br>Mostarnet, Brumunddal, Norway | Brock Commons Tallwood House,<br>Vancouver | Dalston Works, London<br>Stadthaus, London | Sara Kulturhus, Skelleftea<br>Treet, Bergen, Norway |
| **Pros** | | | |
| Commonly used, design/analysis/ construction is well understood due to practitioners' prior experience on low- to mid-rise buildings<br>Enables large grid spacings | Very quick installation time<br>Thin structural floor assembly<br>Uncluttered soffit for easy service distribution | Partition walls are utilized as structural elements<br>Thin structural floor assembly | Quick installation<br>Prefabrication leads to high degree of quality control |

| **Cons** | | | |
|---|---|---|---|
| Deeper structural floor assembly requires greater floor-to-floor heights<br>Routing services through/under/ around beams can be a challenge• | Narrow column spacing constrains programming<br>Requires stacked floor plans<br>Very dependent on supplier panel dimensions<br>Lack of structural redundancy<br>Gaps in code guidance on punching shear for CLT panels | Generally, not suitable for buildings in seismic regions, as wall elements behave as shear walls, which is not ideal<br>Difficult detailing to accommodate shrinkage due to platform framing | Limited suppliers<br>Custom connection detailing<br>Integration with lateral systems is challenging |

*Source:* Wood et al. 2023.

During the design of timber systems, minimizing the number of components where possible, planning simply assembled connections in advance, and ensuring premanufactured parts are accurately prepared are crucial for saving time. In other words, production and assembly details should be predetermined.

Vertical movement in the structural frame is one of the most important considerations in the design of tall timber structures. Factors such as moisture fluctuation, elastic shortening, creep, joint slip, and fabrication tolerance all need to be taken into account. Vertical movements within the structure can lead to differential settlements, causing issues at door and window alignments or even cracks in the structure.

## Case Studies

In this section of the study, the highest 5 mass timber buildings of today, namely Ascent (2022), Mjostarnet (2019), HoHo Wien (2020), Haut (2022), Sara Kulturhus (2021) have been examined.

**Table 2.** *Case Study Buildings*

| Building | Location | Completion Year | Building Function | Height (m) | Number of Floors | Structural Material | Structural Classification | Total Mass Timber Volume |
|---|---|---|---|---|---|---|---|---|
| Ascent | Milwaukee USA | 2022 | Residential | 86.6 | 25 | Mass Timber Concrete | Concrete-Timber Hybrid over Concrete | 7,371 $m^3$ |
| Mjostarnet | Brumunddal Norway | 2019 | Mixed-Use | 85.4 | 18 | Mass Timber Concrete | All-Timber | 2,654 $m^3$ |
| HoHo Wien | Vienna Austria | 2020 | Mixed-Use | 84.0 | 24 | Mass Timber Concrete | Concrete-Timber Hybrid | 4,633 $m^3$ |
| HAUT | Amsterdam Netherlands | 2022 | Residential | 73.0 | 22 | Mass Timber Concrete | Concrete-Timber Hybrid | - |
| Sara Kulturhus | Skelleftea Sweden | 2021 | Mixed-Use | 72.8 | 19 | Mass Timber Concrete Steel | All-Timber over Steel-Timber Hybrid | 12,022 $m^3$ |

### *Ascent Building, Milwaukee-USA, 2022*

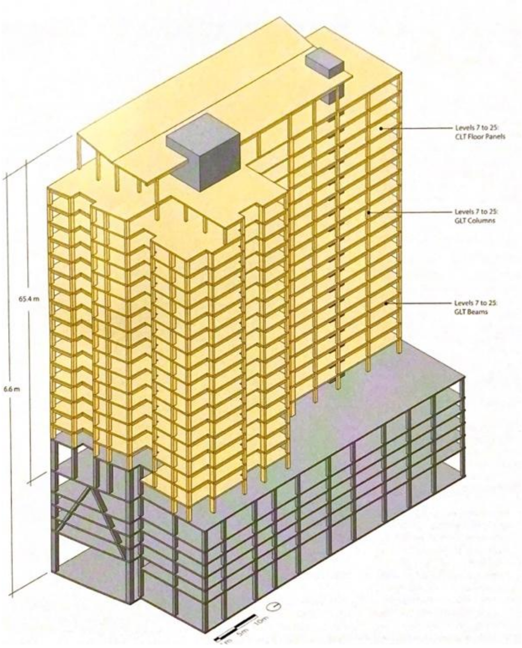
Completed in 2022, Ascent in Milwaukee, United States, is a 25-story residential building. It stands at a height of 86.6 meters and is currently the tallest timber structure (see Figure 5). The ground floor of the building includes a lobby, rental spaces, offices, a bicycle park, storage, and mechanical rooms. Floors 2 through 6 are dedicated to vehicle parking. The 7th floor features a swimming pool, a health center, and some residential units. Residential units occupy floors 8 to 24, with the 25th floor serving as the rooftop.

**Figure 5.** *Ascent Building. Ascent Building, Milwaukee-USA, 2022*

*Source:* Gokhman 2021.

In this concrete-timber hybrid structure, the first 7 floors feature a reinforced concrete structural system, while floors 8 to 24 use mass timber. The building incorporates a reinforced concrete core, which provides horizontal load resistance throughout. Mass timber structure begins at the 8th floor, where each floor features 64 GLT mass timber columns (see Figure 6).

**Figure 6.** *Isometric Diagram Illustrating the Structural System, Depicting the Interplay among the Concrete Structure, GLT Columns and Beams, CLT Floor Panels, and Concrete Core*



*Source:* Wood et al. 2023.

The primary mass timber structure, featuring glulam beams and columns along with one-way spanning Cross-Laminated Timber (CLT) slabs made from Austrian spruce, extends above the reinforced concrete podium starting at level 7. For high-rise projects, efficiency in structural design across multiple floors is crucial for cost-effectiveness.

In mass timber construction, one-way spanning framing systems typically require column grids spaced approximately 4.5-6.1 meters x 6.1-7.6 meters to achieve economical design. While mass timber can span even larger distances, exceeding these dimensions results in deeper beams and thicker floor panels, significantly increasing costs. Therefore, Ascent opted for a standard residential column grid of around 5.2 meters wide with alternating lengths of 6.1 meters to 7.6 meters, ensuring efficient floor assemblies with 5-ply CLT floor panels while maintaining structural integrity and cost-effectiveness (Fernandez et al. 2020). Column dimensions range from 361x480 mm to 701x678 mm, decreasing in size as the vertical load decreases with increasing floor height. GLT mass timber is also used for beams, with beam heights varying based on load distribution. CLT panels are used for the building's floors (see Table 3).

**Table 3.** *Ascent Structural System Details*

| Ascent Structural System | | Structural System Material | Mass Timber Product Thickness/Height/Lenght | Mass Timber Product Dimensions |
|---|---|---|---|---|
| Concrete-Timber Hybrid over Concrete | Core System | Levels 1 to 25: Concrete | | |
| | Floors | Levels 1 to 7: Concrete<br>Levels 7 to 25: CLT | Floors: 5-ply 180-230 mm<br>Roof: 5-ply 140 mm | 2.3x10.5 m |
| | Columns | Levels 1 to 7: Concrete<br>Levels 7 to 25: CLT | Height: 3.2 m | No typical column size; 16 different columns per level |
| | Beams | Levels 1 to 7: Concrete<br>Levels 7 to 25: CLT | Lenght: 6.1 m | No typical beam size; 29 different beam sizes per level |

*Mjostarnet, Brumunddal-Norway, 2019*

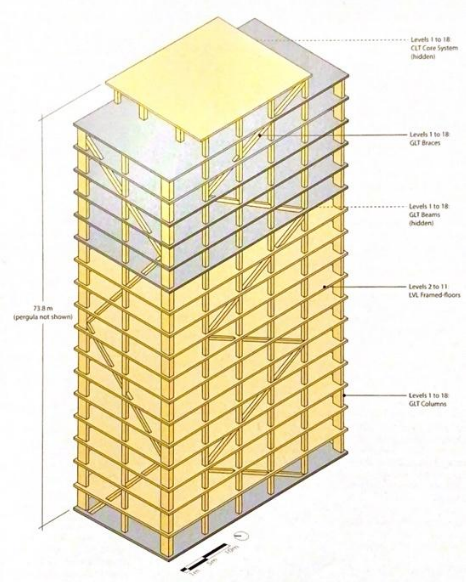
The Mjøstårnet, standing at 85.4 meters tall with 18 floors, is the tallest all-timber structure. It was completed in 2019 and is located in Brumunddal, Norway. This mixed-use building includes restaurants, offices, a hotel, apartments, a conference center, and a rooftop terrace. The footprint of the building, measured from the outer corners, is 16.3 meters by 36.9 meters (Liven and Abrahamsen 2023).

**Figure 7.** *Mjostarnet, Brumunddal-Norway, 2019*

*Source:* Safarik et al. 2022.

The primary structure consists of GLT columns and beams with diagonals in the building perimeter. Between the 2nd and 11th floors, a cassette system is used where GLT beams and laminated veneer lumber (LVL) panels are glued together. Between the 12th and 18th floors, a floor slab is created by pouring 300 mm of concrete into precast wooden molds. This composite floor, combining wood and concrete, increases the building's weight to limit swaying under wind loads. CLT panels are used in the core of the structure, and balconies are formed with CLT panels on floors 12 to 17.

**Figure 8.** *An Isometric Diagram of Mjøstårnet's Structural System Illustrates the Relationship between the Foundation, Pre-Assembled Timber Frame System, and tra8*



*Source:* Wood et al. 2023.

The GLT column-beam frame forms the primary system providing strength against vertical and horizontal loads. CLT is used for secondary load bearing in the staircases and elevator shafts, and is not structurally connected to the GLT frame. The maximum horizontal deflection at the 18th floor level of the building is 140 mm.

Column spacing is 6.5 m in the short direction and 7.1 m in the long direction. Column dimensions vary throughout the building: 725x810 mm on floors 1-4; 675-720 mm on floors 5-13; and 625-630 mm on floors 14-17. Beam lengths are 3.9 m around the perimeter of the building and 5.8 m in interior spaces. Beam sizes also vary across the structure: 395x675 mm for interior beams on floors 1 and 10, and 625x439 mm for perimeter beams; 625x720 mm for interior beams on floors 11-17, and 625x585 mm for perimeter beams. The typical cross-sectional dimension is 625x990 mm (see Table 4).

**Table 4.** *Mjostarnet Structural System Details*

| **Mjostarnet Structural System** | | **Structural System Material** | **Mass Timber Product Thickness/Height/ Lenght** | **Mass Timber Product Dimensions** |
|---|---|---|---|---|
| All-Timber Structural System | Core System | CLT Core | | |
| | Floors | Level 1: Cast-in-place concrete<br>Levels 2 to 11: Tra8 casette system<br>Levels 12 to 18: 300 mm concrete | - | Module lenght: 6.5 to 7.3 m |
| | Columns | Level 1-18: GLT columns | Height: 15-19 m | Levels 1 to 4: 725x810 mm<br>Levels 5 to 13: 675x720 mm<br>Levels 14 to 17: 625x630 mm |
| | Beams | Level 1-18: GLT beams | Lenght:<br>5.8 m (inner)<br>3.9 m (perimeter) | Levels 1 to 10:<br>395x675 mm (interior)<br>625x429 mm (perimeter)<br>Levels 11 to 17:<br>625x720 mm (interior)<br>625x585 mm (perimeter) |
| | Walls | Cross-Laminated Timber (CLT) | Panel Thickness: 120-240 mm | Panel dimensions:<br>Walls: 1.4 to 2.9 x6.8 to 11.3 m<br>Balconies: 2.3 x 5.4 to 7.6 m |

### *HoHo Wien, Vienna-Austria, 2020*

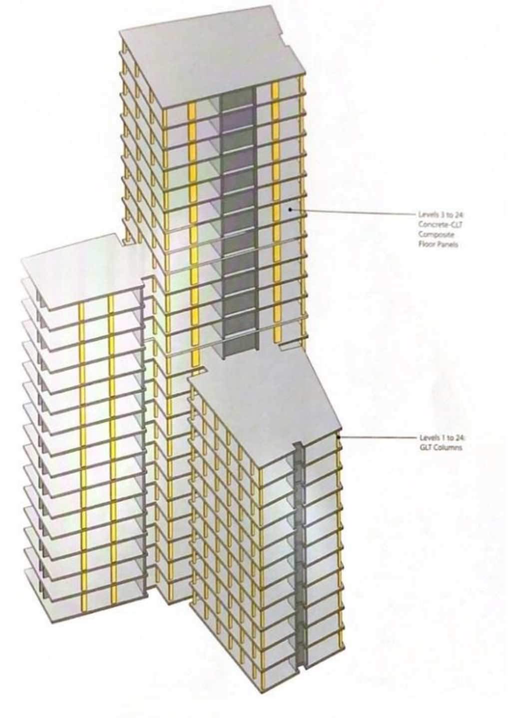
HoHo Wien, completed in 2019 in Vienna, Austria, consists of a 24-story tower reaching 84 meters in height, along with two adjacent towers measuring 57 meters and 40 meters in height (see Figure 9).

**Figure 9.** *HoHo Wien, Vienna-Austria, 2020*

*Source:* Safarik et al. 2022.

HoHo Wien utilizes a concrete-timber hybrid system comprising a concrete core, shear wall system, and timber frame.

**Figure 9.** *An Isometric Diagram of HoHo Wien's Structural System Illustrates the Interplay between the Concrete Core, Shear Walls, and Prefabricated Floor Panels*



*Source:* Wood et al. 2023.

On the 1st to 5th floors of the building, there are a lobby, restaurant, wellness center, and beauty center. The 6th to 10th floors are used as offices; the 10th to 19th floors function as a hotel. The 20th to 23rd floors house serviced suites, while the 24th floor is dedicated to technical facilities. The aim of the system design was to create a flexible, simple, and repeatable module that facilitates relatively easy transformation and modification of programs. One of the main motivations in the project was to showcase wood prominently. GLT columns, CLT walls, and ceilings are left uncovered throughout all units. In addition, some small details such as the inner edges of window jambs are also made of wood.

The building's floors use prefabricated panels. These panels are 2.4 meters wide and 7 meters long. They are composed of a combination of 160 mm CLT panels and a 120 mm concrete layer. These floor panels are supported by concrete beams located on top of GLT columns. The height of the GLT columns is 3.5 meters, with varying dimensions (see Table 5). The concrete beams of the structure are precast, providing both time savings and ease of manufacturing. The longest distance between the structure's perimeter and the core is 7 meters.

**Table 5.** *HoHo Wien Structural System Details*

| **HoHo Wien Structural System** | | **Structural System Material** | **Mass Timber Product Thickness/Height/Lenght** | **Mass Timber Product Dimensions** |
|---|---|---|---|---|
| Concrete -Timber Hybrid | Core System | Cast-in-place reinforced concrete | | |
| | Floors | Levels -2 to 1: cast-in-place reinforced concrete<br>Levels 2 to 24: X-Lam Concrete (XC) system (concrete over CLT system) | Panel Thickness: 160 mm | Panel dimensions: 2.4 x 7 m |
| | Columns | Levels 1 to 24: GLT columns | Height: 3.5 m | 400 x (320-1080) mm |
| | Beams | Levels 2 to 24: Precast concrete edge beams | - | - |
| | Walls | Concrete shear wall system | Wall Thickness: 140 mm | 4.8 x 3.5 m |

CLT panels used on the walls had waterproof membranes applied to their outer surfaces before being transported from the factory to the construction site. Additionally, all exposed surfaces of the timber elements were wrapped in plastic before being lifted into place by crane, with the plastic removed just before lifting.

In this project, a total of 4000 cubic meters of wood was used, including open ceilings, columns, and exterior walls. Compared to a similarly scaled traditional concrete structure, choosing wood resulted in approximately 3000 metric tons of carbon dioxide equivalent saved.

### *HAUT, Amsterdam-Netherlands, 2022*

Haut is a residential building located in Amsterdam, standing 21 stories tall with a height of 73 meters. Situated alongside the Amstel River on the edge of Amsterdam city center, the design process prioritized providing residents with expansive views and vistas (see Figure 10). The architectural concept of Haut focuses on transparency in its façade, aiming to offer ample sunlight and unobstructed urban and natural views to its residents (Linders 2024).

**Figure 10.** *HAUT, Amsterdam-Netherlands, 2022*

*Source:* Linders 2024.

During the structural system design, braced frames or CLT panels were not preferred to ensure facade transparency and the active role of perimeter walls in load distribution. Load-bearing walls were chosen instead, positioned within the structure to also act as partitions between residential units. GLT beams were used along the building perimeter (see Figure 11). The floors consist of prefabricated timber-concrete composite (TCC) panels. (Verhaegh et al. 2020).

**Figure 11.** *An Isometric Diagram of HAUT Structural System*

*Source:* Verhaegh et al. 2020.

In the building, most of the floor slabs are supported on one side by a reinforced concrete shear wall and on the other side by a timber wall or beam. Concrete and timber are two materials with different mechanical properties. The difference in these properties will lead to differential movements between the two materials. Therefore, detailed studies/analyses have been conducted regarding potential differential movements in the structure. The maximum calculated differential shortening between the reinforced concrete core and the CLT wall is 20 mm. This value can also be observed in other buildings of similar height where mass timber is not used (Verhaegh et al. 2020).

**Table 6.** *HAUT's Structural System Details*

| HAUT Structural System | | Structural System Material | Mass Timber Product Thickness/Height/Length | Mass Timber Product Dimensions |
|---|---|---|---|---|
| Concrete-Timber Hybrid | Core System | Cast-in-place reinforced concrete | - | - |
| | Floors | CLT | Panel Thickness: 160 mm<br>80 mm concrete top layer | - |
| | Columns | GLT | - | - |
| | Beams | GLT | - | - |

*Sara Kulturhus, Skelleftea-Sweden, 2021*

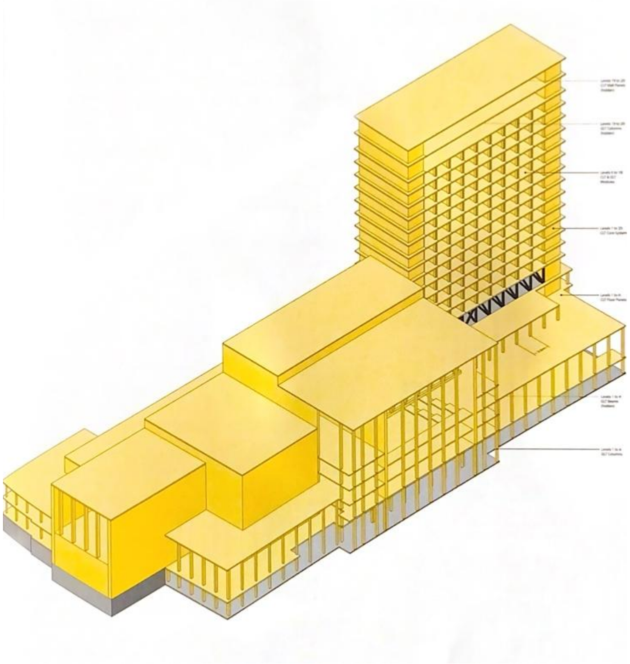
Sara Kulturhus is a 20-story, mixed-use building located in Skelleftea, Sweden. The usage purposes of the spaces within the building vary significantly. The ground floor of the building includes the lobby of the hotel section and the entrance to the cultural center. The 2nd and 3rd floors house a theater. The 4th floor accommodates a conference center, while technical spaces are located on the 5th floor. Floors 6 to 18 are dedicated to the hotel, and the 19th and 20th floors are used for a restaurant and spa.

**Figure 12.** *Sara Kulturhus, Skelleftea-Sweden, 2021*

*Source:* Safarik et al. 2022.

The structure is complex due to the diversity in the structural system of the program. The hotel section, which rises above conference and performance centers requiring large spans without vertical supports within the space, is a significant design point in determining the structural system. The structure's system is created by combining 2 different primary wood systems. In the low-rise podium section of the structure, GLT columns and beams are used in conjunction with CLT cores and shear walls. The high-rise section of the structure consists of prefabricated CLT modules positioned between cores containing vertical circulation elements (see Figure 13).

**Figure 13.** *An Isometric Diagram of HAUT Structural System*



*Source:* Wood et al. 2023.

The reinforced concrete basement floor houses the service areas of the theater. Floors 1 to 4 accommodate the spaces of the cultural center, including the theater and conference center. This section of the building, which requires large spans, has a structural system consisting of columns, beams, and platforms. GLT columns, beams, trusses, and CLT shear walls ranging from 140 to 160 mm in thickness. GLT columns of varying dimensions form a 3.6x7.2 m grid plan (excluding the theater and lobby sections). The largest columns measure 845 mm x 645 mm.

On Level 2, lattice beams composed of GLT and steel tension and compression rods allow spanning of 13.5 m openings. The upper chords and columns of these flat lattice beams are GLT, while the diagonal rods and lower chord are steel. The connection points of the steel elements are concealed within the GLT columns.

Level 5 is constructed from steel truss boxes. The beams of these steel boxes are H-section steel beams, and the columns and diagonals are various sizes of box columns. This floor accommodates mechanical spaces and serves as the base for the hotel floors.

From Levels 6 through 18, prefabricated hotel modules made from CLT panels are positioned within the GLT column-beam frame system located between cores at the two short edges of the plan. The prefabricated modules consist of GLT columns and 140 mm thick CLT panels. The CLT panels used in the flooring include two layers of 20 mm thick mineral wool for fire protection, a 13 mm thick double-layer gypsum board panel, 22 mm thick particle board, and an 8 mm thick floor covering. Ceilings feature a 100 mm insulation layer and a 100 mm CLT panel (See Table 7).

On the 19th and 20th floors where the hotel restaurant and span are located, a combination of steel columns, GLT columns, GLT shear walls, and concrete flooring is used. This allows for larger spans compared to the hotel floors.

**Table 7.** *Sara Kulturhus Structural System Details*

| **Sara Kulturhus Structural System** | | **Structural System Material** | **Mass Timber Product Thickness/Height/Lenght** | **Mass Timber Product Dimensions** |
|---|---|---|---|---|
| Steel-Timber Hybrid | Core System | CLT | Thickness: 5-ply CLT 255 mm | |
| | Floors | Levels -1 to 1, 5, 19 to 20: concrete floors<br>Levels 2 to 4, 6 to 18: CLT floors | Cultural Center floors: 140 mm<br>Hotel ceiling: 5-ply CLT 100 mm<br>Hotel floors: 5-ply 140 mm<br>Roofs: 5-ply 160 mm | |
| | Columns | Levels 1, 5, 19 to 20: steel columns<br>Levels 1 to 4, 19 to 20: GLT columns | Height: 3.2 m | Hotel: 215 x 400 mm |
| | Beams | Levels 1 to 4, 19 to 20: GLT beams<br>Level 5: Steel box truss<br>Level 19 to 20: Steel beams | - | - |
| | Prefabricated modules | Levels 6 to 18: GLT and CLT modules | | |

## Discussion

Tallest five timber buildings worldwide reveal significant advancements and trends in the use of timber as a primary construction material for high-rise structures. Timber's strength-to-weight ratio and sustainability attributes have been leveraged to create efficient and aesthetically pleasing structures. Additionally, hybrid systems integrating timber with other materials like steel and concrete have been utilized to enhance structural performance and address specific design challenges such as large spans and vertical loads.

Looking forward, the findings from this investigation suggest opportunities for further research and development in tall timber construction. Innovations in material science, construction techniques, and digital technologies are poised to unlock new possibilities for taller and more sustainable timber buildings. Addressing technical challenges and enhancing industry collaboration will be crucial in realizing the full potential of timber as a viable alternative in high-rise construction.

Moreover, the environmental benefits associated with timber construction are noteworthy. Timber buildings sequester carbon dioxide during their lifecycle, contributing to carbon neutrality and mitigating the environmental impact of urban development. This aspect is increasingly significant in the context of sustainable urban planning and the global effort to combat climate change.

However, fire resistance, legal regulations and economic concerns were left out of scope for this study. Fire safety remains a critical concern, despite advancements in fire-resistant timber treatments and construction techniques. Building codes and regulations often necessitate rigorous testing and certification to ensure compliance with safety standards, adding complexity and cost to timber projects. The economic feasibility of tall timber buildings compared to traditional materials is another area of ongoing research and debate. While timber construction can offer cost savings in certain contexts, initial investment costs and market acceptance may pose barriers to widespread adoption.

In conclusion, the investigation into the tallest five timber buildings highlights both the achievements and the ongoing challenges in advancing timber as a primary construction material for tall buildings. As urban populations grow and environmental concerns intensify, the role of timber in sustainable urban development is poised to expand, driven by continuous innovation and collaboration across disciplines.

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