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# Advances in Tall Building Design for Sustainable Architecture and Vertical Urbanism: The Case of Mass Timber Structures

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**Abstract** Tall wood buildings of the 21st century are a new breed in the evolution of skyscrapers that originated in the late 19th century. Nonetheless, the contribution of employing mass timber in tall buildings of large scales could be significant to sustainable architecture and vertical urbanism. This paper provides an introductory review of today's tall mass timber buildings. While a holistic review is carried out, emphasis is placed on structural design with mass timber for tall buildings and its performance. Not only all timber but also various hybrid timber systems, such as timber-concrete, timber-steel, and timber-concrete-steel hybrids, are presented with case studies. Supertall mass timber buildings are also discussed as a future of this new breed of skyscrapers.

**Keywords** Tall Buildings, Mass Timber, Cross Laminated Timber (CLT), Glued Laminated Timber, All Timber, Timber-Concrete Hybrid, Timber-Steel Hybrid, Timber-Concrete-Steel Hybrid, Sustainable Architecture, Sustainable Vertical Urbanism.

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## 1. Introduction

Tall Buildings emerged in the late 19th century as office towers of about 10 stories. In order to make constructing tall buildings of unprecedented heights possible structurally, iron columns and masonry walls were typically used as primary vertical structures for the interior and perimeter respectively, as were the cases with the Equitable Building of 1870, Western Union Building and Tribune Building of 1875, all in New York. However, using masonry structure for the perimeter of tall buildings was a serious limitation of building taller because of the extreme thickness of the masonry walls on lower levels. Since the 10-story tall Home Insurance Building of 1885 in Chicago, which used iron/steel frame structures not only in its interior but also on its streetfront for the first time, steel frames began to replace the iron/masonry hybrid construction of early tall buildings. Another material that began to be used for tall buildings was reinforced concrete since the Ingalls Building of 1903, while the predominantly used structural materials for early tall buildings in the early 20th century were still structural steel that led to the world's first supertall Chrysler Building of 1930 and the world's first building of over 100 stories, Empire State Building of 1931, both in New York.

Today, primary structural systems for many tall buildings are continuously constructed with steel, reinforced concrete, or both (composite). At the same time, as sustainable design and construction have become more important than ever these days, wood, which was not traditionally used for tall building structures, has been increasingly employed.

While wood is one of the oldest building materials, its use has predominantly been limited to low-rise buildings. With the developments of mass timber products, such as GLT (Glued Laminated Timber) and CLT (Cross Laminated Timber), the potential of wood as advanced materials for buildings including tall buildings has been significantly enhanced. GLT was originally introduced more than a century ago (Rhude, 1996). When CLT was also developed about a century later in the early 1990s (Karacabeyli & Douglas, 2013), mass timber as structural material for tall buildings was theoretically ready. GLT can create frame members such as columns and girders/beams while CLT or comparable mass timber products can produce shear walls and floor slabs.

Eventually, tall mass timber buildings have been increasingly designed and constructed since the 9-story tall Stadthaus of 2009 in London. Stadthaus was the first 9-story building whose structural system is constructed with mass timber, CLT. As happened at the early stage of tall building developments with structural steel in the late 19th century and early 20th century, the heights of tall buildings with mass timber in recent years have also been increasing. The tallest mass timber building at present is the 25-story tall (86.6 m) Ascent of 2022 in Milwaukee.

The structural design of tall buildings is typically governed by lateral stiffness. Compared to steel or concrete, the modules of elasticity of mass timber are smaller in

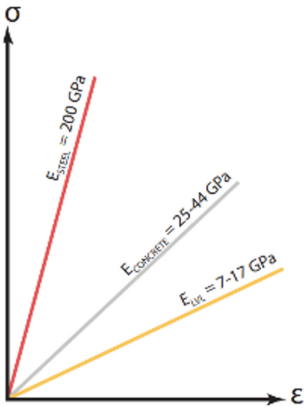



**Figure 1.** Relative elasticity of steel, concrete, and LVL (Laminated Veneer Lumber). © Thornton Tomasetti

general (Figure 1). Therefore, building taller and taller with only mass timber can cause design limitations. In order to overcome this, steel or/and reinforced concrete is/are combined with mass timber, producing hybrid structures. In many cases of hybrid systems, in fact, steel or reinforced concrete is used for their primary lateral load-resisting system while mass timber is employed for the primary gravity system as well as the secondary lateral load resisting system in some cases. The height race of tall buildings with mass timber today is based on these hybrid structures in most cases. For instance, the Ascent employed timber-concrete hybrid structure in which concrete provides the primary lateral load resisting core while mass timber produces the primary gravity system.

From a structural viewpoint, tall buildings are a building type whose structural design is governed by lateral wind loads in many cases. Therefore, historically, when defining and determining the first skyscraper, its primary lateral load-resisting system and the material for it was so important and this led to ceaseless continued debates even today. In a similar sense, many tall mass timber buildings today might be arguable when their height ranks are determined because mass timber does not participate in creating the primary lateral load-resisting system in most hybrid systems. However, the focus of this paper is not on this but understanding today's tall mass timber buildings including hybrids as global architectural efforts towards a more sustainable future.

The tallest all timber building at present is the 18-story tall (85.8 m) Mjøstårnet of 2019 in Brumunddal. In order to make this significant height with all mass timber possible, this building has some substantial "vanity height" at the top. The tallest timber-steel hybrid building is the 20-story tall (84.0 m) Sara Kulturhus of 2021 in Skellefteå, and the tallest timber-concrete-steel building is the 22-story tall (73 m) HAUT of 2022 in Amsterdam.

Due to the limitation of all timber buildings as briefly discussed, the economic height of all timber buildings is limited and therefore it is expected that taller timber buildings in the future will be more hybrid structures. The timeline of the completion of tall timber buildings shows that the number of hybrid tall buildings has been continuously increasing (Figure 2). The typical story heights of all timber buildings range from about 8 to 10 stories, while taller mass timber buildings are built with hybrid structures.

This paper presents the design and construction of tall mass timber buildings of various categories, i.e., all timber, timber-concrete, timber-steel, and timber-concrete-steel hybrids. Each category's characteristics and design/performance considerations are discussed with case study buildings.

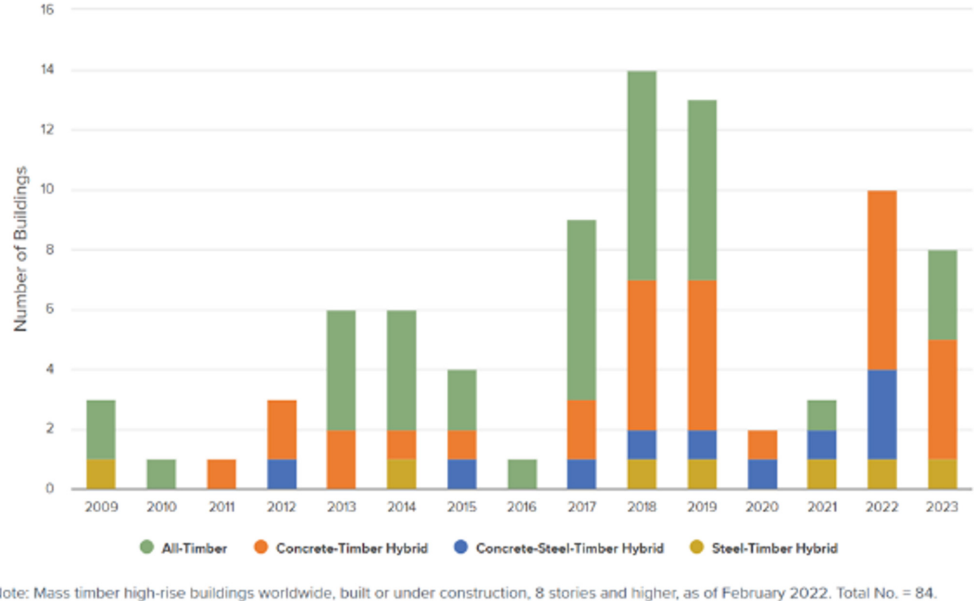



**Figure 2.** Timeline of tall mass timber completions. © CTBUH

As early tall buildings of about 10 stories with structural steel in the late 19th century rapidly evolved to supertall buildings in the early 20th century, tall mass timber buildings that also began from about 10-story buildings are expected to reach the supertall height in the foreseeable future with hybrid structures. For example, W350 Project by Japan's Sumitomo Forestry is expected to reach the height of 350 m by 2041. This paper also discusses the future of tall timber buildings.

In terms of global footprints, Europe and North America have the largest number of tall mass timber buildings, while other regions have limited developments though the interest in tall timber buildings increases almost globally. One of the most significant sustainable features of using wood in tall buildings is reducing carbon footprint as the building and construction are responsible for a very large amount of carbon emissions globally. However, using timber for constructing tall timber buildings itself is not a good solution for global carbon reduction. Sustainable forest management including replanting is essential once trees are cut down for buildings.

## 2. All Timber

The earliest example of tall mass timber buildings is the Stadthaus (Murray Grove, Figure 3) as presented briefly in the introduction. This 9-story residential building is structured with CLT walls and floor slabs. The application of CLT panels worked well with residential floor planning that required many demising walls within as well as between the units in this building.

While CLT walls can be designed to perform as gravity load bearing walls as well as lateral load carrying shear walls, wall structures can limit the spatial organization of the buildings. Frame structures with columns and girders/beams instead can be an option that can provide more flexible floor planning without obstructions by wall structures. However, while frame structures require rigid connections between the vertical and horizontal members to resist lateral loads, it is very difficult to make rigid connections between the frame members of mass timber, e.g., GLT columns and girders.

In the 18-story tall (85.4 m) mixed-use Mjøstårnet in Brumunddal, Norway, mass timber braced frames are used as its primary structural system with added CLT shear walls for its core area (Figure 4). By adding GLT bracings to the orthogonal frames composed also of GLT columns and girders, a primary lateral load resisting system is produced in this building. Braced frames do not require rigid connections between the members to perform as intended, while the braced frames with no shear walls are especially beneficial for buildings with programs that prefer structural wall-free floor plans, such as offices, large conference rooms, etc., as is the case with the Mjøstårnet that contains these programs. In Mjøstårnet with a rectangular floor plan, the four corner columns are about two times larger than the other columns to produce



**Figure 3.** Stadthaus. © Will Pryce



**Figure 4.** Mjøstårnet. © Nina Rundsveen/Moelven (left) © Ricardo/Moelven (right)

greater resistance against overturning moments. Prefabricated wooden panels are used for the facades.

Mass timber is very light structural material. Therefore, using mass timber for tall buildings is advantageous in reducing the size and consequently cost of foundations. However, lightness is not always good structurally. In the Mjøstårnet, floors 12 through 18 are composed of 300 mm thick concrete slabs to add mass primarily to better control wind-induced lateral vibration of the building. By adding mass, excessive acceleration can be reduced for the comforts of occupants. The other stories are composed mostly of lighter LVL framed floors with 50 mm concrete screed on top.

In the 14-story tall (49.0 m) residential Treet in Bergen, also in Norway, a similar mass timber braced frame composed of GLT columns and girders is employed as its primary structural system (Figure 5). This building also has added CLT shear walls to its core area. However, the Treet has its unique story height transfer trusses typically on every five floors in addition to the diagonal bracings

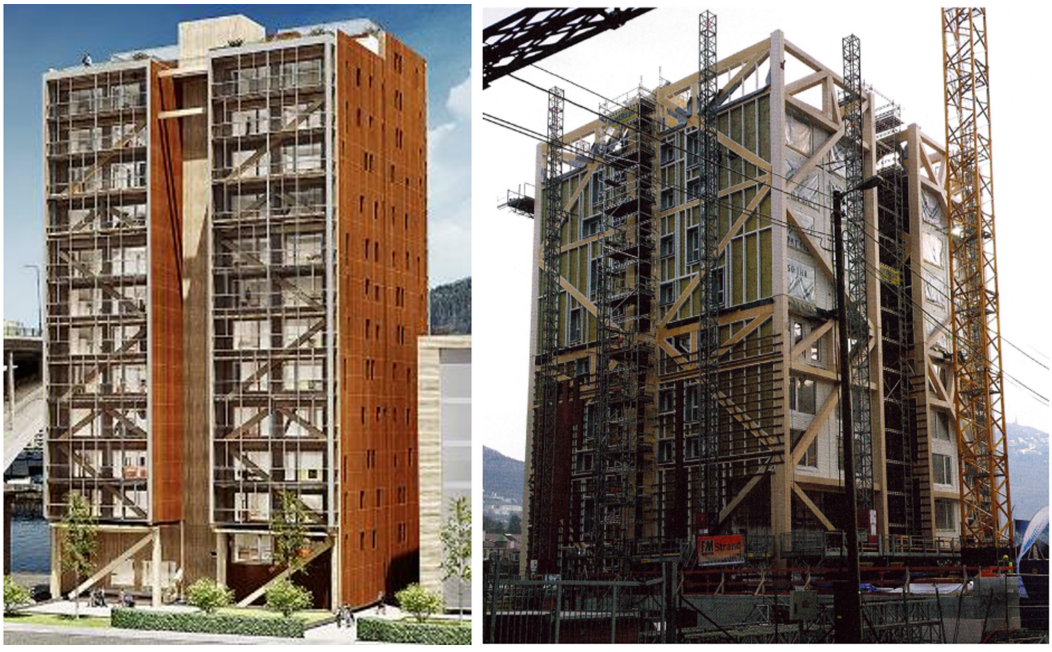


**Figure 5.** Treet. © BOB

that braces five story tall braced frame modules. The Treet's unique mass timber braced frame structure with transfer trusses was configured to accommodate prefabricated modular construction. The building was originally conceived as a residential tower composed of stacked modular units. As stacking all 14 stories was not a feasible solution, its unique structural configuration was developed with mass timber. Beyond the initial stacking on the ground level, modules above are stacked on the transfer floors supported by the transfer trusses so that the gravity loads from the stacked modules on the transfer floors can be transferred directly to the foundation, not to the stacked modules below. Despite the differences, the Treet and Mjøstårnet have similarities in their structural design. The SWECO participated in the structural design of both buildings, and this explains the similarities.

## 3. Timber-Concrete Hybrids

Timber-concrete hybrids are widely used for tall mass timber buildings. In this hybrid, typically, reinforced concrete core structures perform as primary lateral load resisting systems and mass timber structures around the cores carry gravity loads. This configuration is similar to prevalently used conventional structural systems for tall buildings, concrete core and steel or concrete gravity system around the core. As steel or concrete gravity systems are replaced with mass timber, timber-concrete hybrid structures are produced.

In the 18-story tall (58 m) residential (student housing) Brock Commons Tallwood House of 2017 in Vancouver, the lateral load resisting system is composed of two reinforced concrete cores (Figure 6). The gravity system comprises GLT or PSL (Parallel Strand Lumber) columns with CLT floor without any girders or beams. This gravity system with mass timber is similar to plat plate system with reinforced concrete and performs very efficiently for the residential program requiring relatively shallow ceiling height with no obstructions by girders or beams. Despite the extensive use of mass timber except for the concrete cores, exposing timber is very limited in this building due to the code requirements.

The mixed-use HoHo Wien of 2020 in Vienna is composed of three connected towers. The tallest one is 24-story tall (84 m) and the other two towers are 57 m and 40 m tall. This project uses more concrete than most other timber-concrete hybrid system buildings. Different from the Brock Commons without girders/beams, the HoHo Wien uses concrete girders on top of GLT gravity columns to support the floor system. Typical floors are also composed of 120 mm thick concrete slab with 160 mm CLT beneath. While concrete is more extensively used in this building than typical timber-concrete hybrids, this project exposes timber as much as possible including its CLT facades and ceiling.

The 25-story tall (86.6 M) Ascent of 2022 in Milwaukee is the tallest mass timber tower in the world at present (Figure 8). Lower floors from the ground to level 7 are reinforced concrete structures and the typical timber-concrete hybrid configuration begins from level 8 to the



**Figure 6.** Brock Commons Tallwood House. © naturallywood.com



**Figure 7.** HoHo Wien. © cetus Baudevelopment + kito.at



**Figure 8.** Ascent. © Nairn Okler (left) & © Jason Korb (right)

top. The main programs for the lower 7 floors are the ground level lobby, parking garage from level 2 through 6, and swimming pool on level 7. The parking garage and swimming pool work better with reinforced concrete structure than mass timber. The typical hybrid portion employes concrete core to resist lateral loads and GLT columns/girders and CLT floors to carry gravity loads. Timber is exposed as much as possible in the interior of the residential units. While the building façades are metal/glass curtainwalls in order not to directly expose timber in the interior to the outdoor climate condition of Milwaukee, the timber from the interior is still visually exposed through the vision glass panel portions of the curtainwalls.

## 4. Timber-Steel Hybrids

As discussed previously, all-timber tall buildings can be built efficiently up to around 10 stories and there are many built examples of that height range, while hybrid structures including concrete and/or steel are employed in taller buildings typically. For the Carbon 12 apartment building in Oregon, despite its story height of only 8 stories, timber-steel hybrid structure was employed (Figure 9). This



**Figure 9.** Carbon 12. © KAISER+PATH

is primarily because this building is in a seismic zone. BRB (Buckling Restrained Brace) is employed for the braces of the steel braced core of the building to better resist seismic loads. In the BRB system, the steel diagonal braces are encased by stiff metal tubes to prevent buckling of the braces when they are in compression mode. As the buckling of the braces is prevented during the seismic movements that lead to the steel braces to yield, hysteretic damping is provided instead of buckling-induced collapse.

The 20-story Sara Kulturhus of 2021 in Skellefteå is the tallest timber-steel hybrid in the world at present at its height of 84.0 m (Figure 10). In typical hybrid timber structures, steel or concrete are employed for primary lateral load resisting system. However, in Sara Kulturhus, CLT shear walls for the two cores at both ends of the tower are used as the primary lateral load resisting system. Structural steel is used to produce massive transfer trusses between the programs requiring different structural grids. The steel box trusses at level five transfer the gravity loads from the hotel floors above to the GLT columns below located along the two longitudinal perimeter lines of the tower portion. (Note that these GLT columns are not actually perimeter columns below the transfer trusses because there exist large low-rise podium portion around the tower beyond the column lines. See Figure 10.)

The transfer trusses are necessary because the hotel floors above the trusses have double loaded central corridors and there are gravity columns along both sides of the corridor while these columns must not extend below the trusses due to the program requirement of the cultural center. The hotel rooms above the transfer trusses are prefabricated units with CLT panels and GLT columns along the four vertical edges of the rectangular box units and stacked vertically. Among the four columns in each unit, two columns define the perimeter and the other two that define the corridor walls must not extend below the transfer trusses so that they do not interrupt the cultural center program.

The sustainable feature of the Sara Kulturhus is emphasized by one of the architects of the project Schmitz. "Embodied carbon emissions from materials, transport and construction as well as carbon emissions from operational energy during 50 years are less than the carbon sequestration in wood within the building. This is why we claim that the building is carbon negative." Note that as discussed briefly previously, his explanation must be understood including the sustainable forest management including the replanting without which carbon negative concept is impossible.

Due to the mass timber's lightness that makes transportation and installation easier, stacking mass-timber-prefabricated units is a feasible solution as are the cases with the Sara Kulturhus and Treet. Different structural strategies, however, were used in these projects, while the story heights of the stacked portions of the projects are similar. The gravity load carrying frame members are parts of the units in the former and therefore the units can be stacked directly over 10 stories without additional structural system. In the latter, however, the stacked units are in a sense rectangular box structures and therefore braced mega-frames of five story tall modules were constructed first to stack the units within the mega-frame modules.

## 5. Timber-Concrete-Steel Hybrids

Timber is lighter structural material than steel or concrete. Therefore, mass timber is sometimes employed



**Figure 10.** Sara Kulturhus. © Martinsons | Jonas Westling

to add more floors vertically relying on the lightness of the material on top of existing structures as are the case with De Karel Doorman and the 55 Southbank Boulevard.

De Karel Doorman of 2012 in Rotterdam is a mixed-use timber-concrete-steel hybrid at its height of 84 m. It is a 22-story building and mass timber is used from level 7 through 22. De Karel Doorman was constructed on top of an existing local landmark building, Ter Meulen of 1951. Therefore, the selection of mass timber as its primary floor structure to carry gravity loads was determined to be the most feasible solution due to its lightness. Consequently, added structural elements to the existing structure could be minimized to support the vertical extension. Steel columns and beams were used for the extension to connect the new steel frames above with the existing concrete structure below. Reinforced concrete cores were added to carry lateral loads primarily as well as gravity loads partially. This overall configuration resulted in timber-concrete-steel hybrid (Figure 11).

The 55 Southbank Boulevard of 2020 in Melbourne is




**Figure 11.** De Karel Doorman. © www.ibelingsvantilburg.nl



**Figure 12.** 55 Southbank Boulevard. © Peter Clarke (left) © Bates Smart (right)

another example of employing mass timber to reduce the weight of the structure for vertical extension of an existing building. The existing structure at 55 Southbank Boulevard was a six-story office building constructed in 1989. When 220 hotel rooms were planned to be added on top of the existing structure, 10 more hotel room floors were required. Reinforced concrete was not a good option as it could add only six floors, while employing mass timber could add the targeted 10 more floors according to the project engineer. Eventually, the existing concrete core was strengthened and extended vertically with steel structures to carry lateral loads primarily. In addition to the core, CLT shear walls were added structurally as well as architecturally because the CLT walls also perform as demising walls between the hotel rooms. The flooring system is done with CLT panels. A new concrete raft was designed and constructed under the new hotel room floors to transfer the load to the existing structure with different structural configuration. This timber-concrete-steel hybrid structure was possible without adding new piles (Figure 12). In order to maintain the overall aesthetics of the existing building, the timber hybrid extension was also clad with the reflective glass facades.

The 22-story tall (73 m) residential HAUT of 2022 in

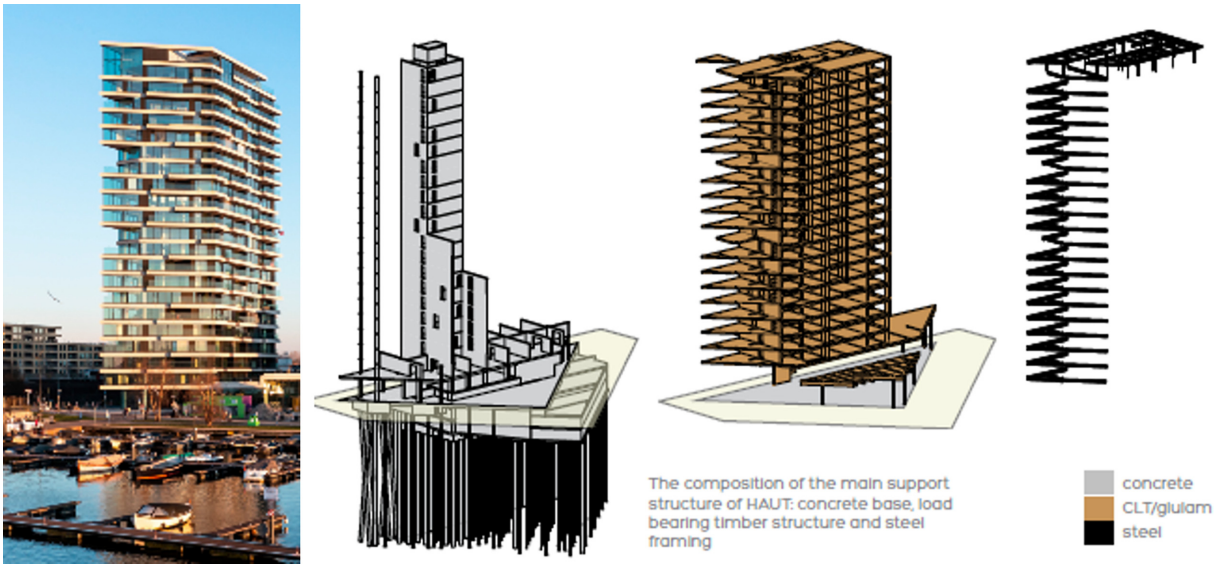



**Figure 13.** HAUT. © Arup

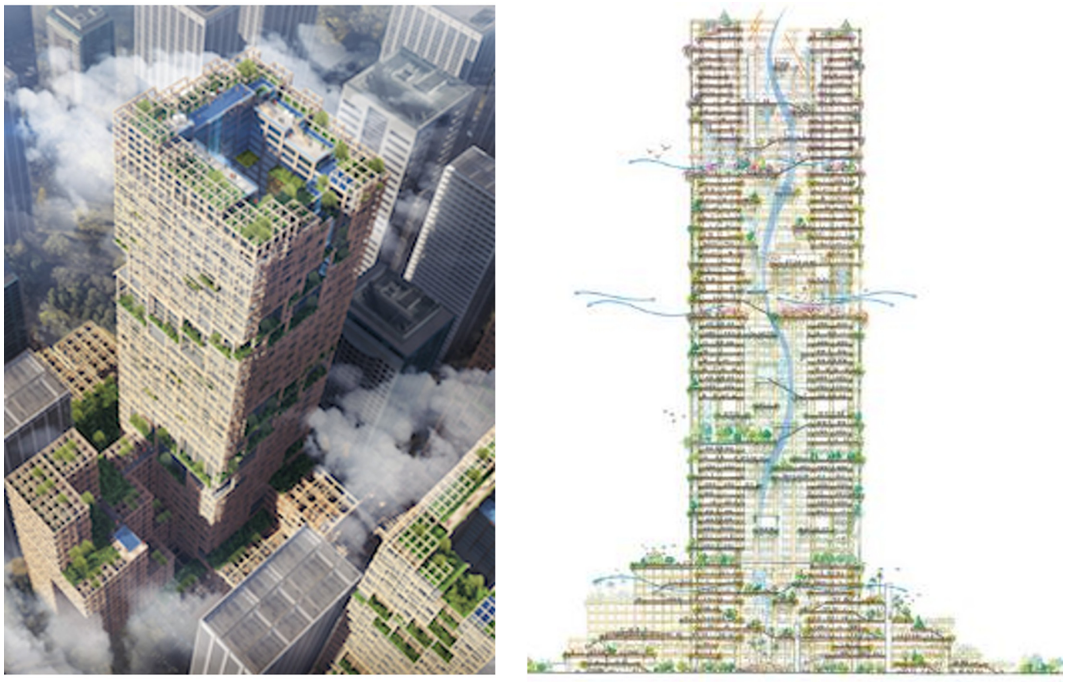


**Figure 14.** W350. © Sumimoto Forestry & Nikken Sekkei



**Figure 15.** Timber-concrete-steel hybrid supertall design project developed in the YSOA tall building design class taught by the author. (3D and preliminary structural module concept model)

Amsterdam is another example of timber-concrete-steel hybrid. Different from De Karel Doorman and the 55 South Bank Boulevard, this is a new building, not extension of an existing building. The overall structural configuration of the HAUT is in fact similar to typical newly built timber-concrete hybrid structures (Figure 13). The primary lateral load resisting system is the reinforced concrete core and CLT shear walls. The flooring system is composed of 160 mm-deep CLT panels and 80 mm concrete on top of them. As this residential building, however, has many cantilever balconies, steel was added as another structural material to support them due to its great stiffness over timber.

## 6. Supertall/Megatall Mass Timber

For sustainable architecture and vertical urbanism, the use of timber in tall buildings has been increasing continuously. Many mass timber hybrid buildings taller than the current tallest Ascent have been proposed or under construction including the 42-story tall (182.6 m) timber-concrete-steel hybrid Atlasian Central in Sydney. Even the supertall, W350, has been proposed for Tokyo (Figure 14). As the early steel tall buildings of around 10 stories evolved to the steel supertalls within less than five

decades, it is expected that timber hybrid structures will also reach the supertall height in the near future especially due to their significant sustainable contribution.

In the tall building design class taught by the author at the Yale School of Architecture (YSOA), a team of two graduate students developed a supertall timber-concrete-steel hybrid mixed use building for the lakefront of Chicago (Figure 15). At its height of over 450 m, this building has been proposed as the tallest building in Chicago. Braced mega-tube type structure, which is similar to what was envisioned by Fazlur Khan as the most efficient structural system for tall buildings, is developed with reinforced concrete and steel as the primary lateral load resisting system. Its braced mega-tube module height between the transfer trusses is about 20 stories. Mass timber structures of the module height are designed as inserted structures within the modules and their gravity loads are transferred to the foundation through the transfer trusses and mega-columns.

## 7. Conclusion

Today, as sustainable design is becoming more and more important than ever, the potential of mass timber as one of the most sustainable building materials has been explored extensively beginning from Europe and now globally. The impact of sustainable design and construction becomes more significant as the scale of buildings is larger. Tall buildings are “urban giants” and their impact on contribution to creating more sustainable architecture, cities, and globe is also gigantic.

This paper has reviewed the current status of using mass timber in tall buildings. Mass timber tall buildings began from all timber tall buildings of about 10 stories. As their heights become taller, the feasibility of all timber is reduced due to the limitation of the material in its structural properties. The efforts to overcome this limitation has led to various mass timber hybrid systems as discussed in this paper.

As mass timber tall buildings were not anticipated until recently, it is difficult to predict the future of tall buildings. As the pursuit for creating a more sustainable world will clearly be continued and even accelerated, however, the future cities are expected to have more and more sustainable tall buildings including mass timber ones. With further research and design studies, even the tallest buildings can be designed and constructed with mass timber, contributing to create a more sustainable world, indeed.

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