CTBUH Research Report

Steel-Timber Hybrid Buildings: Case Studies

Daniel Safarik, Will Miranda & Shea Anthony

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Front Cover: (clockwise from top left) Billie Jean King Main Library corner connection detail © SOM; Houston Endowment HQ hybrid roof system © Kevin Daly Architects, photo by Iwan Baan; Sara Kulturhuus connection detail between the steel box truss and the GLT column below. © Martinsons I Jonas Westling; 843 North Spring Street special concentric braced frame © LEVER Architecture

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Steering Committee

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Preface

At the heart of sustainable urban development lies the challenge of reimagining construction—an industry historically characterized by significant environmental footprints and resource-intensive practices. This research project, conceived against the backdrop of the global climate crisis, seeks to illuminate a more sustainable, resilient, and cost-effective path through the development of steel-timber hybrid buildings.

The quest for sustainable construction materials has never been more critical. Steel and timber, each with their unique properties and environmental implications, present themselves as viable contenders. However, it is the innovative fusion of these materials into hybrid structures that this study considers a transformative approach to construction. Optimal combinations of these materials stand to reduce carbon emissions compared to conventional approaches, while adding additional architectural appeal.

Embarking on this exploratory journey required a multifaceted methodological approach, analyzing of case studies across varied design scenarios. The exploration of six pioneering case studies ranged in height from two to 20 stories, and encompassed myriad programs, including residential, hotel, office, and civic/cultural. However, this exercise also uncovered a critical gap in the industry's readiness to fully embrace these innovations at scale. The absence of consistent, transparent data on both cost and carbon impact highlights a significant barrier to informed decision-making. This lack of clarity, coupled with the challenges presented by current design and analysis software, underscores the necessity for systemic change within the construction sector.

To harness the full potential of steel-timber hybrid construction, a multi-pronged approach is necessary. First and foremost, the industry must overcome its historical resistance to change, requiring the involvement and good will of all stakeholders, and for architects and engineers to be willing to think "outside the box" and examine solutions from all angles. To support this, further greater transparency and data sharing, enabling a more informed and nuanced understanding of the economic ramifications of construction choices, is important. Governmental bodies and industry associations can play a crucial role in this transition, through increased research funding.

The potential of steel-timber hybrid buildings to redefine urban landscapes is immense, but realizing this potential requires a concerted effort across all facets of the construction ecosystem. From policymakers to practitioners, and from software developers to sustainability advocates, collaboration and commitment to change are essential.

1.0 Introduction

1.1 Background of Steel-Timber Hybrid Buildings

The Emergence of Hybrid Structures

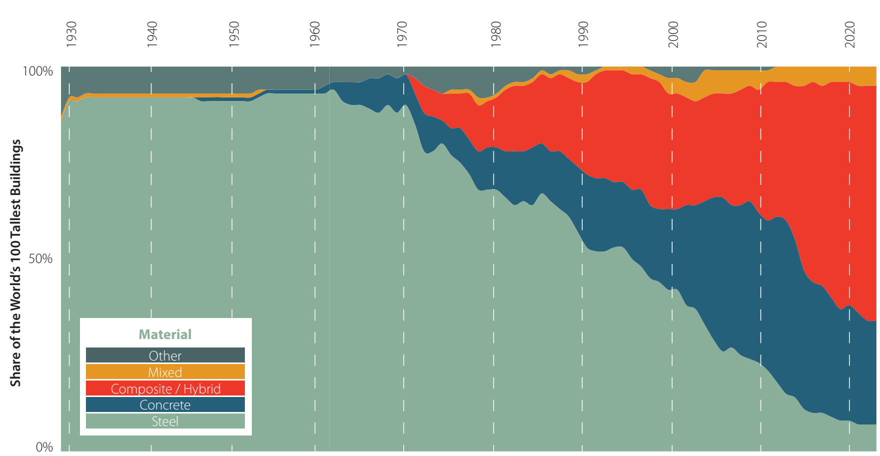
Since the birth of the tall building in the late 1800s, steel-framed structures have been the dominant building system, taking advantage of the rigidity of the material and ability to achieve great spans and heights. All-steel structures made up 94 of the world's 100 tallest buildings as recently as 1963, but with the more recent emergence of composite materials, also referred to as hybrid structures, as well as all-concrete structures, all-steel structures only make up seven of the 100 tallest buildings, as of 2023 (see Figure 1.1.1)

CTBUH defines composite, or hybrid structures, as a combination of two or more materials (e.g., steel, concrete, timber) used together in the main structural elements. This is different from mixed-structure buildings, which CTBUH defines as structures that utilize distinct systems, one on top of the other. Since 1974, when the first hybrid buildings entered the 100-tallest list, the share of these structures has been growing, and in 2023, hybrid structures made up 61 of the 100, with the remainder made up of five mixed-structure buildings and 27 all-concrete structures, along with the all-steel buildings. Even going beyond the 100-tallest buildings, since 2000, 60 percent of all supertall buildings, or buildings 300 meters or greater, have been built with hybrid structures. This trend is expected to continue, with 80 percent of all supertalls expected to be hybrid structures by 2030 (see Figure 1.1.2).

Impact of Region and Function

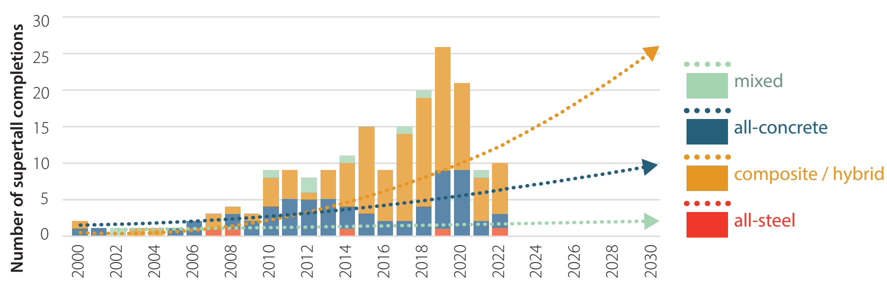
There are numerous influences that could have dictated the trend away from a majority of all-steel structures in the 20th century 100-tallest lists, with hybrid structures and all-concrete now dominating the rankings. This trend could be due to the parallel shift of predominant functions and locations for the tallest buildings in the world. Like all-steel structures, single-function, all-office buildings made up most of the 100-tallest buildings throughout the 20th century, peaking at 93 of the 100 tallest buildings in 1992. Since that point, the share of single-function, all-office buildings has steadily declined, with mixed-use buildings making up the majority of the 100 tallest buildings in 2020 and holding that status with 51 of the 100-tallest buildings in 2023. CTBUH defines a "mixed-use" tall building as containing two or more functions, where each of the functions occupies a significant proportion of the tower's total space, judged as 15 percent or greater of either: (1) the total floor area, or (2) the total building height, in terms of number of floors occupied for the function. These mixed-use buildings, even if inclusive of office space, often also feature residential and/or hotel space, and with the more "cellular" nature of these internal spaces (e.g., that require physical, acoustic, and fire separation), compared against the open-plan nature of typical offices, concrete or hybrid construction may be perceived as a more suitable structural selection (see Figure 1.1.3).

Similarly, North America housed most of the 100 tallest buildings in the 20th century, peaking at 93 of the 100 tallest buildings in 1973 and maintaining the majority share until 2000. Growth of tall building construction in Asia, and to a lesser extent, the Middle East, meant

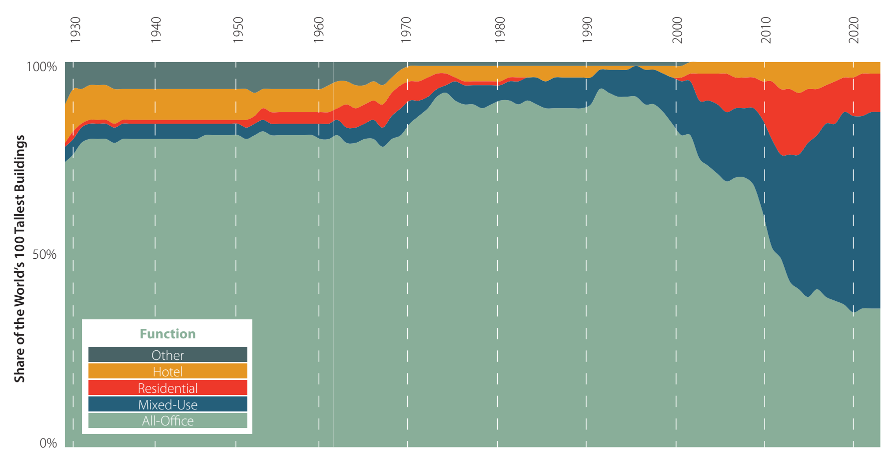


▲ Figure 1.1.1. The share of structural material typologies in the world's 100 tallest buildings, 1930–2023. © CTBUH that by 2016 Asia overtook the majority share of the 100 tallest buildings. By 2023, 61 of the 100 tallest buildings were located in Asia, 19 were in the Middle East, and only 15 were in North America (with the remaining five located in Europe). The reduction in the prevalence of all-steel structures during a similar time period, could be due in part to buildings being constructed in regions where the competence and capacity in production and assembly of steel structural materials may not be as advanced as alternative materials or combinations of materials (see Figure 1.1.4) (Work 2023).

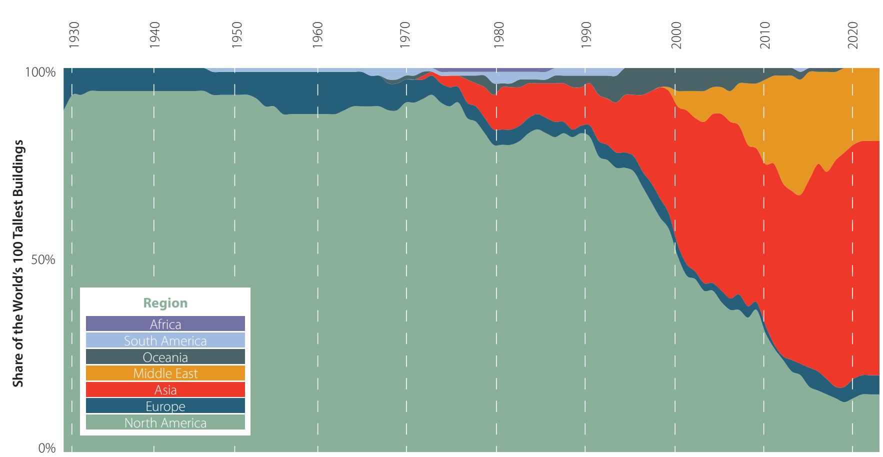
Bringing Mass Timber into the Equation
Concurrent with the global tall building industry's shift away from all-steel, all-office buildings towards hybrid-structured, mixed-use buildings, the beginning of the 21st century also saw the emergence of mass timber as a building material for multistory buildings. As a new building material, there was not an aspiration to heights comparable to those being achieved at this time by all-steel, all-concrete, and concrete-steel hybrid structures. With that said, the history of the first multistory buildings using mass timber in their structure is not dissimilar to the history of the first tall buildings made of all-steel frames at the beginning of the 20th century (see Chapter 1.2). There are several aspects that have motivated the decision to integrate mass timber elements into the design of multistory building structures, but perhaps the most crucial to its growing utilization and recent popularity are the environmental sustainability benefits.



▲ Figure 1.1.2. Trends in structural material typologies for supertall (300 m+) building completions, 2000–2030. © CTBUH



▲ Figure 1.1.3. The share of building functions in the world's 100 tallest buildings, 1930–2023. © CTBUH



▲ Figure 1.1.4. The regional spread of the world's 100 tallest buildings, 1930–2023. © CTBUH

The building industry accounts for approximately 39 percent of the world's energy- and process-related carbon dioxide emissions, and while a large portion of this goes towards the operation of existing buildings, about 11 percent of all emissions resulted from the construction industry and manufacturing of building construction materials, such as steel, cement, and glass (Miranda 2021). Steel and concrete, which have historically been the dominant structural materials for tall buildings, and have been heavily reliant on fossil fuels to produce; However, modern practices of steel production and a high degree of recycling have provided significant improvements to its sustainability, making the steel-timber hybrid approach appealing. A Basic Oxygen Furnace (BOF), also known as a "blast furnace," in which hot air is blown across molten pig iron to oxidize material and separate impurities, accounts for about 71 percent of the world's steel production (wordsteel 2024). An Electric Arc Furnace (EAF) melts steel scrap using the heat generated by a high-powered electric arc. During the melting process, elements are added to achieve the correct chemistry, and oxygen is blown into the furnace to purify the steel. Steel produced in electric arc furnaces (EAFs), representing about 29 percent of global production, can have as much as 100 percent recycled content; the average recycled content of hot-rolled structural shapes is 93 percent. Regardless of origin, it has always been the case that steel is 100 percent recyclable. Some 98 percent of structural steel by weight is recovered and recycled (AISC 2017).

In general, mass timber is less energy-, heat-, or chemical-intensive to grow than what is required to produce other materials, with most energy demands going towards kiln-drying in preparation for use. The savings in emissions achieved during the production of mass timber is supported by timber's ability to sequester carbon, by absorbing carbon as the timber grows and, consequently, removing carbon from the environment. The carbon absorbed as the tree grows is subsequently stored within the timber. Timber structural elements will eventually reach their "end-of-life" and the stored carbon will be released either through incineration or through decomposition. But the same elements can potentially be reused through the practical lifespans of several buildings.

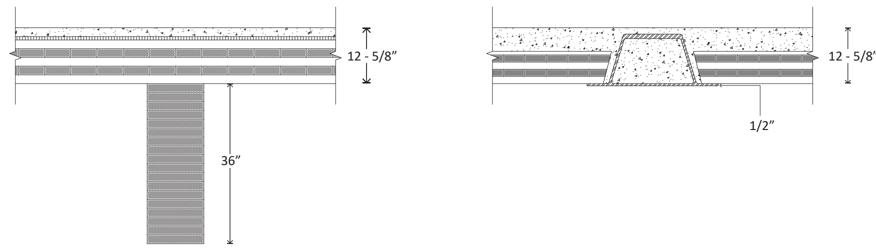
In addition to the savings in emissions that could possibly be achieved during the material production, life cycle assessment (LCA) studies conducted on mass timber buildings, compared against more conventional or traditional structural materials, have shown that the usage of mass timber can further reduce the overall carbon emissions throughout the stages of the building's life, from resource extraction, to processing, transportation, maintenance, and eventual recycling/disposal (Wood et al. 2023).

The end-of-life impact of timber depends heavily on the chosen scenario. If timber is burnt and the energy is recovered, the end-of-life impact is low. The biogenic carbon is released back to the atmosphere and no longer "offsets" the embodied carbon emissions. However, when including the substitution effects (typically reported in Module D of life cycle analysis), use of this biofuel to offset fossil fuels can show additional benefits.

Landfilled timber's uncontrolled decomposition produces methane, a greenhouse gas with 25 times the global warming potential (GWP) of carbon dioxide. However, landfilling wood can result in the highest level of permanent biogenic carbon storage because, on average, 88 percent of the biogenic carbon remains permanently stored in anaerobic landfills (EPA 2024). Oftentimes, landfill gases are captured and used for energy to further offset fossil-based energy; at a minimum, methane gas is often captured and flared to convert it back into CO_2 emissions to reduce its GWP impact. Even when accounting for the higher impact of methane that is released back to the atmosphere, the assumption that wood products end up in a landfill typically results in the lowest GWP impact within the LCA system boundary (A1–C4).

As with the use of any material, the outcome of a steel-timber hybrid design can be dependent on the building typology and other criteria, such as fire-resistance and vibration requirements, the required span distance acoustics, and so on.

With the environmental benefits that mass timber presents, there is interest in adopting this material into tall building structures, potentially reducing the share of emissions directly caused by the construction industry and manufacturing of building construction materials. However, due to the lightweight and flexible nature of mass timber, compared to other conventional structural materials in the tallest buildings, it is generally thought that having timber act in symbiosis with steel will allow the most flexibility in terms of achieving long spans and overall building heights demanded of dense urban environments. Likewise, the flammability of timber must be considered in the balance of material selection for structures.



▲ Figure 1.1.5. Comparing the thickness of a floor system requiring an 8-meter span using an all-timber system with beam support (left), with with a shallow-beam floor system (right). © Peikko

While there are difficulties that present themselves when utilizing mass timber in combination with other structural materials, the benefits have the potential to far outweigh any deterrents. With the building market demanding structures that are more sustainable, while programmatic needs are dictating larger internal spans and thinner floors, an argument can be made for steel-timber hybrid structures as an ideal solution for the future of new multistory construction.

The Benefits of Steel-Timber Hybrid Structures

As mentioned in the prior section, to achieve the heights and floor counts demanded of dense urban environments, mass timber optimally will work in collaboration with other structural materials. The popularity of structural steel products in the early 20th century was due in part due to their lightweight nature and ability to hold large forces (vertically and horizontally) over wide spans, with a relatively small profile. Steel was the ideal solution for the ever-growing need for office space, allowing deep floor plates with minimal vertical interruptions from columns (Trabucco 2015).

In addition to achieving the spans demanded of a modern tall building, particularly offices, the depth of the floor system also needs to be considered. Reducing the thickness of a floor system and horizontal structural elements can increase the internal floor-to-ceiling heights, giving occupants more spacious interiors. As floor-to-ceiling heights are often dictated by the building's programmatic requirements, a potentially more crucial benefit to reducing the floor-to-ceiling heights would be a reduction in the overall building's height. In multistory buildings, savings of a few centimeters per floor can have an exponential effect on the overall building's height. Certain regions and jurisdictions often dictate height restrictions due to aviation or zoning requirements, and sufficiently reducing the floor system thickness could allow additional floors to be added to the design, yielding significantly more lettable space, while still falling within the maximum height allowances. Even if the option to incorporate additional floors into the design is not pursued, a reduction in the thickness of the floor system, and subsequent reduction in the building height, directly impacts the overall project costs and carbon emissions.

For example, a shallow floor-beam system allows timber floor plates to sit within the flange of horizontal steel beams. In addition to taking advantage of a significantly reduced beam size, by using a steel beam compared to a timber glulam (GLT) beam, additional efficiencies in the floor system could be realized by integrating the floor spanning elements and MEP systems within the thickness of the profile of the steel itself. In a hypothetical office building, requiring an 8-meter (26.2-foot) span, a 75 percent reduction in the overall floor system's thickness could be achieved, saving almost a full meter per floor. A similar effect could be achieved with H-beams, arranged so that the timber panels rest on the lower flange or hollow sections, aided by a welded plate. Reducing the overall height of the building through more efficient floor systems means that all emissions and costs against

▲ Figure 1.1.6. 6 Orsman Road, completed in London in 2020, utilizes steel beams with mass timber floor plates, allowing exposed timber in the ceiling. © Waugh Thistleton Architects

▲ Figure 1.1.7. Atlassian Central, Sydney, is currently under construction and expected to be complete by 2026, when it is expected to reach a height of 182.6 meters and become the world's tallest concrete-steel-timber hybrid building. © Dexus

vertical elements in the building, such as the columns, wall finishes, and glazing, could also be reduced (see Figure 1.1.5) (Lemieux 2022).

According to Ricky McLain, Senior Technical Director, WoodWorks, "Really one of the main, if not the main reason, for choosing this system (steel-timber hybrid) was span-to-depth ratio. Being able to span much farther with the structural steel system, with potentially a shallower structural depth" (McLain 2022).

In tall buildings, horizontal elements such as the beams and floor slab systems account for most of the building's total weight. In a tall building, these floor systems are repeated many times on each floor; optimization of horizontal structures can reduce the quantity of structural materials, and their consequential total environmental emissions (Trabucco 2015).

In addition to the inherent environmental benefits of timber's ability to sequester and store carbon, one of these key drivers to incorporating timber is aesthetics, taking advantage of the natural qualities of the material. A common solution in steel-timber hybrid buildings that use steel framing elements, such as in 6 Orsman Road, a six-story office building in London (see Figure 1.1.6), is to utilize cross-laminated timber (CLT) panels in the floor plate system, allowing timber to be exposed in the ceiling.

Information on the benefits of exposed mass timber, especially in multistory buildings, is in its relative infancy and there is not sufficient, comparable data on speculative rent values for financing institutions to assess the benefits of higher investments to expose mass timber. But there are many anecdotal examples of commercial spaces that utilize mass timber, which have experienced faster leasing velocity and/or higher rents. Even with limited long-term data on leasing rates in mass timber buildings, the benefits of the biophilic qualities of mass timber can be measured, and the impact of the positive connection between humans and nature can be reported.

In studies monitoring the impact of biophilia on building occupants, spaces with mass timber exposed reported a more activated parasympathetic nervous system, which acts to reduce stress levels and regulate healing and recovery. Also, reduced blood pressure is reported in spaces with a higher ratio of wood cladding. Through surveying of commercial spaces, it is also reported that green spaces, plants, fresh air, and natural materials all produce calmer, happier, and less-stressed employees, which can translate to higher productivity, reduced absenteeism, and lower rates of turnover. People in workplaces with more than 20 percent wood surfaces express greater satisfaction with both their working life and their physical workspace (Wood et al. 2023).

More information on the benefits of utilizing mass timber can be found in the CTBUH Technical Guide, ***Tall Timber: Mass Timber for High-Rise Buildings,*** or at talltimbercenter.com.

Steel-Timber Hybrid Structural Strategies

Conventional steel-frame lateral systems that work with mass timber include concentric braced frames (CBFs), eccentric braced frames (EBFs), buckling-restrained braced frames (BRBs), and moment frames. Steel-frame lateral systems complement the "kit-of-parts" installation of mass timber and introduce the opportunity for a tightly sequenced installation.

Another multistory steel-timber hybrid strategy includes splitting the building into multiple blocks using belt trusses that are tied to the core using steel outrigger trusses. Using an outrigger system, combined with belt trusses, can provide excellent lateral stiffness, and mitigate the effects of wood column shortening. Furthermore, splitting up buildings into these "blocks" can facilitate taller buildings, by creating distinct code and fire zones within a building, addressed separately instead of holistically, such as the approach used at Atlassian Central, Sydney (see Figure 1.1.7) (Wood et al. 2023).

Due to the relative novelty of multistory steel-timber hybrid projects, extraction and reuse of specific timber and steel structural elements in buildings has yet to be fully developed and executed (Trabucco 2015). There are countless examples worldwide of timber elements being removed from one structure and reused in another, though not often in a structural role. Steel structural elements have also been reused for a very long time. Today it is challenging to achieve composite action (i.e. activating a mechanical link) between steel and timber; it can be seen as a beneficial outcome that most of the steel and timber parts of a structure can easily be dismantled, and hence steel and timber can be reused. (Charlier & Vassart 2023).

Further, new buildings can be designed to maximize the ability to sort, reuse, and recycle materials at the end of their life cycle, which largely can be achieved through Design for Manufacturing and Assembly (DfMA) exercises. This can be achieved through designs that use predominantly standardized, dimensional panels and elements, feature bolted or screwed connections, instead of welded connections, and in which openings for MEP elements and doorways/windows are reduced as much as possible, ensuring that uninterrupted structural elements could be extracted later (Wood et al. 2023).

Important Considerations for Steel-Timber Hybrids

While there are a multitude of benefits to be derived from the use of steel-timber hybrid structural systems in new

> "Most of the steel and timber parts of a structure can easily be dismantled, and hence steel and timber can be reused."

construction, as a building process that is still in its infancy, it must be considered that, while DfMA exercises can have advantages during the operation and end-of-life phases of the building, these exercises are predominantly executed to simplify and accelerate material sourcing and building assembly.

With steel-timber hybrid structures, up-front coordination is imperative, both in the design and construction phases.

In the design phase, early consultation with structural fire engineers is critical. The combustibility of the load-bearing materials may complicate the structural fire assessment due to the interaction between the fire dynamics and the structural system. Accordingly, combustible structural materials can constitute an increased level of fuel load (compared to the existing "movable fuel load"), which must be considered for structural fire calculations to ensure the building's stability and integrity during and after a fire.

As a consequence, it is fundamental to understand the implications of designing a combustible structure, which would help reduce the environmental impact of a building, but may introduce new fire safety hazards and possibly impact the resilience, sustainability, and robustness of the building design (Charlier & Lucherini 2024).

Likewise, in the construction phase, the project will require multiple fabricators and sometimes multiple contractors, with different levels of experience with hybrid approaches. During the process of producing the shop drawings, clarity and attention to detail is necessary, especially when considering details and connections between the two material types. In these connections, differences in tolerances and distinct material properties must be considered, especially when it comes to material movement: timber can expand or contract due to changes in moisture, while structural steel does not; structural steel can expand or contract due to changes in temperature, while timber will not. Where possible, it is also preferable to have the same installer execute both the timber and steel elements, to take advantage of sequenced scheduled deliveries and avoid any delays in one material's installation due to the impact of the other.

> "Differences in tolerances and distinct properties of steel and timber must be considered, especially when it comes to material movement."

Connection details are also important to executing the final aesthetics of the building as well. Often, one of the goals of incorporating mass timber is to take advantage of its biophilic properties, through exposing the timber in the building's interiors. As an element that is both structural and a final finished product, special attention must be paid to any exposed mass timber element during design and assembly to ensure that there is no damage. It is recommended that on-site welding connections are eliminated or reduced, especially in areas where the timber may be exposed, to avoid burn marks or heightened fire risk during assembly. In addition to concerns from on-site welding, moisture management also needs to be comprehensively planned in advance of the construction and assembly phase. As mentioned, these materials react differently to moisture and, in addition to material expansion and contraction, the final aesthetics of the product can be impacted. In addition to the visual damage that water can cause to structural timber elements, steel elements can experience rust when exposed to moisture. Even in cases where the steel will eventually be enclosed, the rust can stain the timber elements as well (McLain 2022).

Defining Hybrid, Composite, and Mixed Structures

As mentioned above, CTBUH defines hybrid, or composite, structures as buildings that include a combination of two or more materials (e.g., steel, concrete, timber) used together in the main structural elements, while mixed structures are in buildings that utilize distinct structural systems, one on top of the other. For the purposes of this publication, all buildings that utilize hybrid/composite structural systems will be indicated by "hybrid," preceded by the structural materials in use, listed alphabetically and separated by dashes (e.g., Steel-Timber Hybrid Structures; Concrete-Steel-Timber Hybrid Structures). Mixed structures will list both structural systems separately, listing the highest structural system first. For example, a "Steel-Timber Hybrid Over Concrete" designation indicates a steel and timber hybrid structural system located on top of an all-concrete structural system.

Combinations of hybrid and mixed structures are very common in buildings that utilize both structural

▲ **Figure 1.1.8. 55 Southbank, Melbourne, Australia adds a 10-floor, steel-timber hybrid hotel on top of an existing nine-story office.** © Peter Clarke

▲ **Figure 1.1.9. De Karel Doorman, Rotterdam, adds a 16-floor residential tower on top of a six-story department store.** © Ossip van Duivenbode steel and mass timber. In fact, 58 percent of all buildings that utilize both structural steel and mass timber, complete or under construction and six stories or higher, are both hybrid and mixed structures. In most cases, these instances are steel-timber or concrete-steel-timber hybrid structures that are located on top of one or two floors of an all-concrete podium. In two cases, the lightweight nature of steel and mass timber in combination is exploited, and hybrid-structured vertical extensions could be added on top of a preexisting all-concrete structure. A 10-floor, steel-timber hybrid hotel was added on top of an existing nine-story office building at 55 Southbank in Melbourne, Australia (see Figure 1.1.8 and Chapter 2.1).

De Karel Doorman in Rotterdam, Netherlands adds a 16-floor residential tower on top of a six-story department store (see Figure 1.1.9). More details on the breakdown of structural systems and trends for multistory, steel-timber or concrete-steel-timber hybrid buildings can be found in Chapter 1.3.

Steel-Timber Hybrid Structures
In steel-timber hybrid buildings, all above-ground vertical, floor spanning, and lateral-force-resisting structural elements must be constructed from timber, steel, or a combination of the two. This system will often consist of a lateral-force-resisting system that utilizes structural steel, such as steel-framed cores, buckling-restrained braces, perimeter-frame or exoskeleton steel bracing systems and a gravity system composed of columns and beams that interact with a timber floor or wall system. In cases where concrete is used on the floor system but is not structural and added for weight and/or acoustical reasons, this building would still be considered a steel-timber hybrid. The current tallest steel-timber hybrid building is Sara Kulturhus, a 73-meter mixed-use building in Skellefteå, Sweden (see Figure 1.1.10 and Chapter 2.9) (Wood et al. 2023).

A building that uses entirely timber elements, except for steel connections (steel plates, bolts, screws, nails) would not be considered a steel-timber hybrid. However, a building with timber gravity framing elements and steel lateral elements would count as a steel-timber hybrid, for example.

Concrete-Steel-Timber Hybrid Structures
In concrete-steel-timber hybrid buildings, all above-ground ground vertical, floor spanning, and lateral-force-resisting structural elements must be constructed from timber, steel, concrete or a combination of the three. The most typical combination would be a concrete core working in tandem with steel beams and columns, with timber flooring and partition walls, but many variations exist. The current tallest concrete-steel-timber hybrid building is the previously mentioned De Karel Doorman, in Rotterdam, at 71 meters. This title is expected to be surpassed by the upcoming Atlassian Central headquarters project in Sydney, currently under construction and expected to be complete by 2026, which is expected to reach a height of 182.6 meters (refer back to Figure 1.1.7). More details on significant steel-timber and concrete-steel-timber hybrid projects can be found in Chapter 1.2 (Wood 2023).

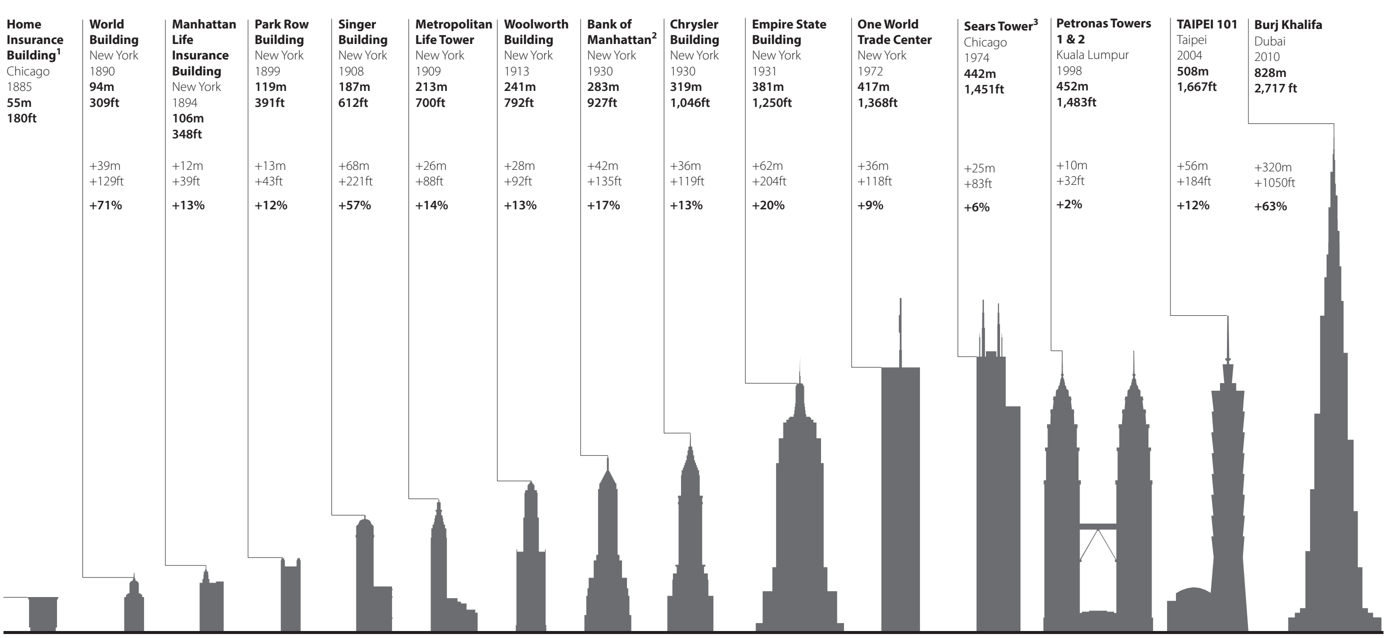
1.2 A Brief History of Steel-Timber Hybrid Buildings

Steel and the Skyscraper

Prior to the 1800s, processing iron ore into mass-produced building materials was an expensive and challenging process. Developments throughout the 19th century set the scene for iron, and eventually steel, to be used as a mass-produced building material. These developments included the introduction of a hot blast furnace by James Beaumont Neilson in 1828, the so-named Bessemer process and converter developed by Henry Bessemer in 1856, and the rolling process developed by Henry Gray in the late 1890s. These developments gave way to the very first skyscrapers, a building typology demanded of dense, urban environments that were previously unrealistic. Prior to steel framing, masonry was the dominant building material for multi-story buildings, but reaching higher floor counts was not feasible due to the sizing of columns at the ground levels (Finnigan 2015).

The Home Insurance Building, a 10-story office building completed in Chicago in 1885, is generally accepted as the first tall building because of its curtain wall construction on an iron and steel frame. In response to the ever-growing need for office space and high-value rentable areas, using a rigid all-steel frame as the primary structure became the preferred choice over the use of conventional load-bearing masonry walls, which were considered outdated (as they were not fire resistant) (Trabucco 2015). Between the 1885–1929 period, greater heights began to be achieved and the rank of the world's tallest building changed numerous times (see Figure 1.2.1), with all record-breakers utilizing a steel frame structure. In 1930, the Chrysler Building was completed at 1,046 feet (319 meters) in New York City (see Figure 1.2.2), becoming the first

▲ Figure 1.1.10. Sara Kulturhus, Skellefteå, Sweden, was completed in 2021 and is currently the world's tallest steel-timber hybrid project at 72.8 meters (239 feet). © White Arkitekter



[1]While the Home Insurance Building was never the tallest building in the world, it is largely considered the first skyscraper constructed (framed/non-loadbearing façade construction) and thus the first "tall building" as defined by the CTBUH. It officially reached its 55-meter height after a two-floor addition in 1890.

[2]Now known as The Trump Building, "Bank of Manhattan" was the building's title when it was the "World's Tallest Building."

[3]Now known as Willis Tower, "Sears Tower" was the building's title when it was the "World's Tallest Building."

▲ Figure 1.2.1. History of the "World's Tallest Building," which illustrates the rapid increase in height experienced over time, after the introduction of the steel frame structural system.

▲ Figure 1.2.2. In 1930, the Chrysler Building was completed at 1,046 feet (319 meters) in New York City, becoming the first steel-framed building to surpass the height of the previously tallest-ranked structure, the iron-framed Eiffel Tower. © Rolf Obermaier (cc by-sa)

▲ Figure 1.2.3. The record set by the Chrysler Building was quickly surpassed in 1931 by the Empire State Building, completing at 1,250 feet (381 meters), also in New York City. © Triston Dunn via Unsplash

▲ Figure 1.2.4. In 1974, the Sears Tower, now named the Willis Tower, became the tallest building in the world at 1,451 feet (442 meters). © Marshall Gerometta/ CTBUH

steel-framed building to surpass the height of the previous-ranked tallest structure, the iron-framed Eiffel Tower. This record was quickly surpassed once again, 11 months later by the Empire State Building, completing at 381 meters 1,250 feet (381 meters), also in New York City (see Figure 1.2.3).

As demands for stronger materials that were less energy intensive to produce increased, innovations in steel production and manufacturing continued to be developed. Throughout the first half of the 21st century the blast furnace was the standard choice for steel production, but in 1969, mills started to utilize electric arc furnaces, as they were less time- and energy-intensive. Furthermore, between the 1950s and 1990s, steel producers adopted the thermo-mechanical control process (TMCP), allowing a new method for rolling sections that produced steel with improved toughness and yield strength. This higher-strength steel, up to 65 percent stronger than the steel used to construct the Chrysler Building, drove a resurgence of the skyscraper in the 1970s. In 1972, this culminated in One World Trade Center (1,368 feet /417 meters) taking the World's Tallest Building ranking from the Empire State Building, which had held the title since 1931. This record was once again surpassed less than two years later, by the Sears (now Willis) Tower in Chicago, at 1,451 feet (442 meters) (see Figure 1.2.4) (Finnigan 2015).

As mentioned in Chapter 1.1, since 1974, when the first hybrid buildings entered the 100-tallest (also the year that Sears Tower completed), the share of these hybrid structures has been growing. In parallel with this shift towards hybrid structures, the tallest buildings are also becoming more regionally diverse and are trying to incorporate multiple functions and programs. This, combined with the emergence of engineered mass timber as a building material and demands to reduce carbon emissions in new construction, may mean that the next evolutionary state and innovation in steel structure design is in how it can work compositely with timber, taking advantage of the benefits of both materials.

The Introduction of Mass Timber as a Building Material

The modern era of engineered mass timber began with the invention of cross-laminated timber (CLT) in the mid-1990s, when Gerhard Schickhofer delivered his PhD dissertation on applying existing mechanical theories to multilayered timber. Schickhofer collaborated with Austrian sawmills to eventually develop a marketable structural five-layer timber panel system, which we know as CLT.

Today, there is a CLT plant on every continent except Antarctica, but the expertise and core of the industry remains highly concentrated in Northern Europe. The forest products industry quickly realized the potential synergies between CLT and the other major engineered products, glued laminated timber (GLT) and laminated veneer lumber (LVL). GLT could be pressed into both beams and columns, with LVL limited to thinner beams and blocking.

A number of experiments began to be undertaken with the new mass timber products throughout the 1990s and early 2000s. In 1997, Ölzbündt, a three-story post-and-beam structure with concrete wall inserts by the architect Hermann Kaufmann, was completed in Dornbirn, Austria (see Figure 1.2.5). In 2002, in Judenberg, Austria, Frauengasse I & II, was the first significant project to reach four stories and the first to have all load-bearing components made of CLT; coupled with a 2001 relaxation of Austrian building codes allowing buildings of up to four stories to be built in timber, the record was soon topped by Spöttlgasse, Vienna, which totaled five stories (four in CLT above one floor framed in concrete) (see Figure 1.2.6).

▲ **Figure 1.2.5. Ölzbündt, a post-and-beam mass timber building completed in 1997 in Dornbirn, Austria.** © Ignacio Martinez (cc by-sa)

▲ **Figure 1.2.6. Spöttlgasse, Vienna. The social housing project has five stories; levels 2–5 are constructed of CLT, over a concrete-framed structure on Level 1.** © Sozialbau AG | Vienna

▲ Figure 1.2.7. Carbon12 is an eight-floor steel-timber hybrid residential building that completed in Portland in 2018. © Will Miranda

▲ Figure 1.2.8. The Hybrid Timber Tower is a prototype tall building design that would see concrete-steel-timber hybrid construction surpass 100 floors. © DIALOG

▲ Figure 1.2.9. Atlassian Central, Sydney, is currently under construction and expected to be complete by 2026, when it is expected to become the tallest concrete-steel-timber hybrid building. © Dexus

Sweden also had changed its building regulations to allow buildings of up to eight stories to have a timber structure in 1994 (Wood et al. 2023). Encouraged by the development of the Nordic Wood Program, which ran from 1993 to 2000, numerous light-timber-framed structures rising up to five stories were constructed in the late 1990s, particularly in the city of Växjö, which continues to be a "timber hotspot," particularly through their mer trä i byggandet (more timber in construction) policy that was instituted in 2005 (Salvadori 2021).

The History of Steel-Timber Hybrid Buildings

In fact, the first project to take advantage of this mer trä i byggandet program and the first project globally to reach eight or more floors with engineered mass timber in its primary structure is Limnologen, a residential steel-timber hybrid over concrete building completed in 2008. Due to pore soil conditions, Limnologen includes a one-story concrete podium, with a seven-story CLT core and shear wall structure on top. In order to resist uplift forces from the wind, the CLT structure is anchored to the concrete podium through steel rods that run the entire height of the building.

Completed one year earlier in Berlin, Germany, E3, a seven-floor residential concrete-steel-timber hybrid over concrete building, includes dowel-laminated timber (DLT) floor plates, bracing with steel beams, and a concrete core with a one-story concrete podium. Although not a common hybrid solution, it grew popularity in Germany, with C13, also in Berlin, specifically commissioned to be designed similarly to E3, and completing with a similar system in 2014. These heights were soon surpassed, in 2019, after the completion of the 10-floor SKAIO in Heilbronn, Germany, which used a similar system to E3 and C13, but used CLT in the floor plates, instead of DLT (Salvadori 2021). Construction continued to spread across Europe, as further case studies were completed and building regulations were relaxed or clarified. In 2012, De Karel Doorman became the tallest building to incorporate mass timber and steel into its structure, at 70.5 meters and 22 floors. De Karel Doorman is a concrete-steel-timber hybrid over concrete project that adds a 16-floor residential tower on top of a six-story department store. The concrete-steel-timber hybrid structure includes a concrete core, with steel framing, and an LVL-framed mass timber floors. The Cube Building, also known by its address, 17–21 Wenlock Road, was also completed in London in 2015. This 10-floor residential project includes a concrete core, with a steel frame infilled with CLT panels (Wood et al. 2023).

At the same time as these developments, steel-timber and concrete-steel-timber hybrid was beginning to emerge in North America. Bullitt Center, a six-floor concrete-steel-timber hybrid over concrete office building, completed in Seattle, United States in 2013. Similar to C13 being built following the observed successes of E3, the sustainability goals sought for Bullitt Center inspired additional steel-timber hybrid construction in the United States, eventually leading to Carbon12, an eight-floor steel-timber hybrid residential building in Portland (see Figure 1.2.7) (Salvadori 2021). Additional tall building hybrid construction continues to across North America, with some select examples including: Tallwood 1 at District 56, a 12-floor steel-timber hybrid over concrete residential project completed in Victoria, Canada in 2022; Heartwood, an eight-floor steel-timber hybrid residential project completing in Seattle soon, as of this writing; and Limberlost Place, a 10-floor steel-timber educational project, expected to complete in Toronto in 2024.

Steel-timber hybrid innovation continued in Sweden, with Sara Kulturhus completing in Skellefteå in 2021. Upon completion, Sara Kulturhus became the tallest steel-timber hybrid building at 72.8 meters and 20 floors. Sara Kulturhus includes a hotel above a cultural center with six performing arts stages for the Västerbotten Regional Theatre, two restaurants, a library, the Anna Nordlander Museum, and Skellefteå Art Gallery. The spans needed for the cultural center on the lower levels were only made possible in-part thanks to the unique steel and timber hybrid systems that are employed (see Chapter 2.9) (Wood et al. 2023).

The Next Step for Steel-Timber Hybrids

How can we design a mixed-use high-rise building in the most cost-efficient, energy-efficient, low-carbon, and elegant manner, that is also conducive to human well-being, and the well-being of the environment? Several ambitious projects indicate where the typology can go next.

The Hybrid Timber Tower, a prototype design put forward by DIALOG, demonstrates how a concrete-steel-timber hybrid project can surpass 100 floors and 400 meters. The design maximizes the use of mass timber, with a patented and tested hybrid timber panel system design, but the entire building is additionally supported and stabilized by an external steel frame, as well as a concrete core, tuned mass dampers, and outrigger floors (see Figure 1.2.8) (Applegath 2022).

This external steel skeleton—or exoskeleton—idea is being applied to a project currently under construction, Atlassian Central. Atlassian Central expected to be complete by 2026 and to reach a height of 599 feet (182.6 meters), which would make it the tallest concrete-steel-timber hybrid project, as of the publication of this book (see Figure 1.2.9). If completed at its expected height, this would be more than double the current tallest building to utilize a mass timber hybrid structure, Ascent, a 284-foot (86.6-meter) concrete-timber hybrid over concrete building in Milwaukee, United States. This continued upward trend of greater heights being reached for steel-timber hybrid projects is not dissimilar to what was already observed for single-material all-steel structures, when the rigid steel frame was introduced (see Figure 1.2.10).

1.3 Audit of Steel-Timber Hybrid Buildings

Introduction/Definitions

As of the end of 2023, there were more than 250 buildings being tracked and monitored by CTBUH that utilize mass timber in their above-ground structure, which were at least five stories tall. More information on all mass timber projects being evaluated by CTBUH can be found in the CTBUH Technical Guide ***Tall Timber: Mass Timber for High-Rise Buildings,*** or at talltimbercenter.com.

For the purposes of this audit, only projects that include both steel and mass timber in their above-ground structures, and which are completed or under construction, are catalogued and compared. Furthermore, to ensure a high level of confidence and consistency, a minimum height threshold of six stories above grade is established. Other criteria for this dataset are presented below (CTBUH 2023).

Building Characteristics

Buildings vs. Towers

To be considered a "building," at least 50 percent of the structure's height must be occupiable, or conditioned space which is designed to be safely and legally occupied by residents, workers, or other building users on a consistent basis. It does not include service or mechanical areas which experience occasional maintenance access, etc. Telecommunications or observation towers that do not meet the 50 percent threshold are not included in this audit. For instance, this means that Malahat Skywalk (see Figure 1.3.1), a 40-meter tower outside of Vancouver, Canada, is not included in the audit of steel-timber buildings, although it is a steel-timber hybrid structure.

Function

The Council defines a "single-function" building as one in which 85 percent or more of its total height is dedicated to a single function. A "mixed-use" tall building contains two or more functions, where each of the functions occupies a significant proportion of the tower's total space. Support areas, such as car parks and mechanical plant space, do not constitute mixed-use functions. Functions are denoted in descending order, i.e., "hotel/office" indicates the hotel function is above the office function.

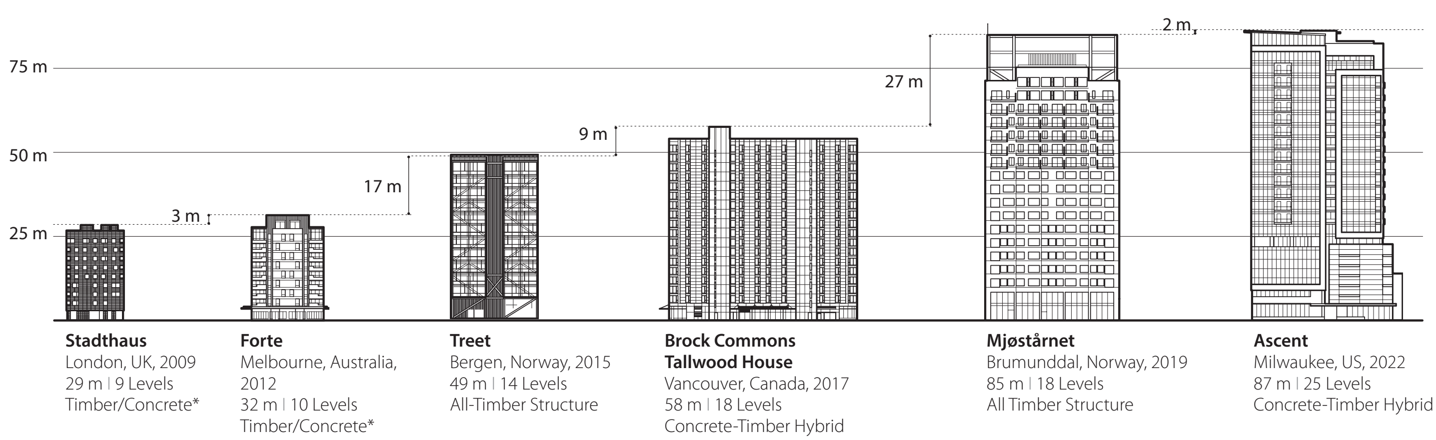
Number of Floors

The number of floors listed for a building includes all above-ground floors, including the ground floor itself, and significant mezzanine/major mechanical plant floors, unless they have a significantly smaller floor area than the major floors below. Mechanical penthouses or plant rooms above the general roof area are not counted. As mentioned above, only buildings six stories or greater are considered in this audit.

Building Status

Vision

A "vision" is a theoretical design concept for a building which either had no intention of being realized or is at an early stage of development and does not yet satisfy the criteria of a "proposal" (see next section). Although visions are not included in this audit, it is important to consider them in research when evaluating the future potential of steel-timber hybrid projects. For example, the Hybrid



* Apart from the concrete-built ground floor, the noted timber/concrete tall buildings are designed and built with an entirely mass timber structure.

▲ **Figure 1.2.10. A graphical history of the tallest mass timber buildings in the world.** © CTBUH

▲ Figure 1.3.1. The Malahat Skywalk, located in a rural area of Vancouver Island, British Columbia, Canada, is a tall steel-timber hybrid structure – but not a building, per CTBUH criteria. © Jake Elbrecht

▲ Figure 1.3.2. The Hybrid Timber Tower by DIALOG, is considered a "Vision" by CTBUH building status criteria, as it is a theoretical steel-concrete-timber design, not an actual proposal. © DIALOG

Timber Tower, a patented building design and concept by DIALOG, evaluates how structures that integrate mass timber could eventually surpass 100 floors, made feasible in part due to the structural support of a steel exoskeleton (see Figure 1.3.2).

Proposed

A "proposed" building:

- Has a specific site, and ownership interests within the building team.
- Has a full professional design team progressing the design beyond the conceptual stage.
- Has obtained, or is in the process of obtaining, formal planning consent or legal permission for construction.
- Has a full intention to progress to construction and completion.

Due to the changing nature of early-stage designs and client information restrictions, this audit is limited to complete and under-construction projects only, reducing the dataset to 31 buildings of at least six stories in height, which are listed in Table 1.3.1.

Under Construction

A building is "under construction" when site clearance has been completed and foundation/piling work has begun. This means that C6, Perth, is not included in this list, which upon completion, is expected to become the tallest concrete-steel-timber hybrid building, and tallest building to use mass timber in its structure, at 50 floors and an anticipated 183.5 meters (see Figure 1.3.3).

Completed

A completed building must fulfill all the following criteria:

- It must be topped out structurally and architecturally. The architectural topping-out of a building implies that all structural and finished architectural elements are in place.
- It must be fully clad. Note that the omission of cladding panels to

▲ Figure 1.3.3. C6, Perth, is a proposed concrete-steel-timber hybrid building, expected to become the world's tallest building to use mass timber in its structure upon completions. © Inplace Visual

> "This audit considers only those buildings which use steel-timber and concrete-steel-timber structures as their primary above-ground gravity or lateral system."

allow fixing of a construction hoist or crane while interior fit-out of some building areas is continuing does not affect the status of "fully clad."

- It must be open for business, or at least partially occupiable.

Steel-Timber Hybrid Buildings, by Structural System

With the above criteria as guidance, this audit considers only those buildings which use steel-timber hybrid and concrete-steel-timber structures as their primary above ground gravity or lateral system—a notable exclusion would be Treet, Bergen, Norway, which uses steel piles in its foundations but is otherwise considered an all-timber building. Projects that only feature steel in ancillary elements, such as Traloftet, Vallastaden, Sweden, which has steel-supported balconies, would also be excluded.

Building Name	City, Country	Floors	Structural System	Function	Status (as of Oct 2023)	Completion Year
Atlassian Central	Sydney, Australia	42	Concrete-Steel-Timber Hybrid	Office / Hotel	Under Construction	2026
Metropolitan Park Building 7/8	Arlington, United States	23	Concrete-Steel-Timber Hybrid Over Concrete	Office	Under Construction	2023
De Karel Doorman	Rotterdam, Netherlands	22	Concrete-Steel-Timber Hybrid Over Concrete	Residential / Retail	Complete	2012
Sara Kulturhus	Skellefteå, Sweden	20	Steel-Timber Hybrid	Hotel / Exhibition	Complete	2021
55 Southbank	Melbourne, Australia	17	Steel-Timber Hybrid Over Concrete	Hotel / Office	Complete	2020
Baker's Place	Madison, United States	14	Steel-Timber Hybrid Over Concrete	Residential	Under Construction	2025
Lighthouse Joensuu	Joensuu, Finland	14	Steel-Timber Hybrid Over Concrete	Residential	Complete	2019
BCIT Student Residence	Burnaby, Canada	12	Steel-Timber Hybrid Over Concrete	Residential	Under Construction	2024
Westralia Square 2	Perth, Australia	12	Steel-Timber Hybrid	Office	Complete	2023
Tallwood 1 at District 56	Victoria, Canada	12	Steel-Timber Hybrid Over Concrete	Residential	Complete	2022
SKAIO	Heilbronn, Germany	10	Concrete-Steel-Timber Hybrid Over Concrete	Residential	Complete	2019
The Cube Building	London, United Kingdom	10	Concrete-Steel-Timber Hybrid	Residential	Complete	2015
38 Berkeley Square	London, United Kingdom	9	Concrete-Steel-Timber Hybrid	Office	Under Construction	2024
Heartwood	Seattle, United States	8	Steel-Timber Hybrid	Residential	Under Construction	2023
Pont de Flandres Batiment 007	Paris, France	8	Concrete-Steel-Timber Hybrid Over Concrete	Office	Complete	2019
Green Office ENJOY	Paris, France	8	Concrete-Steel-Timber Hybrid Over Concrete	Office	Complete	2018
Carbon12	Portland, United States	8	Steel-Timber Hybrid	Residential	Complete	2018
Opalia	Saint-Ouen-sur-Seine, France	8	Concrete-Steel-Timber Hybrid	Office	Complete	2017
Strandparken	Stockholm, Sweden	8	Steel-Timber Hybrid Over Concrete	Residential	Complete	2014
Limnologen	Vaxjo, Sweden	8	Steel-Timber Hybrid Over Concrete	Residential	Complete	2008
Caisse d'Epargne Bourgogne-Franche-Comté Headquarters	Dijon, France	7	Timber Over Concrete-Steel Hybrid	Office	Complete	2022
T3 West Midtown	Atlanta, United States	7	Steel-Timber Hybrid Over Concrete	Office	Complete	2019
Iceberg Residential Building	Berlin, Germany	7	Steel-Timber Hybrid	Residential	Complete	2019
Kibori	Nantes, France	7	Concrete-Steel-Timber Hybrid Over Concrete	Office	Complete	2018
C13	Berlin, Germany	7	Concrete-Steel-Timber Hybrid Over Concrete	Residential / Office	Complete	2014
E3	Berlin, Germany	7	Concrete-Steel-Timber Hybrid Over Concrete	Residential	Complete	2007
6 Orsman Road	London, United Kingdom	6	Steel-Timber Hybrid	Office	Complete	2020
Ki-etude	Namur, Belgium	6	Concrete-Steel-Timber Hybrid	Residential	Complete	2018
Clay Creative	Portland, United States	6	Steel-Timber Hybrid	Office	Complete	2016
Curtain Place	London, United Kingdom	6	Steel-Timber Hybrid	Residential / Office	Complete	2015
Bullitt Center	Seattle, United States	6	Concrete-Steel-Timber Hybrid Over Concrete	Office	Complete	2013

▲ Table 1.3.1. Complete and under-construction Steel-Timber Hybrid and Concrete-Steel-Timber Hybrid buildings, six stories above grade or higher as of October 2023. Find out more and access updated data at: talltimbercenter.com.

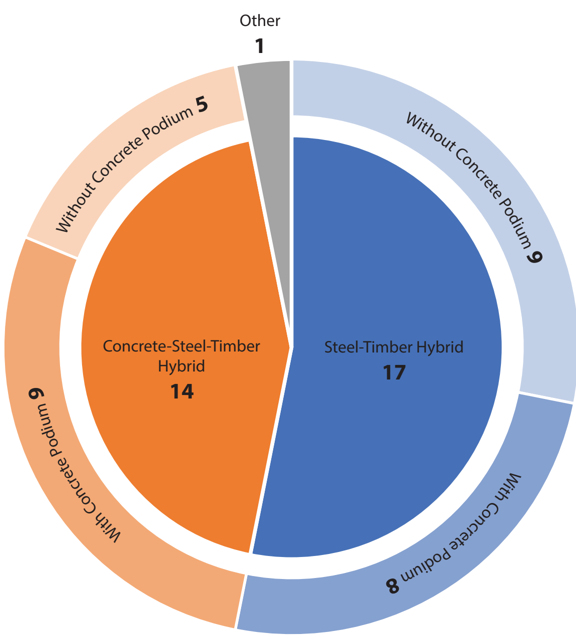
The audit counts 31 buildings utilizing steel and mass timber in their structure, of six stories or higher, completed or under construction. Of these, 14 are concrete-steel-timber hybrids; nine of which have a concrete podium; five of which do not. There are 16 steel-timber hybrids; eight with a concrete podium and eight without. The Caisse d'Epargne Bourgogne-Franche-Comté Headquarters, Dijon, France, is an unusual configuration that has no apparent peers in its height category. The upper stories of the structure are reinforced by a timber exoskeleton that also supports a double-skin façade, while the exoskeleton is held up by thin white steel columns on the ground floor. Over half of the projects being tracked by CTBUH (17 of 31) include a concrete podium on the ground-level floor (see Figure 1.3.4).

Steel-Timber Hybrid Buildings, by Region

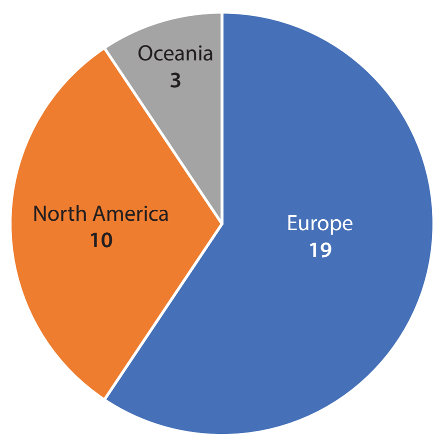
As the birthplace of cross-laminated timber (CLT) and modern methods of engineered mass timber generally, it is unsurprising that Europe is the region with the greatest number (19) of steel-timber hybrid buildings, one of which, 38 Berkeley Square, London, was under construction at the time of this report (see Figure 1.3.5).

North America counts nine such structures, with two under construction: Baker's Place in Madison (WI) and BCIT Student Residence in Vancouver.

Oceania hosts the remaining three buildings, including what is likely to become the next tallest building with mass timber in its structure, Atlassian Central, Sydney, a concrete-steel-timber hybrid office and hotel building of 42 floors and 182.6 meters in height.



▲ Figure 1.3.4. Breakdown of structural systems for under-construction and complete building, six floors or greater, that use steel and mass timber in their structure.



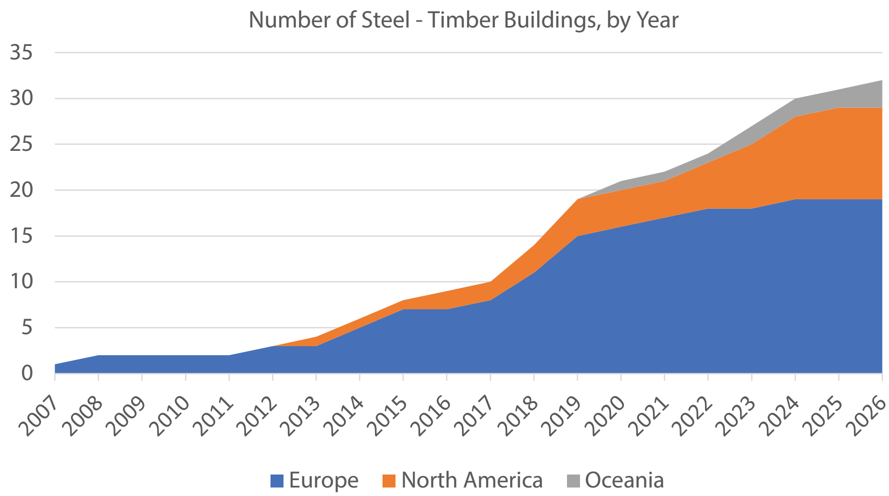
▲ Figure 1.3.5. Breakdown of region for under-construction and complete building, six floors or greater, that use steel and mass timber in their structure.

As a proportion of the global total, both North America and Oceania are gaining on Europe in terms of tall steel-timber buildings in the pipeline. Over a 12-year period, from 2007 to 2019, 15 of these buildings were in Europe; four were in North America, and none were in Oceania. From 2020, including buildings under construction in 2023, four are in Europe, five are in North America, and three are in Oceania (see Figure 1.3.6).

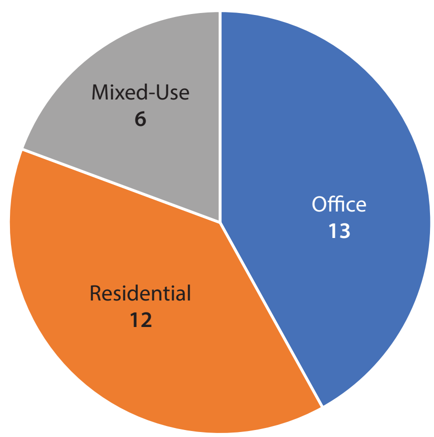
Steel-Timber Hybrid Buildings, by Function

The functional breakdown of steel-timber buildings six stories and higher

> "As a proportion of the global total, both North America and Oceania are gaining on Europe in terms of tall steel-timber buildings in the pipeline."



▲ Figure 1.3.6. Timeline for under-construction and complete building completions, broken down by region.



▲ Figure 1.3.7. Breakdown of function for under-construction and complete building, six floors or greater, that use steel and mass timber in their structure.

is as follows: 12 are office buildings; 13 are residential, and six are mixed-use buildings. Mixed-use projects include office and residential spaces; but can also feature exhibition space, hotels, and retail. The mixed-use and hotel segment has grown noticeably over the years, as a proportion of the total (see Figure 1.3.7).

From 2007 to 2019, there were nine residential, seven office, and three mixed-use steel-timber buildings completed. Two of these mixed-use projects featured residential units above office space, C13, completed in Berlin in 2014, and Curtain Place, completed in London in 2014. The remaining mixed-use project is De Karel Doorman, a vertical extension, with residential space built atop existing retail space (see Figure 1.3.8). From 2020 onwards, including buildings under construction in 2023, four residential, five office, and three mixed-use steel-timber buildings, with portions of all mixed-use buildings including hotel space (see Figure 1.3.9).

▲ Figure 1.3.8. De Karel Doorman, Rotterdam, Netherlands, includes 16 floors of residential space built atop the existing department store, originally completed in 1951. © Ossip van Duivenbode

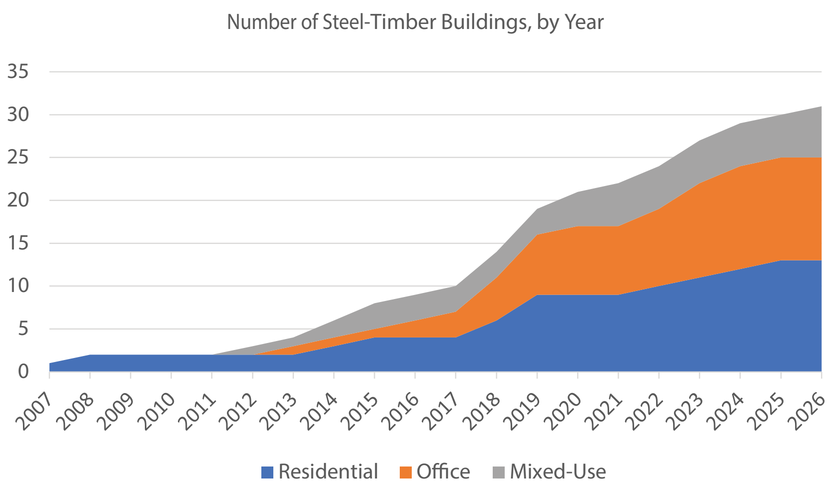
Steel-Timber Hybrid Buildings, by Area

As a typology with beginnings in relatively modest multifamily residential development, the current wave of steel-timber hybrid buildings is increasing in scale, in terms of floor area. While the average remains at 1,151 square meters per floor, collectively, steel-timber hybrid buildings of six stories or greater comprise almost 500,000 square meters of floor space. As a testament to the larger scale of the more recent wave, the outliers include the new Metropolitan Park Building 7/8, part of Amazon's HQ2 development outside of Washington D.C., which is a 113,857 square-meter building, with floor plates of 4,950 square meters on average. An outlier on the other end of the spectrum includes Ki-etude, a six-floor residential building that completed in Namur, Belgium in 2018. Although this building is only 720 total square meters and averages 120 square meters per floor, it validates steel and timber's flexibility when it comes to navigating the extremely limited sites, with a plot size of only 96 square meters.

Selected Case Studies

In the following section, we explore six case studies of steel-timber hybrid buildings from around the world. These were selected on several bases.

Availability of information: As a relatively new typology, there is not yet a standard method of



▲ Figure 1.3.9. Timeline for under-construction and complete building completions, broken down by function.

documenting the embodied carbon, material sourcing or life-cycle impacts of steel-timber hybrid projects, and not all stakeholders are committed to gathering or releasing this data. As such, we have chosen those case studies for which the greatest preponderance of information could be gained. We have sought to correct for inconsistencies where possible, we but believe that the value of amassing the information in one place supersedes that of comprehensiveness.

Geographical diversity: Although mass timber has its roots in regions with a long history of forestry, the practicality and appeal of steel-timber hybrid structures has led practitioners to construct them globally. Even in a small dataset, it was important to demonstrate this.

Architectural appeal: Steel-timber hybrids can be both a practical and beautiful solution to complex project briefs. The long-span, airy spaces and extensive exposed timber surfaces in many of these projects demonstrate what can be achieved through innovative use of these materials.

Variations in technique: Even within this small dataset, each project demonstrates a different approach to hybridization, using different relative quantities and formats of steel and timber.

2.0 Case Studies

2.1 Case Study

55 Southbank, *Melbourne, Australia*

▲ Figure 2.1.1: An overall view of the completed 55 Southbank development in Melbourne. The project seamlessly places 10 stories of hotel rooms above an existing seven-story office building. © Peter Clarke

Project Base Metrics

Status
- Completed: 2020

Building Function
- Mixed-Use
  Level 1: commercial lobby
  Levels 2: hotel lobby
  Level 3 to 8: offices
  Level 9: pool and hotel amenities
  Levels 10 to 19: hotel rooms

Structural Classification
- Steel-Timber Composite over Concrete

Structural Materials
- **Mass Timber:**
  Floors (CLT): levels 11 to 19
  Walls (CLT): levels 10 to 19
- **Steel:**
  Columns: levels 10 to 18
  Cores: (1) levels 1 to 19; (1) levels 9 to 19
- **Concrete:**
  Floors: levels 1 to 9
  Columns: level 1 to 9
  Core: levels 1 to 9

Building Milestone Dates
- Construction start: 2019
- Construction complete: 2020
- Construction period: approx. 24 months

Height
- Height to architectural top: 69.7 meters
- Height to highest occupied floor: 64.4 meters
- Height to tip: 69.7 meters

Number of Floors
- Above grade: 19
- Below grade: 1

Building Floor Area
- Total gross floor area: 15,977 m^2
- Net internal area:
  Existing building: 8,507 m^2
  Hotel building: 13,599 m^2
  Commerical: 1,253 m^2
- Area of building footprint: 23,539 m^2

Number of Apartments
- 220

Number of Elevators
- 3

Background/Overview

This project leveraged steel and timber to transform a seven-story concrete office building into a 19-story mixed-use building with hotel rooms on the top 10 floors, with offices and amenities in the lower nine (see Figure 2.1.1). It is one of the world's largest extensions of an existing building using mass timber and is Australia's first cross-laminated timber (CLT) extension project.

The building consists of 10 levels of new CLT hotel rooms, sitting on top of two levels of steel and concrete transfer structure, and seven levels of the existing concrete building (see figures 2.1.2 and 2.1.3). One new steel-framed core, and one steel-framed extension of an existing concrete core, contain the lifts and fire stairs and provide lateral stability.

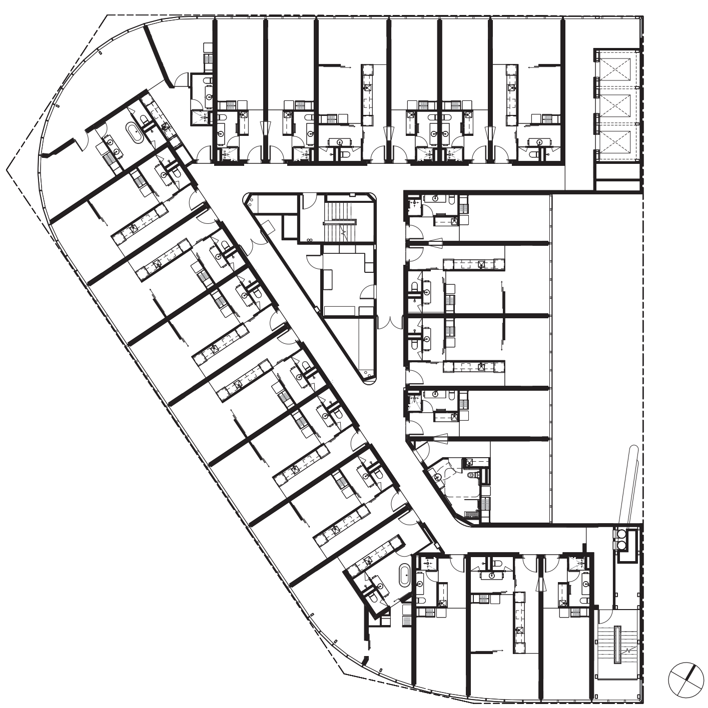
The new addition amplifies the curved architecture of the existing building and provides a more contemporary articulation. Rather than simply echoing the spandrel banding of the prevailing building, the new addition responds with a series of large and small recesses, which complement the original design but deliver a more dynamic façade expression. Internally, the ground floor lobby is lined with timber, which highlights the new method of construction (Archello 2020).

Notably, during the entire construction process for 55 Southbank, the existing commercial building remained in operation, which played a role in the choice of steel and timber throughout the building.

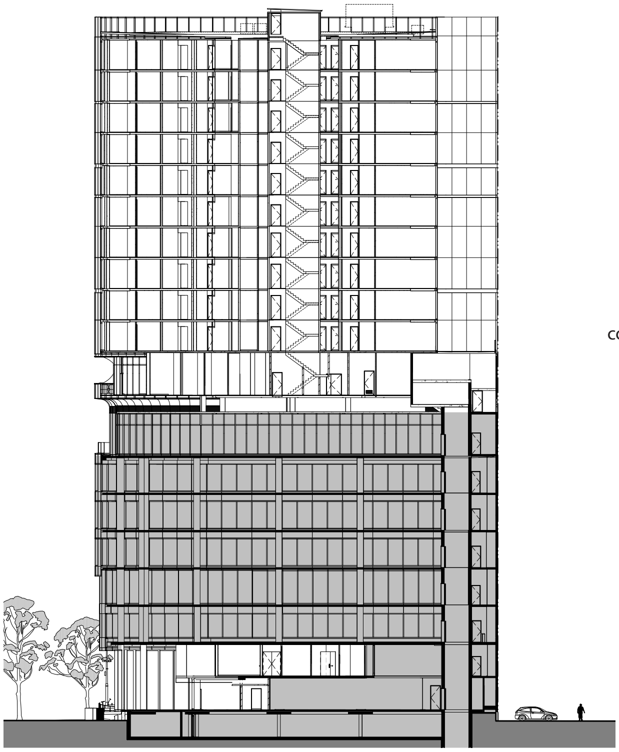
Please see "Project Base Metrics" for a full breakdown of where each material appears in the building.

Owner/Developer Motivations

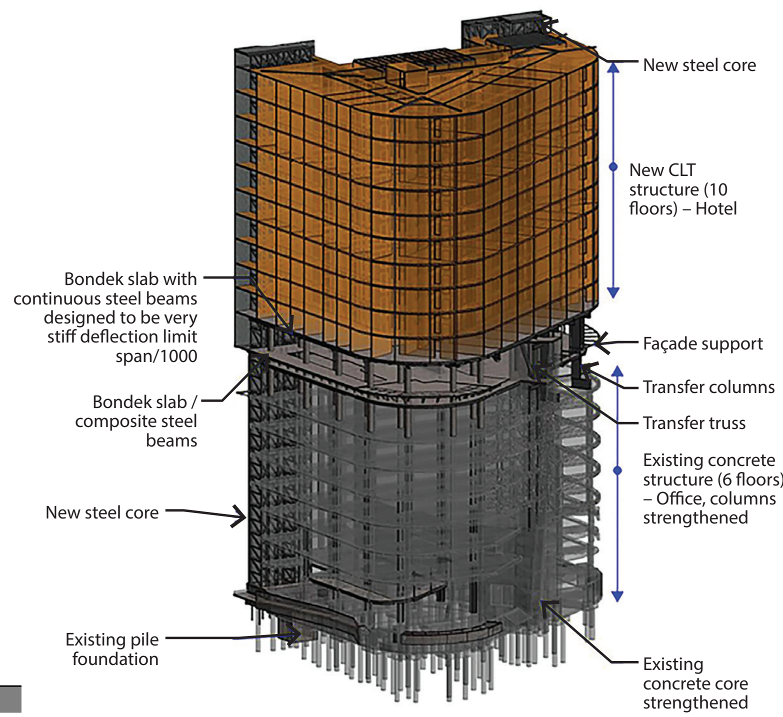
The original concrete structure, built in 1989, was designed to allow for future flexibility with built additions. This structure could take an additional six levels of concrete, as determined by conducting a static load test on the existing piles underlying the project. The resulting geotechnical report showed that the vertical load would need to be limited to six stories in concrete to avoid the cost-intensive need for new foundation-strengthening piles. However, to meet financial objectives, developers



▲ **Figure 2.1.2: A typical hotel floor plan (Level 10) for the upper portion of 55 Southbank. Solid walls are CLT panels, as is the base flooring. The new steel lift core, constructed for the addition, is at upper right.** © Bates Smart Architects



▲ Figure 2.1.3: Section drawing of 55 Southbank, showing original office floors in dark grey, the transfer floors containing a steel truss and the pool, and the upper 10 hotel floors, a CLT and steel hybrid structure.
© Bates Smart Architects



▲ Figure 2.1.4: Axonometric drawing. Original office building is extended by a steel transfer truss, steel columns, two steel cores, and CLT walls and flooring in the upper section. © WSP

wanted this building to transform into a hotel with more capacity than six floors could accommodate.

Timber was chosen for the addition because it is 20 percent of the weight of concrete and allowed for 10 additional stories. Steel was used for the core, transfer truss, and columns to provide reinforcement to both the new and existing construction.

Other factors that led to the choice of steel and timber included the less disruptive nature of on-site and off-site fabrication and reduced on-site noise, congestion, and waste, when compared to traditional concrete construction. Steel and timber were also the most cost-effective options.

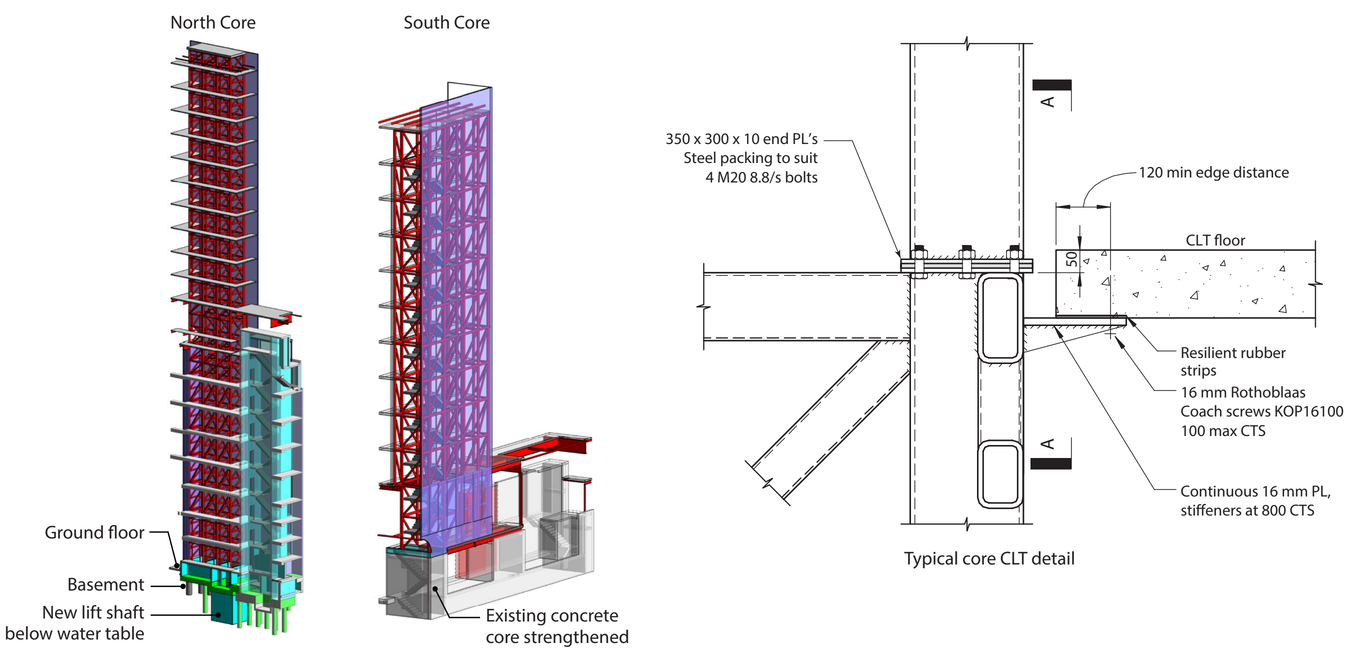
Structural Systems

The main structural scheme consists of a 10-story cross-laminated timber (CLT) structure, including floor platforms and load-bearing walls, with two additional steel braced-frame cores, constructed atop a seven-story concrete building (see Figure 2.1.4).

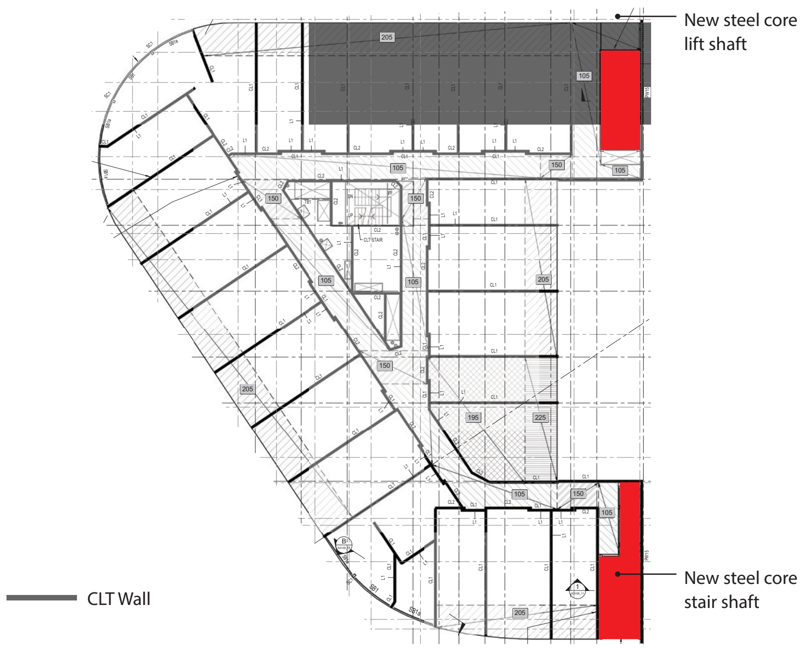
Additional levels were well-supported by the existing building columns. Concrete core walls and columns were strengthened with steel tension rods and plates to accommodate the additional load from the extension. Two new steel cores—one set atop an existing concrete core and running from levels 9 to 19; and the second, a new structure positioned on the site's northeast corner, running the full height of the building—extend to the top of the CLT extension (see Figure 2.1.5). A new raft was designed under the steel core to transfer the new loads to the existing piles, relieving the need for new piles. To achieve uninterrupted views from all corners of the hotel, steel beams and columns form the curved northwest corner, where CLT walls would not have allowed this (see Figure 2.1.6) (WoodSolutions 2020).

The existing reinforced concrete transfer beam at level two did not have sufficient capacity to support the additional 10 stories of CLT. The structural engineers designed a concrete-steel composite slab transfer deck at the first hotel level to transfer the vertical loads from the walls to the existing concrete columns (see Figure 2.1.7).

> “The existing office floors were occupied during construction, driving the use of steel to support the extension and strengthening operation, instead of concrete.”



▲ Figure 2.1.5: Structural plan of floor in existing concrete building, identifying locations of strengthened concrete columns and core, and the new steel core on a new raft foundation, in preparation for the addition. © WSP

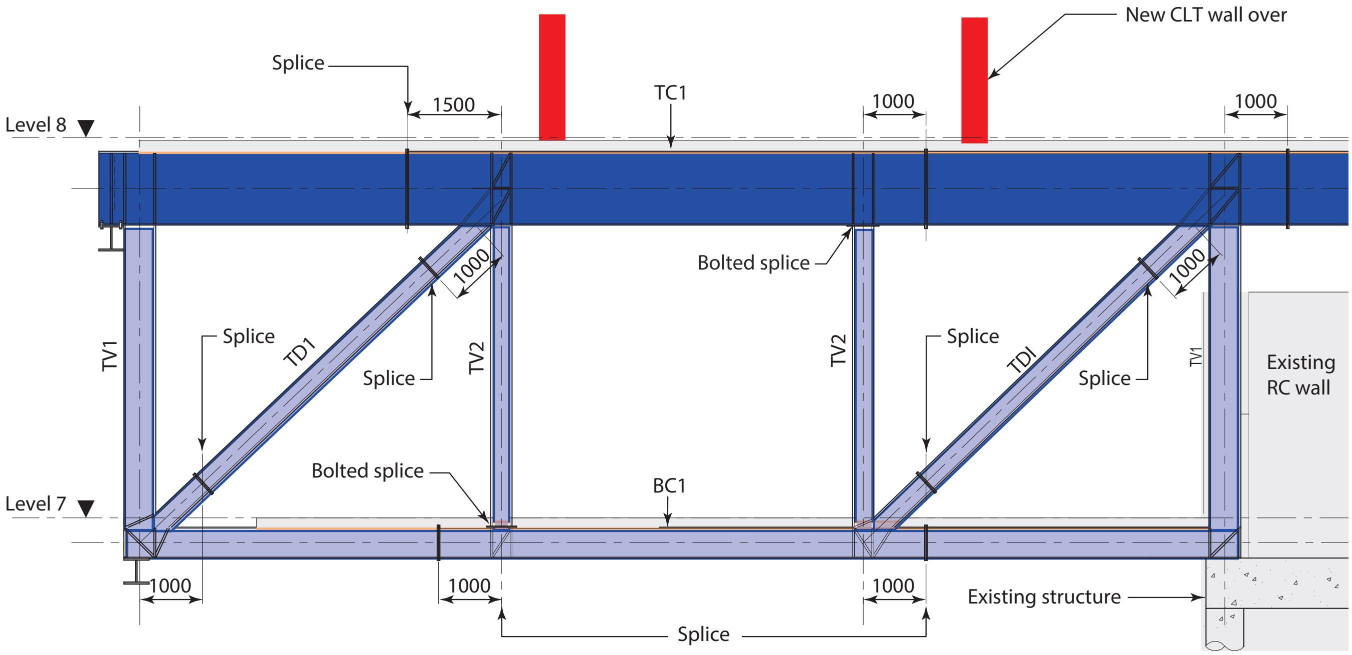


▲ Figure 2.1.6: Structural plan of typical CLT floor, showing new full-height steel core and steel extension of an original concrete core. © WSP

The existing office floors were occupied during construction, which is why steel was used to support the extension and strengthening operation, instead of concrete. To strengthen the columns using concrete would have required significant interior demolition and disruption. Additionally, because it was an existing building, there were services ducts running next to the columns that the builder did not want to disturb; the strengthening panels were located to suit these conditions (WoodSolutions 2020).

Fire Engineering

The Metropolitan Fire Brigade (MFB) decided that the building was out of their capability of certification, due to



▲ Figure 2.1.7: Steel transfer truss at junction between existing building and extension, which transfers loads from the new CLT addition to the existing concrete building. © WSP the scale of mass timber usage, deferring the project to the Building Appeals Board (BAB) of the Government of Victoria state. 55 Southbank was the first mass timber project to go through the BAB, which led to extra work going into fire strategy. It took just over 11 months to get the project certified. Australian regulations require timber to be encapsulated by 16-millimeter fire-rated plasterboard. A decision was made early on to take the path of least resistance and go with a fully encapsulated system (ibid.).

MEP Systems

The CLT panels were pre-cut in the factory to allow exhaust fan ducts, fire dampers, and other MEP services to enter the hotel rooms (see Figure 2.1.8). This provision offered an easily repeatable model for the hotel floors and allowed the services to be easily extended from existing ducts in the cores.

Construction Process

Sourcing and Supply Chain

The 1,850 CLT panels used in the project were shipped by from KLH facilities in Austria. The CLT was originally intended to come from a factory in Wodonga, Victoria, Australia, about 330 kilometers from the site, but the factory was not ready when 55 Southbank commenced construction (Good Design 2023).

▲ **Figure 2.1.8: CLT panels arrived on-site pre-cut with openings for MEP services, easing the installation process.**
© Robert De Brincat

Prefabrication

The success of the project largely relied on the high degree of prefabrication available. While the hotel rooms were assembled from pre-cut CLT panels brought to site, bathrooms and kitchenettes were entirely prefabricated off-site, to accelerate construction and to minimize office tenant disturbance (Good Design 2023).

On-Site Construction

The CLT panels were all pre-cut, which, while advantageous to assembly, did create challenges from a logistical and material handling perspective. Only one crane could fit on the job. Its purpose was to erect the CLT and drop the bathroom pods. The team segmented construction into two zones and assigned floors to zones to maximize the efficiency of assembly. A crawling crane was then used on the slabs of the recently completed zones to drop the façade panels from above, which followed one floor behind the structure as it was erected (see Figure 2.1.9). The team was able to install roughly 40 CLT panels per day.

Tolerances

The interface between the steel core and CLT was critical and complex due to timber's tendency to shrink, creep, and settle over time. Careful attention was given to this attribute throughout the construction process (WoodSolutions 2020).

The façade installers noted that the use of CLT floor panels made the installation of the curtain wall easier than would have been the case with concrete, due

"The interface between the steel core and CLT was critical and complex due to timber's tendency to shrink, creep, and settle over time."

CLT Carbon Content				
Product Components	Weight (kg)	Post-Consumer Material, Weight (%)	Biogenic Material, Weight (% Dry Mass)	Weight Biogenic Carbon (KgC/kg per Product)
Sawn wood board from softwood (u=12%)	466	0	88	0.5
Glue	4.0	0	0	0
Total	**470**	**0**	**88**	**0.5**
Packaging Materials	Weight (kg)	Weight (%)(versus the product)		Weight Biogenic Carbon (KgC/kg per Product
Polyethylene	1.1	0.2	-	0
Polyester	0.17	0.002	-	0
Total	**1.27**	**0.23**	**-**	**0**

▲ Table 2.1.1: Accounting of carbon content of the CLT panels in the 55 Southbank project, including packaging. © KLH

Number of CLT Panels	1,850 approx.
Metric Tons of CLT	1,730 approx.
Cubic Meters of CLT	**3,675 approx.**
Metric Tons of CO_2 Sequestered	**2,800 approx.**

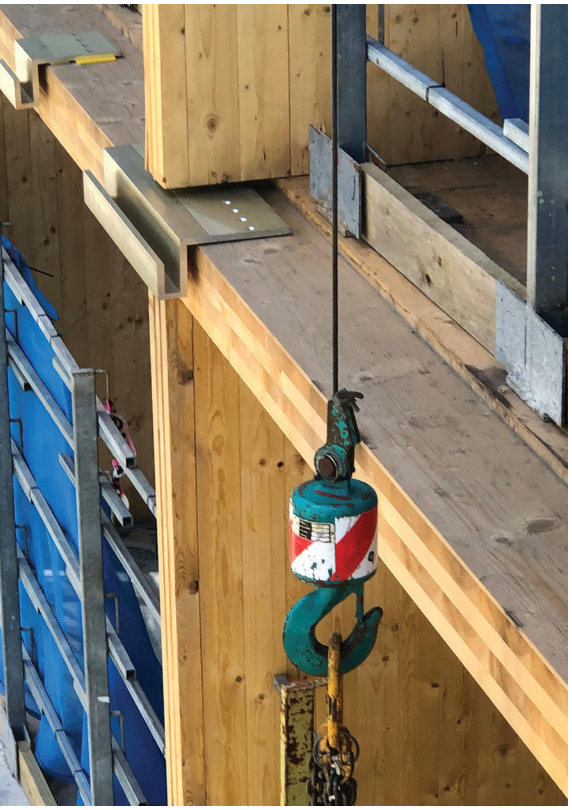
▲ Table 2.1.2. Accounting of timber panels' overall effect on sequestered carbon in the 55 Southbank project.

to their dimensional accuracy. The team collectively indicated that the façade installation process was among the biggest successes of the entire project. The façade installers were able to move efficiently by simply screwing the façade into place at each floor.

Nevertheless, there were some on-site issues related to tolerances, which were designed to be 2 to 4 millimeters at most. Some difficulties were encountered in fitting perimeter façade spandrels to CLT floor and wall panels at pre-drilled holes. The construction team discovered that some of the larger panels were delivered to the site 3 to 5 millimeters larger than documented. Excess moisture content, either from transportation or storage, was the suspected cause for this discrepancy. The cumulative effect of these small discrepancies began to impact the floor-to-floor heights and overall height of the building. To correct this, each oversized CLT panel on the initial discrepancy floor was trimmed with a saw on-site and reinstalled, bringing the overall height of the building back to expected levels.

Acoustics

The acoustics planning leveraged a CLT wall structure with 16-millimeter fire-rated plasterboard directly fixed to the CLT. A false wall with insulation was installed in front of the CLT wall, which enabled the team to achieve both the targeted fire and acoustic ratings. The greater challenge to acoustics was in the CLT flooring. Atop the CLT panel, the floor was built up with rigid



▲ Figure 2.1.9: A crawling crane was used for raising façade elements into place, which could then be bracketed to the CLT floor panels. © Bates Smart

insulation, medium-density fiberboard (MDF), and fiber-cement sheets, topped by carpet or ceramic tiles.

Carbon/Sustainability Overview

The use of CLT on the project is credited with sequestering approximately 2,800 metric tons of carbon-dioxide equivalent. See Table 2.1.1 for an accounting of the carbon impact of the CLT panels in the project and Table 2.1.2 for a general project account of carbon impact.

Costs & Insurance Elaborations

The overall cost of construction was AU$55 million (US$35 million). Insurance premiums were not higher on the project than would have been the case if rendered in concrete, due to the full encapsulation of the timber elements.

In 2015 the independent valuation of 55 Southbank's original structure was AU$27.8 million (US$18,232,630). Independent valuations are calculated using a handful of variables such as the location of the property, type of property, developmental potential, age and condition of the property, and available amenities. The original structure had 8,506 square meters of net leasable area (NLA) defined as the area that can be used by property tenants not including common areas, stairways, and utility areas (Good Design 2023). The net rent of the building, defined as the total rent minus the costs of general maintenance and operations of a commercial building and rental rebates, was AU$2,278,941 (US$1,454,238). The original structure's weighted average lease expiry (WALE), which measures the average period that all leases in a property will expire, was 2.8 years.

Once the building extension was completed in 2022, the independent valuation of 55 Southbank grew to AU$156,700,000 (US$99,993,404) which factors in the AU$55 million project cost of the new construction. This valuation is nearly 6 times greater than the 2015 valuation. The NLA increased to 23,360 square meters and the net rent increased to AU$6,622,990 (US$4,226,262), which is nearly triple the amount from 2015. The 2022 WALE was 10 years, which is more than three times longer than its 2015 duration (ibid).

Project Team

Owner/Developer: Hume Partners Property
Architect: Bates Smart
Structural Engineer: WSP (Base Building), Vistek (Steel-Timber Extension)
MEP Engineers: Rudds Consulting (M, E, Hydraulics and Fire Services)
Fire Performance/Life Safety Consultants: Rudds Consulting Engineers
Main Contractor: Atelier Projects
Project Manager: Duo Projects
Steel Manufacturer: OneSteel
Engineered Mass Timber Designer: XLam
Engineered Mass Timber Material Supplier: KLH Australia
Timber Engineer: Vistek
Acoustic Consultants: Marshall Day Acoustics
Timber Planning/Coordination Specialist: Icon Construction/Certis
BIM/Digital Twin Modeling Consultants: Bates Smart
Façade: Inhabit Group
Wind: MEL Consultants Pty Ltd
Marketing: TFE Hotels

2.2 Case Study

843 North Spring Street, *Los Angeles, United States*

▲ **Figure 2.2.1: 843 North Spring Street, Los Angeles.** © LEVER Architecture

Project Base Metrics

Status

- Completed: 2023

Building Function

- Mixed-Use
  Level -1: Parking
  Level 1: Parking, Office & Retail
  Level 2: Office & Retail
  Levels 3-5: Office

Structural Materials

- **Mass Timber:**
  Floors: Levels 3 to 5
- **Steel:**
  Columns: Levels 1 to 5
  Beams: Levels 1 to 5
  Diagonal Braces: Levels 1 to 5
- **Concrete:**
  Floors: Levels -1 to 2
  Columns: Levels -1 and 1
  Cores: Levels -1 to 5

Building Milestone Dates

- Construction start: April 2021
- Construction complete: November 2023
- Construction duration: 31 months

Height

- Height to architectural top: 29.4 meters
- Height to highest occupied floor: 23.2 meters
- Height to tip: 29.4 meters

Number of Floors

- Above grade: 5
- Below grade: 1

Building Floor Area

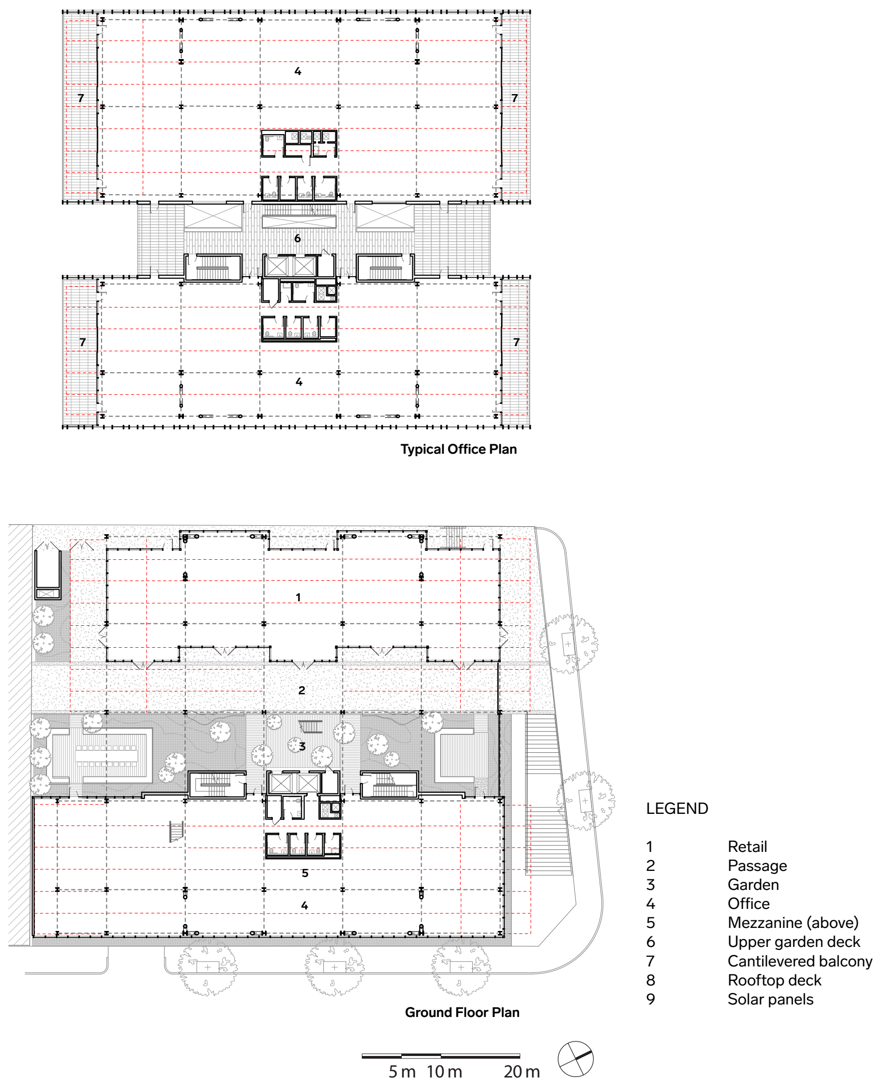
- Total gross floor area: 13,471 m^2
- Area of building footprint: 2,416 m^2

Background/Overview

This project, also known as CT7, short for "Chinatown 7," is a five-story mixed-use building located at 843 North Spring Street in Los Angeles (see Figure 2.2.1). An adaptive reuse of a commercial building garage that was partially submerged into the sloping site, the project places great emphasis on open space, flowing air circulation, and the aesthetic rewards of a disciplined steel-timber hybrid structure. Level 1 contains neighborhood-facing retail establishments within the structure of the original building, while levels 2 through 5 consist of two wings connected by bridges. One wing also provides retail on Level 1. The building is split into two volumes with wide balconies, with a tiered vertical courtyard garden at its center (see Figure 2.2.2).

Owner/Developer Motivations

The appeal of the steel-timber hybrid approach included the light weight of these materials relative to concrete, which allowed for construction on the existing commercial building, which had supported a two-story steel-frame "big-box" store, without the need to substantially increase foundation strength or add piles. There was a strong desire for the project to incorporate mass timber. The aesthetic appeal of exposed timber soffits and the light, airy appearance of the frame



▲ Figure 2.2.2: Ground floor and typical office floor plans. © LEVER Architecture

▲ Figure 2.2.3: Section perspective of 843 North Spring Street. Original concrete commercial building and parking structure is topped by a double-height space framed in steel. An open-air courtyard runs through the center, and is filled with greenery. The top three floors are framed in steel and floored in CLT. © LEVER Architecture

structure was also expected to be a market differentiator that could command a premium. The siting of the project near the Chinatown station of the Metro adds to the overall sustainability and marketability of the undertaking.

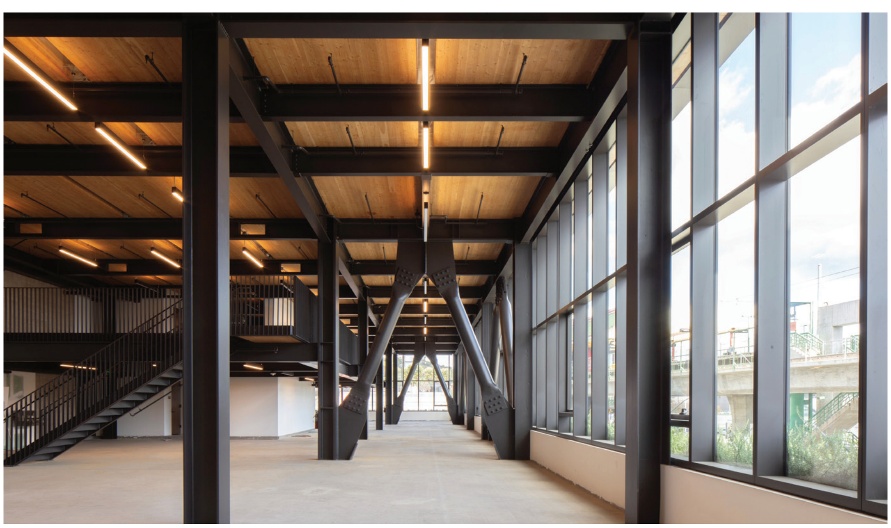
Structural Systems

The base building is a concrete-steel frame structure. The design team understood the constraints imposed by the grid spacing and was looking for ways to creatively incorporate mass timber in a way that made sense for the project. The project team was determined not to undertake additional piling works or reinforcement to support the new structure atop the base.

Because Los Angeles is in a seismic zone, and there was a desire for long-span tenant spaces and breezeways, there also needed to be some supplemental lateral bracing. Lastly, the column grid of the existing building that was being extended upwards was not ideal for an all-timber superstructure. The steel-timber hybrid solution was the most lightweight and flexible option (see Figure 2.2.3). Steel W14x columns are extended from strengthened concrete columns in the existing structure (see Figure 2.2.4). Concrete masonry-unit (CMU) cores are extended upwards from the existing building's cores and contain the stairs and elevators.

At key locations along the line of structure in two wings, a steel special concentric braced frame

▲ Figure 2.2.4: Steel columns (W14x) are placed atop existing 14-inch (366-mm)-diameter concrete columns, then fitted with the steel wide-flange perimeter frame. Round HSS braces are on view at upper right and center left. © LEVER Architecture



▲ Figure 2.2.5: Near-finished view of interior, showing orientation of the special concentric braced frame and exposed timber ceiling. © LEVER Architecture

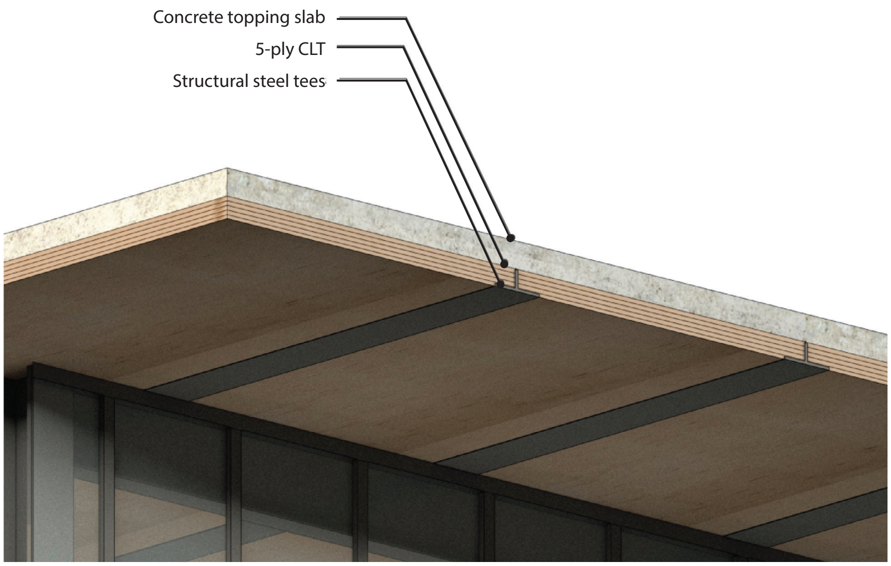
(SCBF), using round HSS braces, provides in-plane lateral stability in two directions (see Figure 2.2.5). A frame of W14x steel columns and wide-flange beams in turn supports the five-ply CLT decking. At key locations, decks are notched by one ply at the edges to overlap the steel beams supporting them, exposing the timber to below and providing a smooth, continuous ceiling surface. Cantilevered balconies, extending up to 14 feet (4.3 meters) were achieved by placing structural steel tees atop the main steel support beam (see Figure 2.2.6).

The timber decks are finished with 3 inches (76 millimeters) of concrete topping for interior spaces and 4 inches (101 millimeters) on the exterior cantilevered balconies.

MEP Systems

The sprinkler system and mechanical ducts are suspended below the steel beams and are routed through penetrations in the cores. The layout of the structural grid and ceiling heights of 13 to 20 feet (4 to 6 meters) were such that no beams, CLT or steel, needed to be penetrated.

Another detail that required close coordination was the design of slots between the CLT floor panels for electrical conduit runs. Since the concrete topping slab works as a diaphragm, a direct connection was needed to the steel beams, and the size and quantity of electrical penetrations were closely coordinated.



▲ Figure 2.2.6: Detail view of overhang/balcony condition, showing intersection of steel tees and CLT panels. © LEVER Architecture

Construction Process

The construction process required close collaboration between the architectural, structural, and contractor teams to prove the concept. This collaboration was evident throughout the construction process.

Sourcing and Supply Chain
The timber in the project was supplied by Structurlam (now part of Mercer International) from its forests in Penticton, British Columbia, Canada, a distance of about 2,113 kilometers to site. The steel came from a fabricator in Anaheim, California, about 43.4 kilometers away. The location of the steel mill is unknown. Both materials traveled by truck.

Prefabrication
The CLT panels were prefabricated at Structurlam and shipped in pallets to the site. The steel was fabricated off-site but was conventionally assembled on-site.

On-Site Construction
The combination of steel and wood presents unique challenges on a construction site. Before the building is closed in, it is common for the CLT panels in contact with unfinished steel to be stained black in the presence of moisture. Bleaching and sanding the CLT panels after installation was required in some cases to clean up the finished surface. Similarly, it can be challenging to avoid burning when welding is necessary next to wood members.

▲ Figure 2.2.7: Tower crane at site center places a CLT panel on the steel frame. © LEVER Architecture

A tower crane situated at the center of the project site did most of the heavy lifting on the job, hoisting both steel elements and CLT panels (see Figure 2.2.7). The panels were placed sequentially and bolted into the primary steel frame (see Figure 2.2.8).

Tolerances
As with most hybrid projects, construction challenges emerged around intersections of materials. In this case, the CLT floor panels needed to slide into the space between the webs of the wide-flange beams. The architect worked with the steel erectors to develop a sequence of beam installations, whereby steel members did not get tightened until after the CLT panels were placed. This allowed beams to slide aside and gave working tolerances for the wood decks.

▲ **Figure 2.2.8: Constructors guide a CLT floor panel towards the frame, where it will be bolted in place.** © LEVER Architecture

Carbon/Sustainability Overview

The total carbon impact of the structure was not calculated, but the project team has determined that approximately 2.1 million kg CO_2 eq has been saved from being emitted into the atmosphere due to the project's siting and material choices.

Approximately 480,000 kg CO_2 eq was prevented from atmospheric release due to reuse of existing elements in the new structure, and another 330,000 kg CO2 eq was saved due to preserving the existing structure and preventing demolition and excavation that would have had to take place under

"At key locations, decks are notched by one ply at the edges to overlap the steel beams supporting them, exposing the timber to below and providing a smooth, continuous ceiling surface."

▲ **Figure 2.2.9: East elevation view, with courtyard at center.** © LEVER Architecture

a traditional approach. This represented about 31 percent of the total amount of concrete in the building (Habch & Smith 2023).

The use of wide-flange beams allowed 86 percent of the steel on the project to be produced through an electric arc-furnace (EAF) process, which has a lower carbon impact than the basic oxygen furnace (BOF) approach. The building's Type III-B designation under the California Building Code allowed both the steel and CLT structural framing to be exposed to the elements, reducing the embodied carbon that would be present in architectural finishes and fireproofing (see Figure 2.2.9) (ibid.)

The project's location near multiple transit routes allowed a reduction of one entire level of parking that would otherwise have been required, contributing a further 360,000 kg CO_2 eq in avoided emissions from concrete production.

Project Team

Owner/Developer: Redcar Ltd.
Architect: LEVER Architecture
Structural Engineer: Glotman Simpson
MEP Engineer: AMA Group
Contractor: Shawmut Design and Construction
Steel Manufacturer: Orange County Erectors
Engineered Mass Timber Supplier: Structurlam
Landscape Architect: James Corner Field Operations

2.3 Case Study

Billie Jean King Main Library, *Long Beach (CA), United States*

▲ **Figure 2.3.1: The exterior of Billie Jean King Library.** © Benny Chan | Fotoworks

Project Base Metrics

Status

- Completed: 2019

Building Function:

- Institutional

Structural Materials

- **Mass Timber:**
  Structural System (girders and joists): levels 1 and 2
  Diaphragm (plywood): Level 2 and Roof
- **Concrete**:
  Foundations/Parking Structure: Level -1
  Columns: Level 1
- **Steel:**
  Columns: levels 1 and 2
  Frame: Level 2

Building Milestone Dates

- Construction start: 2017
- Construction complete: 2019

Height

- Height to architectural top: 14 meters
- Height to highest occupied floor: 5 meters
- Height to tip: 14 meters

Number of Floors

- Above grade: 2
- Below grade: 1 (existing garage)

Building Floor Area

- Total gross floor area: 8,686 m^2
- Net internal area: 8,686 m^2
- Area of building footprint: 5,249 m^2
- Entire site/plot: 7,244 m^2
- Site coverage: 84%

Number of Elevators

- 2 cores, 3 cabins

Cost of Construction:

- US$48 million

Background/Overview

Billie Jean King (BJK) Main Library is a two-story building located in the civic center of Long Beach (CA) hosting more than 1,000 visitors daily (Gonzalez 2020) (see Figure 2.3.1). This building serves the community with a range of space types, including group study rooms, independent work areas, a family learning center, a children's reading room, a veterans' resource center, a maker space, and over 300,000 books (see figures 2.3.2 and 2.3.3) (SOM n.d.). The structure replaced an existing public library dating back to 1970 that lacked significant daylight and community spaces (Marani 2020). The new library was named after the legendary tennis player who grew up in Long Beach (CA) (Parab 2021). Billie Jean King was famed for her serves and the efficiency of her groundstrokes and volleys, which translated to the building's design form of long, rectilinear glass framework and reddish Douglas fir (ibid).

Owner/Developer Motivations

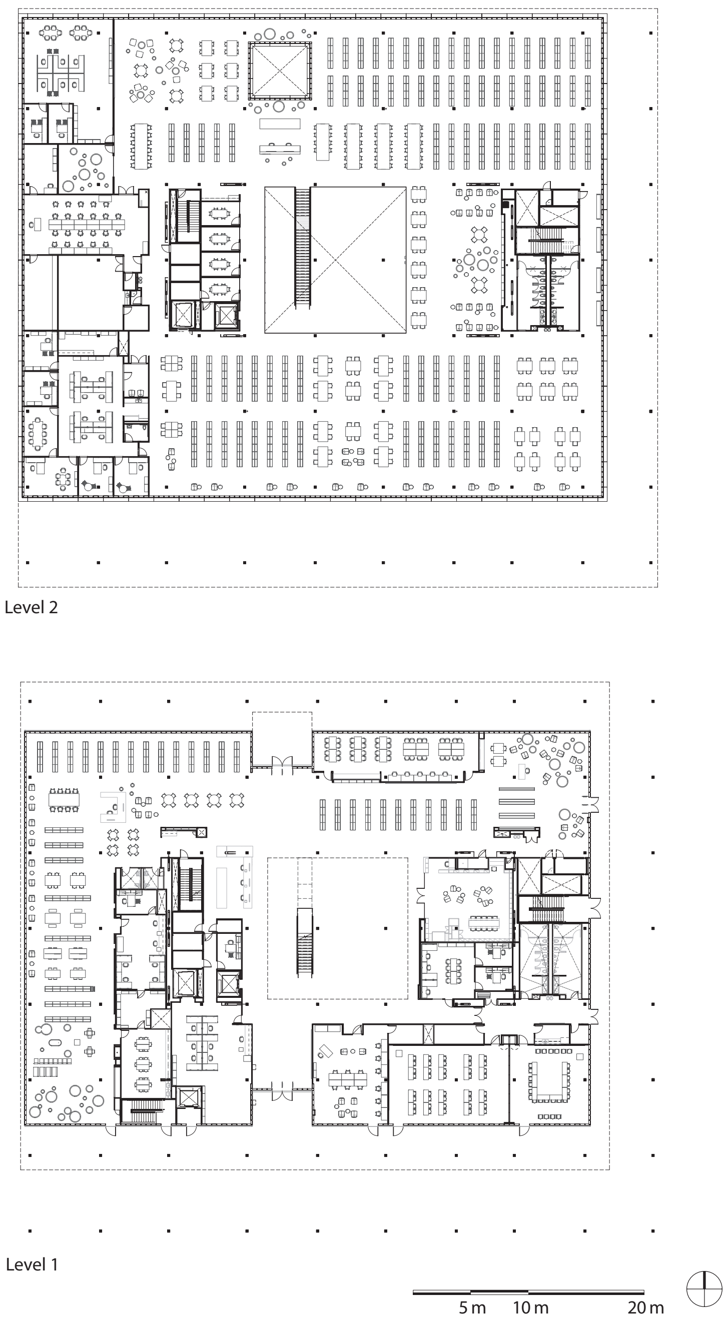
BJK Main Library was built on an existing underground concrete parking garage, which was the basis for the building's material decisions. The low weight of timber enabled the existing structure to be built upon, allowing for a 65 percent reduction in material waste compared to a conventional concrete building, which came with associated carbon emission reductions (SOM n.d.). Steel was used to optimize the building's structural properties (ibid). Quality and durability were also a big focus of planning discussions because the project is slotted to be maintained by the developer over the next four decades (AIA LA 2020).

Structural Systems

Billie Jean King Library is one of the few buildings in Southern California that uses a heavy timber structural system with steel and concrete pulled in for reinforcement. Timber comprises nearly

▲ Figure 2.3.2: The interior of Billie Jean King Library showcases the community-centric layout. The long spans are achieved by glulam beans sitting on brackets on either side of concrete-filled steel columns. © Benny Chan | Fotoworks

"The high seismic demands necessitated a ductile steel braced frame, both for economy and to maintain low foundation loads."



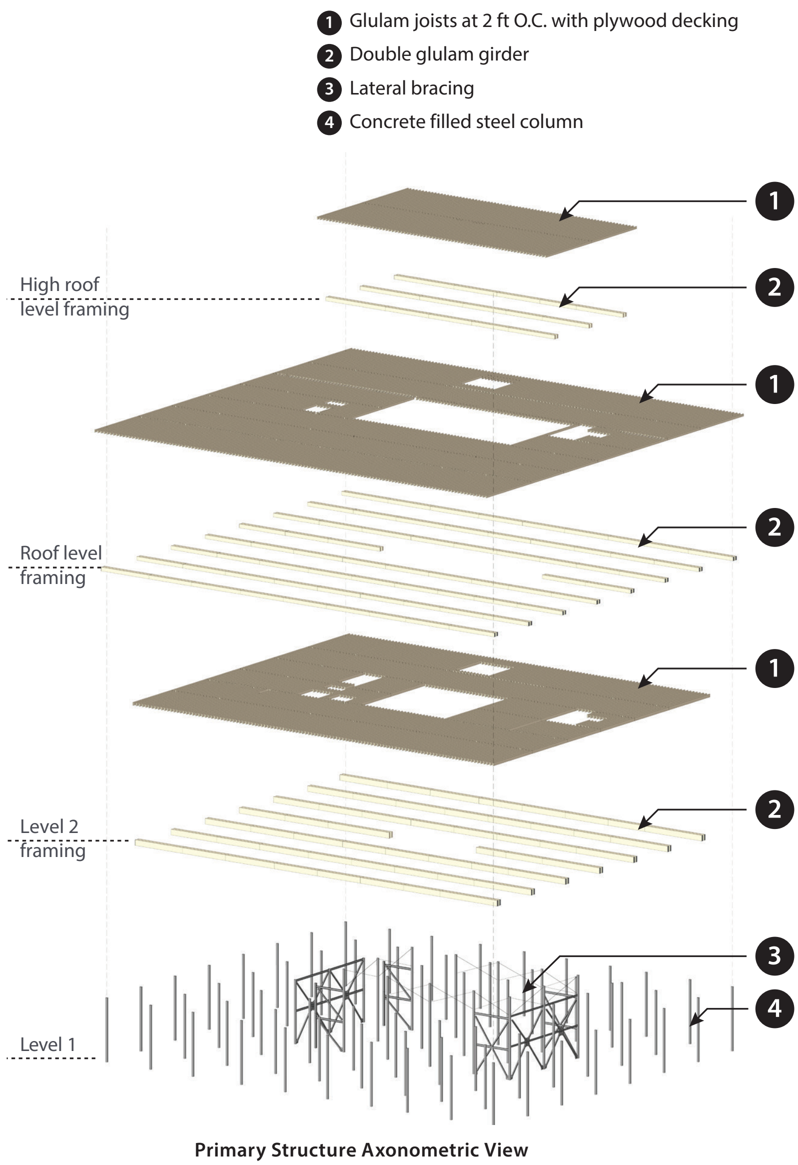
▲ Figure 2.3.3: Floor plans of Billie Jean King Library. © SOM

80 percent of the new library (Stephens 2020). The library was built on top of an extant concrete parking structure and consists of a perimeter of concrete-filled hollow-steel columns, supporting a structural system of 36-inch (914 mm)-deep glulam girders spaced 30 feet (9 meters) apart, which, in turn, support 19.5-inch-(495-millimeter)-deep glulam joists spaced at 2-foot (610-millimeter) intervals (see figures 2.3.4 and 2.3.5) (Marani 2020). Both elements handle the compressive load of the floor plate, which consists of a 3-inch (19-millimeter) lightweight concrete slab placed atop a 3/4-inch (76-millimeter) plywood diaphragm (ibid.) (see Figure 2.3.6).

Timber's lighter material weight compared to steel and concrete, paired with a plywood diaphragm significantly reduced the weight of the building (Johnson 2022). If timber had not been used for the structural system, concrete floor slabs would have been utilized, adding significant weight. Structural alignment was prioritized from the offset to avoid structural transfers that would have increased cost (ibid.).

The library has a loading capacity of up to 140 pounds per square foot (0.97 MPa) due to the weight of the stacks and books. The double-glulam (GLT) girder system supported the heavy load (ibid).

The high seismic demands necessitated a ductile steel braced



▲ Figure 2.3.4: An axonometric drawing detailing the constituent components of the structure at Billie Jean King Library. © SOM

frame, both for economy and to maintain low foundation loads. Steel gravity columns were extended throughout the floor plate once steel was selected for the seismic resisting system. The steel columns are single posts with no splices (Johnson 2022). Glulam joists allowed for a blocked plywood diaphragm, which is lighter than a CLT deck, to be used (ibid).

The west façade of the building has no overhang, which prompted the architects to make the curtain wall more opaque via an aluminum vertical plank system, alternated with strips of glass (Stephens 2020).

Figure 2.3.7 breaks down the library's components.

MEP Systems

The library's MEP systems routing required enhanced collaboration and coordination to minimize disruption to the timber elements (Marani 2020). This coordination was made possible through a shared digital building information model (BIM) and a large physical mock-up, which became the prototype for experimenting and evaluating the different building systems and their integration (ibid.). The MEP systems were left uncovered to feature the timber structure (see Figure 2.3.8) (SOM n.d.).

Building Envelope

The building's envelope comprises a curtain wall system of aluminum and

▲ Figure 2.3.6: Corner connection detail, showing the concrete-filled steel columns, glulam girders and joists, and plywood decking. © SOM

▲ Figure 2.3.5: Corner connection detail, showing the concrete-filled steel columns, glulam girders and joists, and plywood decking. © SOM

> “Glulam joists allowed for a blocked plywood diaphragm, which is lighter than a CLT deck, to be used.”

glass that maximizes daylight while mitigating glare (see Figure. 2.3.9 and Figure 2.3.10) (AIA LA 2020).

Construction Process

Sourcing and Supply Chain
Early engagement with mass timber suppliers and erectors were considered in selecting the structural systems to manage cost and schedule. The red-stained Douglas fir was sourced from Oregon and Washington (Stephens 2020).

Prefabrication
The design and structure of the library were optimized to keep the project delivery on time and within budget

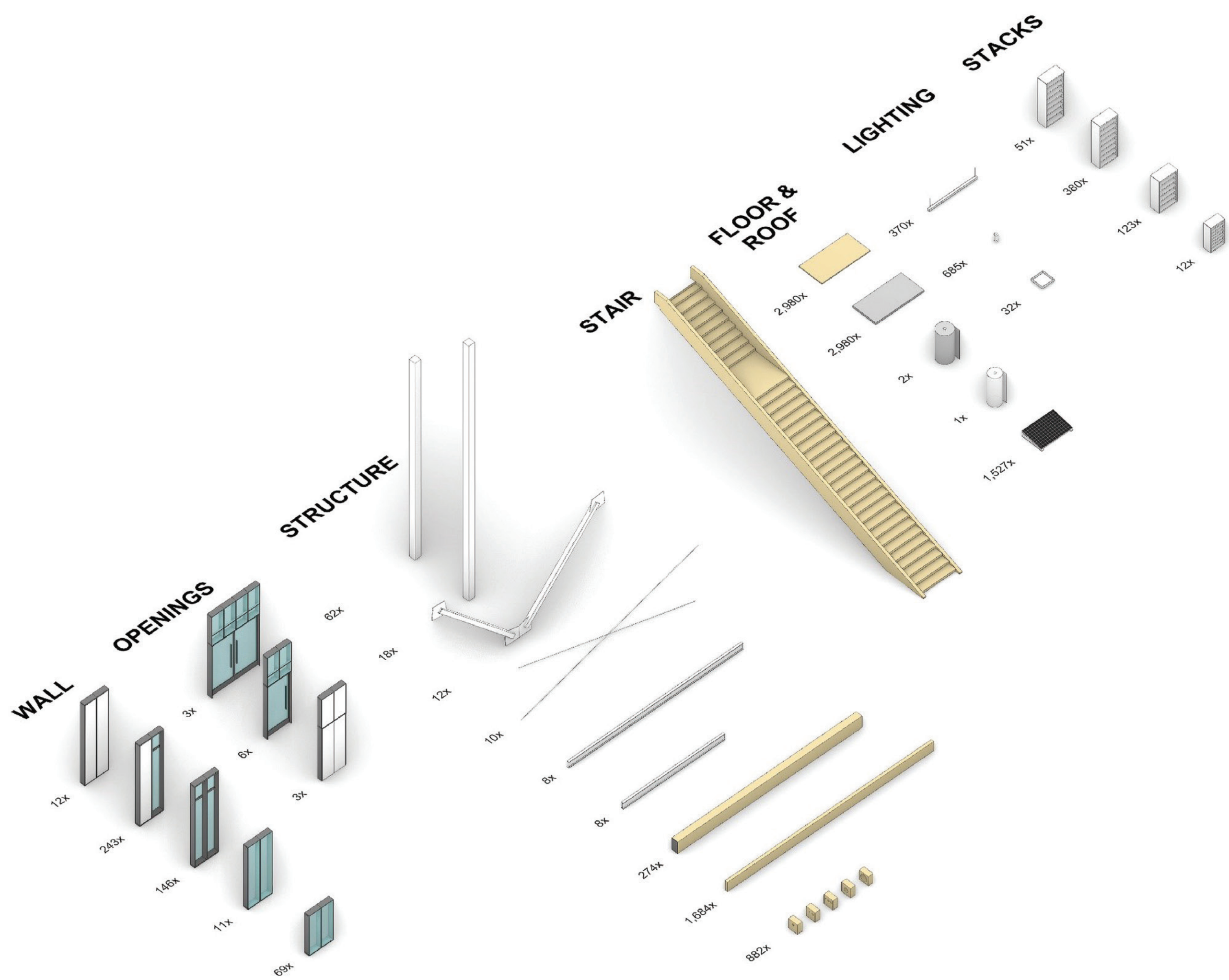
(Marani 2020). This planning resulted in a kit-of-parts with repetitive members that could be fabricated off-site (see Figure 2.3.11) (ibid.).

Carbon/Sustainability Overview

The building is LEED Platinum-certified due to features like the flat roof outfitted with 1,590 photovoltaic modules paired with an efficient HVAC system, reducing energy use by 63 percent (Stephens 2020). The 39-foot- (12-meter)-high atrium with clerestory windows permeates the inside with ample daylight, reducing the need for electrical lighting (ibid.).

Approximately 1,700 metric tons of carbon were sequestered within the timber of this project. The net sequestration of the entire structure is -500 metric tons.

Using wood paired with the reuse of the existing parking garage foundation reduced the embodied carbon by 61



▲ Figure 2.3.7: A drawing detailing the different components of Billie Jean King Library. © SOM

▲ Figure 2.3.8: An interior photo of Billie Jean King Library, highlighting the significant presence of exposed timber and the clerestory window surrounding the atrium. © Benny Chan | Fotoworks

▲ Figure 2.3.10: Billie Jean King's exterior emphasizes the ample use of aluminum and glass. © Benny Chan | Fotoworks

▲ Figure 2.3.9: An exterior photo of Billie Jean King Library, highlighting the interfacing of the building's envelope with daylight. © Dave Burk I SOM

percent, compared with erecting a new parking garage and a conventional concrete building (Stephens 2020).

An integrated water-storage system, drip irrigation, and low-flow fixtures save 138,909 gallons (525,828 liters) of water resulting in a 42 percent reduction of total water consumption compared to conventional construction (ibid.).

The building was developed on a brownfield site and consists of 47 percent native planting, as well as 53 percent drought-tolerant planting (ibid.).

▲ Figure 2.3.11: With columns in place, the prefabricated glulam beams were brought to the site and hoisted individually. © SOM

Project Team

Owner: City of Long Beach
Developer: Plenary-Edgemoor Civic Partners
Architect: Skidmore, Owings, & Merrill
Structural Engineers: Skidmore, Owings, & Merrill
Civil Engineers: KPFF Consulting
Vertical Transportation: Syska Hennessy Group
Wood Scientist: Anthony & Associates, Inc.
MEP Engineer: Syska Hennessy Group
Main Contractor: Clark Construction Group
Acoustics: Newsom Brown Acoustics
Fire & Life Safety: Jensen Hughes
Sustainability/Environmental Consultants: SOM
Other Consultants: HLB Lighting Design (lighting); Johnson Controls (operations and maintenance); International Parking Design (parking); Curtainwall Design (roofing/waterproofing)
Metal panels: VNSM
Metal/Glass Curtain Wall: Benson Industries
Glass: Viracon (exterior curtain wall); Vitro (interior); Paints, stains, coatings: Sherwin-Williams; PPG, Tnemec
Acoustical Ceilings: Armstrong, USG
Built-up Roofing: Sika Sarnafil

2.4 Case Study

Houston Endowment Headquarters, *Houston, United States*

▲ Figure 2.4.1: The Houston Endowment headquarters is a two-story steel-timber hybrid office building, adjacent to Spotts Park. © Kevin Daly Architects, photo by Iwan Baan

Project Base Metrics

Status
- Completed: 2022

Building Function
- Office

Structural Materials
- Three-ply CLT decking supported by steel columns and beams

Building Milestone Dates
- Construction start: March 2021
- Construction completion: September 2022
- Construction period: 18 months

Height
- Height to architectural top: 13.8 meters
- Height to highest occupied floor: 6.2 meters
- Height to tip: 13.8 meters

Number of Floors
- Above grade: 2
- Below grade: 1

Building Floor Area
- Total gross floor area: 9,662 m2
- Net internal area: 5,780 m^2
- Area of building footprint: 3,178 m^2
- Entire site/plot: 20,699 m^2

Number of Elevators
- 1 core, 1 cabin

Background

Houston Endowment Headquarters is a 32,000-square-foot (2,973 square-meter) office building designed to be a welcoming base for a nearly 90-year-old philanthropic foundation that provides regional funding for projects in the realm of arts, culture, parks, green spaces, and public education (PRODUCTORA 2003; Think Wood 2023). The building is the first steel-timber hybrid structure in Houston (see Figure 2.4.1).

The structure features three-ply cross-laminated timber (CLT) decking supported by steel columns and beams, enshrouded by a 40-foot (12-meter) aluminum canopy with perforated louvers. The timber slabs provide a strong low-carbon alternative to concrete, while the steel columns and beams offer added flexibility and stability (Think Wood 2023). The inside of the building includes an extensive mix of enclosed and open office spaces, multi-use public event spaces, and flexible conference rooms (Arup 2023).

The building is designed as an asymmetrical sequence of framed boxes clad in white scalloped surfaces which exist underneath the perforated custom-made canopy that provides shade to a series of outdoor terraces, as well as the interior (Think Wood 2023). This canopy supports solar panels and protects windows from direct light without closing off the space (Kinetica 2023). The façade supports high daylight transmission, with a visible light transmission rating of 70 percent (Transsolar 2023).

Owner/Developer Motivations

One of the primary goals of this project was to reduce the building's environmental impact at different junctures of its lifecycle. To reach this goal, the project team prioritized energy-efficient planning and design with intent to achieve carbon neutrality by 2030. Photovoltaic panels collect solar energy, and a closed-loop system of 30 geothermal wells contribute to this goal (PRODUCTORA 2023). CLT was selected over concrete to reduce the embodied carbon output. The building achieves net-zero operations for 80 percent of the year.

Concrete was originally scoped as the material of choice, but its heavy weight combined with narrow site conditions and poor soil quality reduced its viability (Think Wood 2023). Ultimately steel and timber were chosen which cut the project's structural cost in half and shortened the construction period due to the smaller mobile cranes that wouldn't have been possible with concrete construction (ibid).

The location of the building also motivated the design decisions and material choices. Houston is known for its intense heat and direct sunlight which made the envelope of the building one of the most critical components to consider (Kinetica 2023). It needed to shade itself and reflect heat with a light physical weight to reduce the mass of the building and therefore reduce thermal load (ibid). Houston is known for its landscape of trees which was channeled in the building's filtered light and shaded dwellings meant to evoke the welcoming feeling of shadow beneath a tree (kdA n.d.).

Structural Systems

The basic structure of the building is a system of steel H-section columns and beams, supporting three-ply CLT on the second floor. The vertical loads are borne by CLT floor panels and steel beams and columns. The lateral loads are managed by steel braced frames.

The CLT is covered by a sound mat, a 2-inch (51-millimeter) gypcrete slab, a raised floor system (305 millimeters), and a finished floor (see Figure 2.4.2).

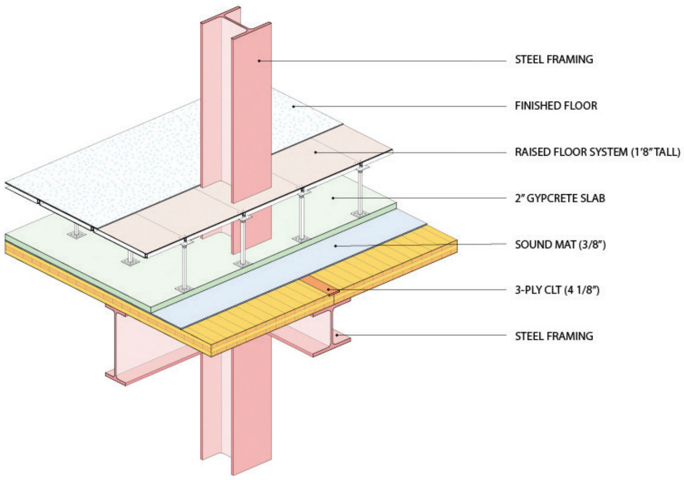
The roof is a hybrid system, with steel framing, topped by a CLT slab and roofing materials. The main roof is raised about 1 meter above the finished architectural soffit ringing the top floor, allowing a bay of clerestory windows to filter light into the building interior (see Figure 2.4.3).

Fire Engineering

As a type III-B building, the structural steel frame did not require additional fire protection and was purposefully left exposed to view. This reduced the embodied carbon, compared to what normally would be present in architectural finishes and fireproofing.

Acoustics

The client required acoustic separation between spaces and the CLT floor assembly needed to be augmented by additional materials,



▲ **Figure 2.4.2: Diagram of a typical junction in the structural system of Houston Endowment Headquarters.** © Kevin Daly Architects

▲ **Figure 2.4.3: The building interior features exposed timber and steel structure, a double-height atrium, and clerestory windows.** © Kevin Daly Architects, photo by Iwan Baan

in this case a 3/8-inch (9-millimeter) sound mat, to meet this requirement. Sound transmission through the floor assembly is reduced by the raised floor assembly. The suggested guideline was STC 50, but there was no code-mandated standard. Acoustic materials were also required in meeting spaces, as the exposed hard-surfaced structural finishes were sound-reflective.

Construction Process

Sourcing

Both the steel and CLT packages were procured early on in construction, which safeguarded the contractor from escalating material costs that occurred during the COVID-19 pandemic.

Prefabrication

Nordic Structures, the timber supplier, was brought on for a Design-Assist contract prior to fabrication and collaborated closely with Arup, the structural engineer, to finalize connection details and panel layouts. During fabrication, the design team shared models with Nordic to ensure all conditions were accounted for and on-site changes would be minimal.

On-Site Construction

A crawler crane located just off the center of the site was used to place the CLT panels, steel beams and steel columns (see Figure 2.4.4).

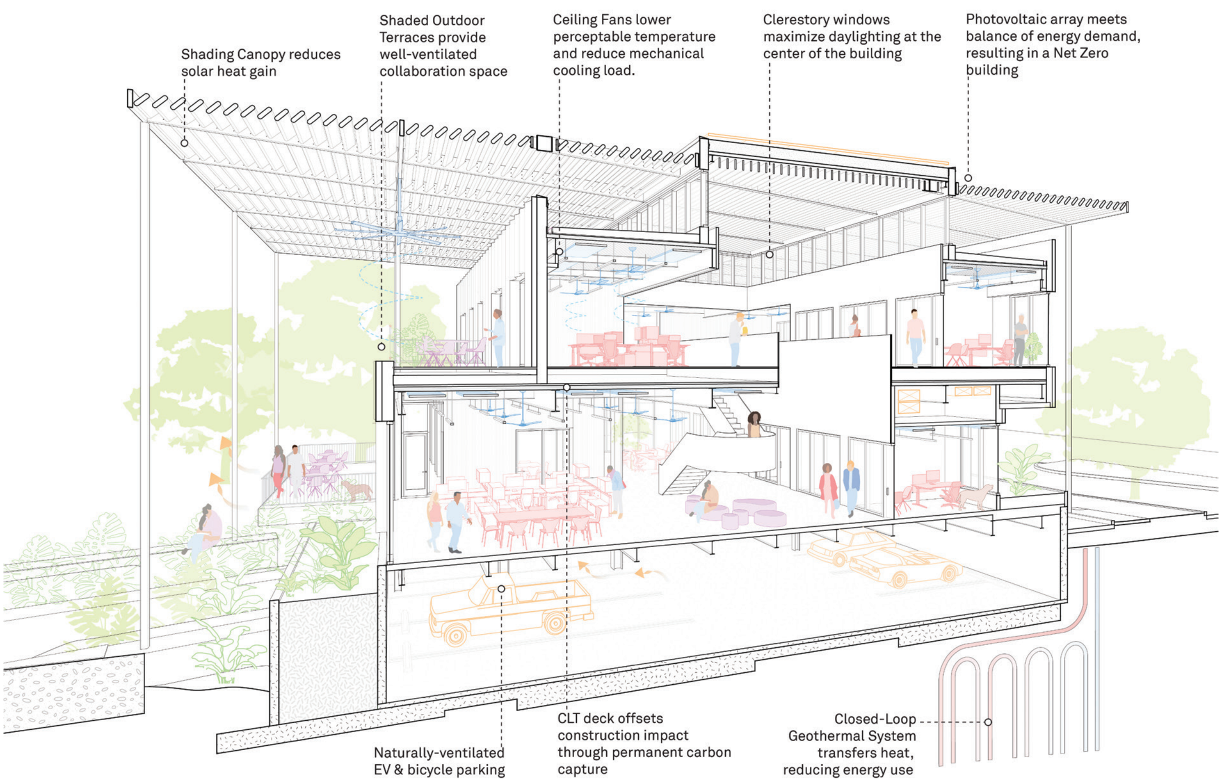
Costs + Insurance Elaborations

The cast-in-place concrete structural system initially proposed to create a high-mass building proved disproportionately expensive in the Houston market. The steel/ timber hybrid structure that was finally adopted reduced the anticipated cost of the primary structure by about 50 percent, shortened the construction schedule, and significantly reduced the extent of the foundation. The final project cost was US$21.5 million. The insurance premiums for this steel-timber hybrid project were on par with concrete material construction insurance premiums.

Carbon/Sustainability Overview

With sustainability at the forefront of developer motivations, the building achieves net-zero operations for 80 percent of the year. These optimized features include the shading canopy, which reduces solar heat gain; the CLT, which sequesters carbon; and the closed-loop geothermal system, which reduces energy consumption (see Figure 2.4.5), clerestory windows admitting indirect daylight, and 320-kilowatt photovoltaic solar panels balancing energy demand. The building achieves 351.18 $MTCO_2$ eq carbon reduction each year (CMTA 2023).

▲ Figure 2.4.4: Construction view of the project, with crawler crane for CLT panel and steel beam and column hoists at center. © Kevin Daly Architects, photo by Iwan Baan



▲ Figure 2.4.5: Cross-sectional view of project, notating sustainable strategies. © Kevin Daly Architects

2.5 Case Study

Lighthouse Joensuu, *Joensuu, Finland*

▲ Figure 2.5.1: Overall view of Lighthouse Joensuu, a 14-story student dormitory in Joensuu, Finland. The structure is predominantly LVL and CLT panels, fully encapsulated and stabilized by a system of connected post-tensioning bars. The exterior envelope is an aluminum panel system. © Daniel Safarik

Project Base Metrics

Status

- Completed: 2019

Building Functions

- Residential (dormitory)

Structural Classification

- Steel-Timber Hybrid over Concrete Podium Slab

Structural Materials

- **Mass Timber:**
  Walls: LVL-G, levels 2 to 14
  Ledgers: LVL-S, levels 3 to 14
  Floors: CLT, levels 3 to 14
- **Steel:**
  Post-tensioning bars: levels 1 to 14
  Brackets: levels 2 to 14
- **Concrete:**
  Walls: Level 1
  Floors: levels 1 and 2
  Columns: Level 1

Building Milestone Dates

- Construction start: 2018
- Construction complete: 2019

Height

- Height to architectural top: 48 meters
- Height to highest occupied floor: 41.2 meters
- Height to tip: 48 meters

Number of Floors

- Above grade: 14

Building Floor Area

- Total gross floor area: 5,936 m^2

Number of Rooms

- 117 rooms

Number of Elevators

- 2

Background/Overview

Lighthouse Joensuu is a student dormitory near the campus of Karelia University of Applied Sciences in Joensuu, Finland, a town of 77,250 people about 440 kilometers northeast of Helsinki (see figures 2.5.1 and 2.5.2). The project uses a mass-timber frame and shear wall system, with high-strength post-tensioning bars providing stability and anchoring the timber structure to the concrete podium slab.

Owner/Developer Motivations

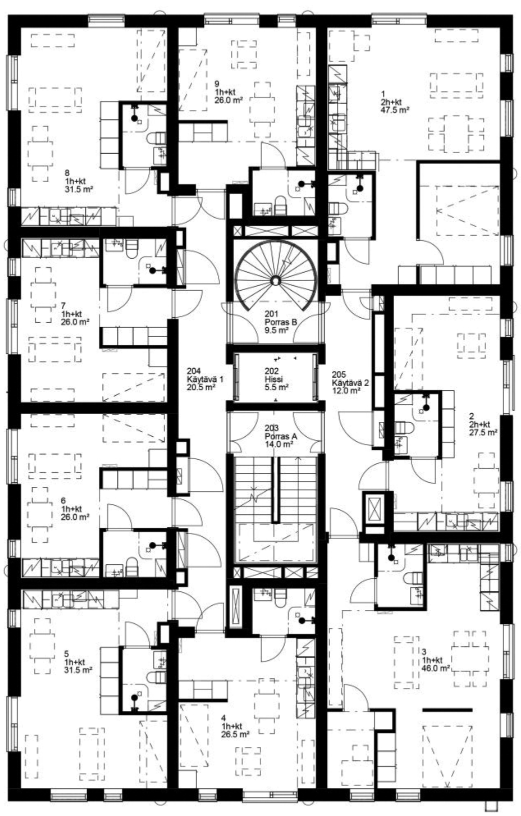
The region's main industry is forestry, and the Joensuu region has advanced research programs in building science. The building site was zoned for an allowable height exceeding its surroundings on the condition that timber be explored as a construction material. The Finnish Ministry for Environment provided funding for research supporting the construction of a low-carbon, efficient and rapidly constructable residential facility for the university's growing student population. Some 30 percent of the town's residents are students.

Structural Systems

The structure of Lighthouse is predominantly 13 floors of load-bearing, multiple-glued laminated veneer lumber (LVL) type "G" walls and seven-ply cross-laminated timber (CLT) floor plates, with a one-story concrete podium at its base. "LVL-G" refers to a type of LVL with about one-fifth of the veneer layers being glued crosswise, which increases load-bearing capacity as well as dimensional stability and rigidity. Three thicknesses of LVL-G are used—162 millimeters from levels 2 to 4, 144 millimeters from levels 5 to 11, and the top levels, 12 to 14, have LVL-G walls 126 millimeters thick. A total of 381 pieces, at 29 per level, were used (see Figure 2.5.3).

The floors are made from spruce CLT and are supported from below by LVL beams , connected with self-driven screws to the LVL-G wall. Across these two types, 587 pieces, with 47 per floor level, were used.

Because the self-weight of the structure was much less than if it had

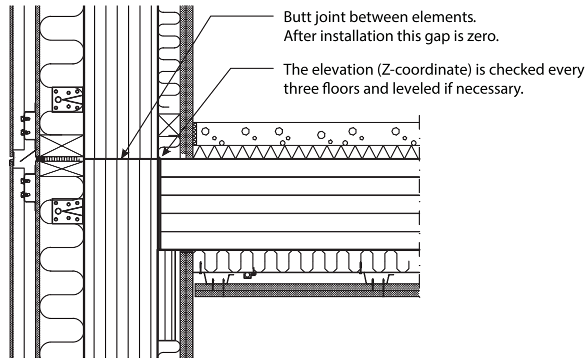


▲ **Figure 2.5.2: Typical dormitory floor plan.** © Arcadia Oy Arkkitehtitoimisto been rendered in concrete, there was concern about the potential overturning moment and uplift forces from winds that could damage the building. Although a concrete core was considered, the team and city planners decided to push forward with a more sustainable steel-timber hybrid approach.

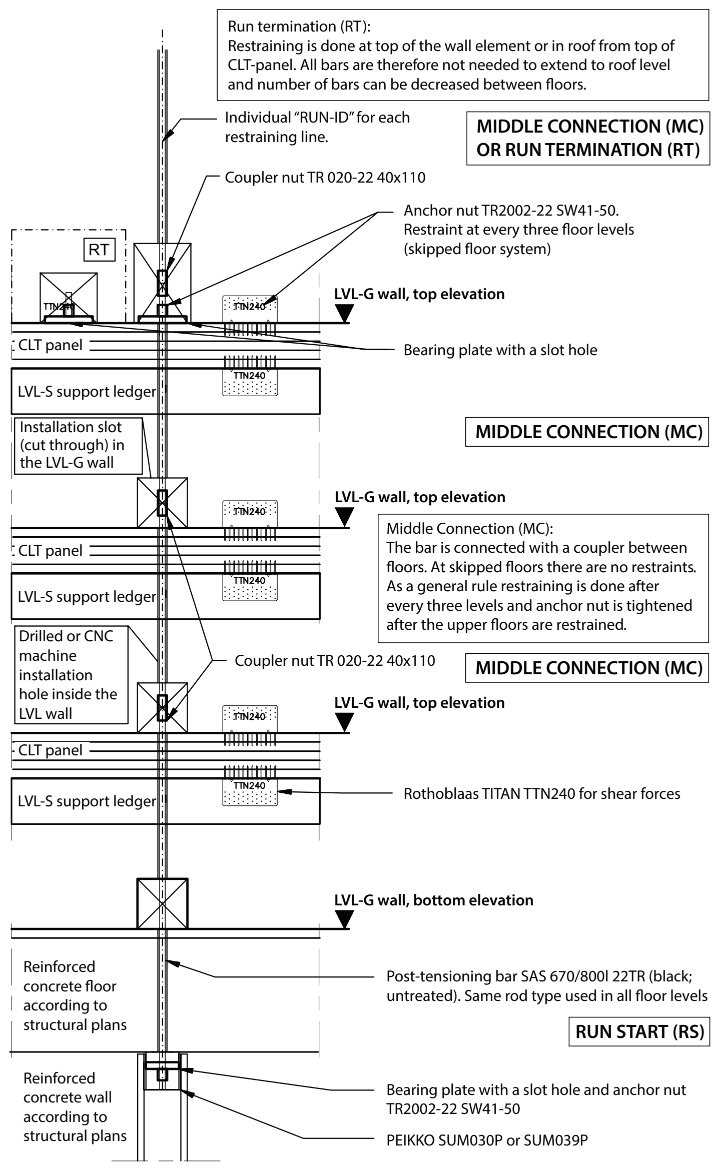
The main use of steel in the structure is post-tensioning bars within the LVL walls, anchoring the mass-timber assembly into the concrete foundation. The post-tensioning bars used in the project were 22-millimeter-diameter SAS 670/800, hot-rolled and ribbed. These reside in 40-millimeter-diameter pre-drilled holes within the LVL walls, connected via couplers at each level and anchor nuts at every third level, with a bearing plate and a slot hole for the continuation of the bars (see figures 2.5.4, 2.5.5, 2.5.6, and 2.5.7).

The tie-down system skips floors, meaning that shear walls are not restrained at each level, but only at every third level (Keskisalo 2018). The bars are unbonded and can move freely inside the LVL-G wall elements. The wall elements are post-tensioned after installation and act against overturning moments.

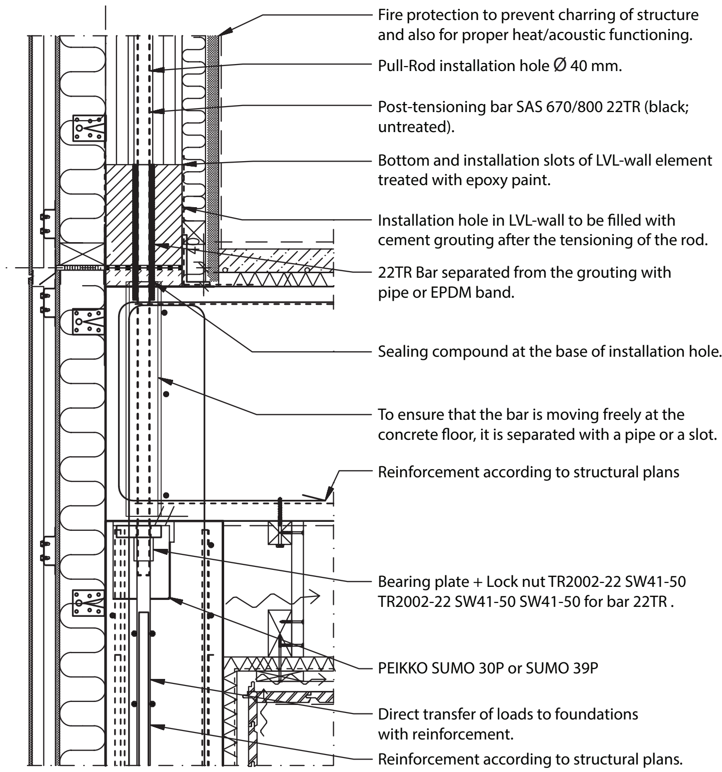
A total of 277 SAS 670/800 22TR bars were used in the project, including those connecting to upper floors: levels 2–4: 94 pieces; levels 5–8: 59 pieces; levels 9–10: 45 pieces; Level 11: 45 pieces; levels 12–14 had a total of 34 pieces.



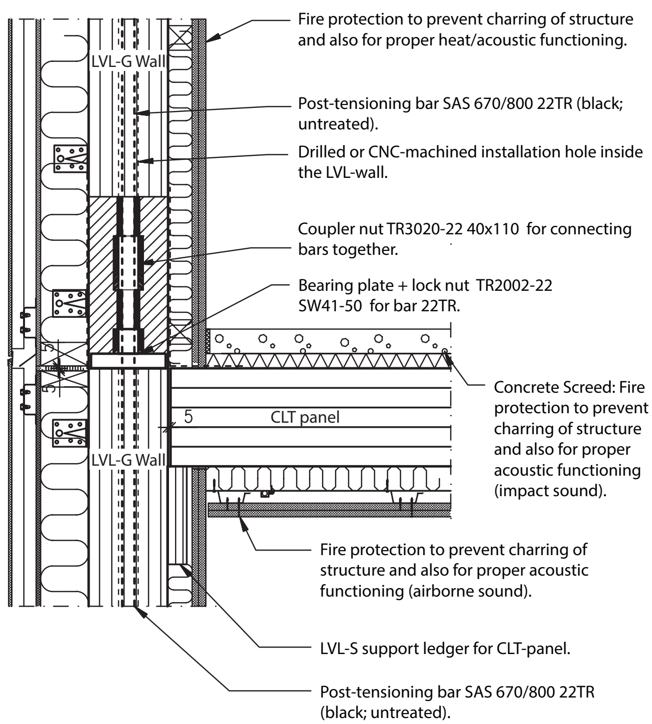
▲ Figure 2.5.3: Detail of LVL wall and CLT panel junctions. © A-Insinöörit



▲ Figure 2.5.4: Overall post-tensioning bars diagram. Multiple bars are connected via coupler nuts. At every three floors, tension is applied at a bearing plate with anchor nut. © Mika Keskisalo



▲ Figure 2.5.5: Post-tensioning bar intersection with concrete floor at base of LVL wall. © A-Insinöörit



▲ Figure 2.5.6. Building midpoint structural detail, showing tensioning of bar at a typical wall-to-floor intersection. © A-Insinöörit

Walls and floors were connected using Rothoblaas TTN240 steel angle brackets (see Figure 2.5.7).

The design was arrived at via hand calculations and counterchecks with Dlubal RFEM software. Generally, horizontal displacement was limited to H/500.

Fire Engineering

In the Finnish code, there was no specific fire design chart applying to timber buildings taller than eight stories, so a functional (performance-based) fire design approach was taken. The main structure on levels 2 to 14 was rated for 90 minutes of fire resistance, with the first-floor areas within the concrete podium and the vertical shafts rated at 120 minutes. There was no exposure of the timber on either side of the walls. They were instead covered and encapsulated with gypsum board and rock wool insulation. The building is also equipped with a sprinkler system.

Acoustics

Zoning for the site of Lighthouse Joensuu dictated high-rise construction and favored the use of wood for all load-bearing structures. With the latest legislation requiring strict measurement and insulation for impact and airborne sound, the structural and sound engineers were presented with a challenge. Furthermore, to meet stiffness requirements, the building is reinforced with post-tensioning bars

▲ Figure 2.5.7. Wall and floor intersection on the building interior, showing brackets and holes cut for tensioning the rods. © Mika Keskisalo

Embodied Carbon Share of Materials, A1–A3 (%)	
Steel and other metals	31
Plastics, membranes, and roofing	16
Concrete	14
Wood	11
Insulation	8
Windows and doors	7
Gypsum, plaster and cement	7
Building systems and installations	3
Other	2

▲ Table 2.5.1. Percentage share of embodied carbon represented by construction materials used at Lighthouse Joensuu. © Stora Enso

and rigid joints, which provide direct routes for further sound transmission.

Lighthouse Joensuu employed a variety of methods to address sound transmission, noise reduction, and impact isolation: the ceiling panels in the apartments were hung from the floor structure with a spring; a dampening wool layer was added into the wall structures; and concrete screed rest above an impact sound insulation layer on the floor structure.

In accordance with standards, measurements were taken throughout the construction process to ensure impact and airborne sound requirements were met. Measurements indicated that impact sound insulation significantly improved as the floor structure, insulation, spring suspension, and drywall were installed, but did not show major change when finishes and furnishings were added. Airborne sound measurements were conducted throughout the construction process as well. As drywall was sealed, the airborne sound insulation improved in some apartments, but did not show improvement in others; however, the boundary level requirement of 55 decibels was met.

After completion, a comprehensive acoustic survey was conducted for building residents. The results showed that occupants considered Lighthouse Joensuu to have comparable sound levels to detached houses, and some residents indicated it is "the quietest residence they had lived in." According to the measurements taken, Lighthouse Joensuu just met the local acoustic requirements, but based on occupant feedback, there is a discrepancy between local requirements and occupant perception. With a student population, there was actually a higher tolerance, even a desire, for more sound transmission, as students sometimes would use sound to locate parties. Such discrepancies could reinforce an argument for acoustic requirements to be performance-based, instead of prescriptive.

Construction Process

Sourcing and Supply Chain

Timber was sourced from Stora Enso. CLT panels were produced in Austria, LVL panels are produced in Finland.

▲ Figure 2.5.8. "On-site prefabrication" of LVL wall panels involved fitting with door and window hardware in a tent. © Mika Keskisalo

▲ Figure 2.5.9. A panel is lifted from the truck onto the structure. Note the cutouts at bottom for access to tension rods. The roof is temporary, also lifted in and off by crane, for protection of exposed timber and comfort of the workers. © Mika Keskisalo

Wall shoes, the steel connectors used for anchoring the tensioning bar into the concrete foundation, came from Peikko in Lahti, about 330 kilometers by truck. The carbon impact of manufacturing and transporting these products to the site is covered in Table 2.5.1, in the A1–A3 and A4–A5 phase.

Prefabrication

The project was modeled in BIM with Autodesk Revit, and shared among all parties via IFC file exchange. This allowed for a high degree of accuracy during shop assembly. Panels were CNC-machined in the shop, with holes for the post-tensioning bars predrilled.

The exterior LVL-G wall elements were "on-site prefabricated" with insulation, façade panels, windows and doors, in a tent next to the main construction site, then lifted into place (see figures 2.5.8 and 2.5.9).

Site Delivery

Elements were lifted from delivery trucks by a mobile auto crane that was present at the work site for the duration of the project. A separate construction lift was in place during erection.

The wood products used at Lighthouse required about 50 truck deliveries, as compared to an estimated 270 deliveries, had concrete been used to construct the entire building (Stora Enso 2019).

On-Site Construction

Post-tensioning bars were adjusted using a hydraulic jack. The initial tension was 20 percent of the ultimate, to allow for length deformation measurement. The bar was then tensioned to the maximum design force of 216.4 kilonewtons per bar. Individual walls were restrained in "zig zag" fashion, so that one side of the building would not have an excess of post-tension force compared to the other.

Walls were installed after the previous floor's CLT elements were in place, allowing crews to move freely on the topmost completed level, with the temporary weather protection erected overhead removed when the wall elements were delivered, then replaced until the next floor's CLT panels arrived (see Figure 2.5.10).

▲ Figure 2.5.10. Underneath the temporary roof, the tops of the LVL walls with post-tensioning bars and anchor plates visible at center-left. © Mika Keskisalo

"Overall installation speed was two weeks per level to start, improving to one week per level as the crew gained experience."

Overall installation speed was two weeks per level to start, improving to one week per level as the crew gained experience.

Tolerances

There was a need to test for building settlement, since wood member swelling and shrinkage had to be accounted for, alongside long-term creep and the fact that the floors were restrained by post-tensioning bars that were gradually tightened as more floors were added during construction. Reported settlement was around 3 millimeters for each three-story stack of floors tied by a single bar. The sleeves for the post-tensioning bars were 40 millimeters across, twice the bar's diameter, to account for deflection and settlement.

For wall-to-wall connections, the maximum tolerance allowed was 2 millimeters at each end; 5 millimeters for wall-to-floor connections, and 10 millimeters for support-beam-to-wall connections.

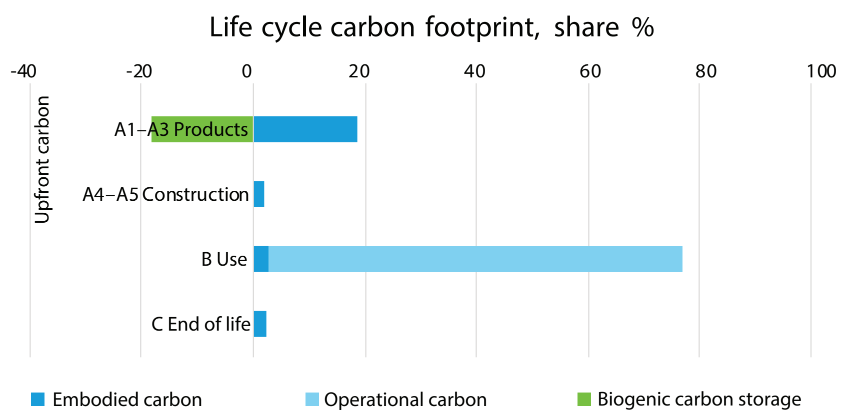
The construction team used displacement sensors to measure deformations post-construction; the largest recorded within the first 4 months was 15 millimeters; in the next 24 months, further deformation was limited to 5.5 millimeters.

Moisture Management

Wood members were delivered to site, wrapped in protective plastic, with moisture content of 10 to 14 percent for CLT and 8 to 10 percent for LVL-G. Fluctuations of two to five percent were expected during

Total Embodied Carbon (kg CO_2 eq/m²), Based on EPD Modules		
Stages	**Phases**	**Estimated GHG Emissions (kg CO_2 eq/m²)**
Manufacturing and construction	A1–A3 A4–A5	5.52 0.58
Use	B1–B7	22.59
End of life	C1–C4	0.74
Results	**Total estimated GHG emissions**	**29.42**

▲ Table 2.5.2. Total embodied carbon estimates for Lighthouse Joensuu. © Stora Enso



▲ Figure 2.5.11. Share percentages of life cycle carbon used in each phase of the life cycle of Lighthouse Joensuu. © Stora Enso

construction, due to outdoor air humidity and indoor heating is applied.

Carbon/Sustainability Overview

The overall carbon emissions impact of the Lighthouse project was captured by the project team and used as a case study by its timber supplier, Stora Enso (2019). The building was calculated to have stored more than 1,600 metric tons of CO_2 throughout its lifespan. This quantity is estimated to represent 88 percent of the embodied carbon from all construction products used in the project. This was accomplished via the use of 1,200 cubic meters of LVL-G for the walls, 900 cubic meters of CLT for the floors, and about 100 cubic meters of other timber products (Keskisalo 2018).

The carbon impact overview of the building materials used at Lighthouse is catalogued in Table 2.5.1; material embodied carbon shares are shown in Table 2.5.2 and Figure 2.5.11.

Out of the three systems that could have been used to achieve the anchoring capability of 216 kilonewtons, the options were:

- Reinforced concrete, C20/25 strength, 9 m³ = 2,600 kg CO_2 eq
- Post-tensioning bar, 22-TR + plate + nut = 200 kg CO_2 eq
- Steel plate: 650 x 550 x 10 mm, + 100 d10 screws = 120 kg CO_2 eq

The team's selection of the post-tensioned bar system ensured that the wall cross-sections were not subject to extensive tension forces, but instead were compressed, which was seen as the most structurally optimal (Hirvonen 2022).

Project Team

Owner/Developer: Joensuun Elli Student Housing Company
Architect: Arcadia Oy Arkkitehtitoimisto
Structural Engineer: A-Insinöörit (AINS Group Joensuu)
MEP Engineer: Granlund Oy
Fire Engineer: KK-Paloonsultit Oy
Life Safety Engineer: Palotekninen Insinööritoimisto Markku Kauriala Oy
Main Contractor: Rakennustoimisto Eero Reijonen Oy
Steel Manufacturers: Peikko (wall shoes); Rothoblaas (connectors); SAS Systems (post-tensioning bars)
SPost-tensioning Contractor: Naulankanta Oy
Engineered Mass Timber Supplier: Stora Enso Wood Products Oy Ltd

2.6 Case Study

Sara Kulturhus, *Skellefteå, Sweden*

▲ **Figure 2.6.1. Overall view of Sara Kulturhus, Skellefteå.** © Jonas Westling

Project Base Metrics

Status
- Completed: 2021

Building Function
- Mixed-Use
  Level 1: hotel lobby and culture center entrance
  Levels 2 to 3: theater
  Level 4: conference center
  Level 5: mechanical spaces
  Levels 6 to 18: hotel
  Levels 19 to 20: restaurant and spa

Structural Classification
- All-Timber over Steel-Timber Hybrid

Structural Materials
- **Mass Timber:**
  Columns (GLT): levels 1 to 4 and levels 19 to 20
  Floors (CLT): levels 1 to 4
  Beams (GLT): levels 1 to 4
  Modules (GLT/ CLT): levels 6 to18
  Walls (CLT): levels 19 to 20
  Core (CLT): levels 1 to 20
- **Steel:**
  Columns: levels 19 to 20
  Box truss: Level 5
- **Concrete:**
  Foundations
  Floors: levels -1 to 1, 5, 19, and 20
  Columns: Level -1

Building Milestone Dates
- Construction start: November 2018
- Construction complete: October 2021
- Construction period: 36 months

Height
- Height to architectural top: 72.8 meters
- Height to highest occupied floor: 66.8 meters
- Height to tip: 72.8 meters

Number of Floors
- Above grade: 19
- Below grade: 1

Building Floor Area
- Total gross floor area: 28,000 m^2
- Net internal area: 27,867 m^2
- Area of building footprint: 5,957 m^2 (52 x 122 m)
- Entire site/plot: 7,100 m^2
- Site coverage: 84%

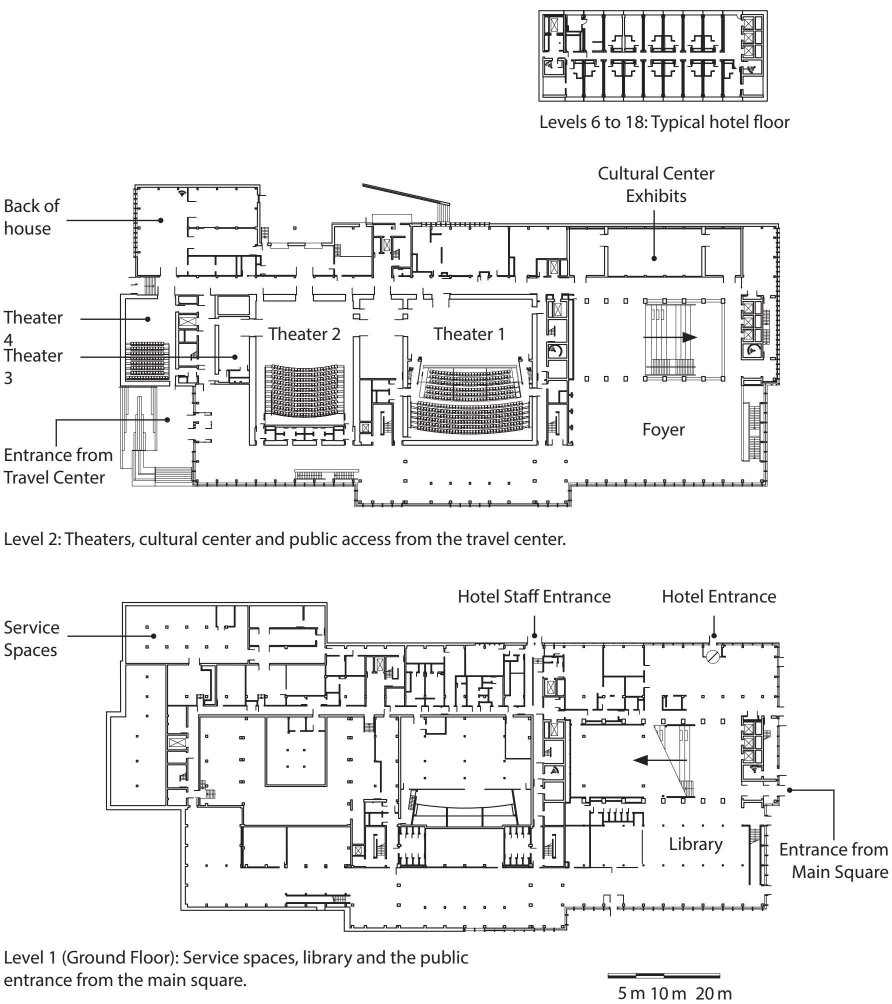
Number of Apartments
- 208 Hotel rooms

Number of Elevators
- 8

Background/Overview

Sara Kulturhus is a 20-story mixed-use building (see Figure 2.6.1) that has become the symbol of Skellefteå, Sweden, an industrial city of 33,000 on the Gulf of Bothnia, best known as a gold-mining hub. Its program is highly diverse, while centered around the arts.

In the low-rise portion of the project is a cultural center with six performing arts stages for the Västerbotten Regional Theatre, two restaurants, a library, the Anna Nordlander Museum, and Skellefteå Art Gallery. The high-rise portion contains a hotel with spa, conference center, and a rooftop restaurant (see Figure 2.6.2).



▲ **Figure 2.6.2. Ground and typical floor plans.** © White Arkitekter, redrawn by CTBUH.

Owner/Developer Motivations

The municipality of Skellefteå sought a building that would play a role in regenerating a relatively small industrial city in the far north of Sweden, which had been losing population. It was important to the city to make a statement about sustainability, keep carbon emissions low, and highlight local timber resources. An open international competition was staged in 2015, and the project was awarded to White Arkitekter in May 2016.

Structural Systems

Sara Kulturhus (see Figure 2.6.3) uses two different primary systems constructed of timber. The low-rise portion has glued laminated timber (GLT) columns and beams (see Figure 2.6.4), with cores and shear walls in cross-laminated timber (CLT). The high-rise portion uses a modular structural system, with prefabricated CLT modules stacked between the elevator cores (see Figure 2.6.5). The column-and-beam system is extended over the rooftop deck of the low-rise portion, to express the timber construction as a pergola. The deck itself is also surfaced in timber, as is the exterior cladding on the low-rise portion. On the high-rise, CLT panels are visually revealed to the exterior, but are protected by a glass curtain wall.

The project is complex structurally, due to the variety of the program and the need to support the hotel structure on top of a long-span conference and performing arts center.

The basement is structured in reinforced concrete and supports the theaters' service spaces. Levels 1 through 4 house the cultural center, made up of the theaters and conference center. The necessary spans are accommodated by the column-beam-platform structural system, which includes GLT columns, beams, and trusses and CLT shear walls of either 140 or 160 millimeters' thickness (see figures 2.6.6–2.6.10).

GLT columns are generally set on a 3.6-by-7.2 meter grid, except in theaters and lobbies, and range widely in size. The three most typical dimensions are 215 by 450, 430 by 450, and 330 by 495 millimeters. The largest-dimensioned columns are 845 by 645 millimeters (see Table 2.6.1).

Where there is a gap in the Level 2 floor to open up the raked seating area into a large volume, GLT beams form a perimeter band and tie together the massive columns.

A set of trusses composed of GLT beams, with an array of GLT chords, are held in tension by steel rods running parallel to the beams, with spans 13.5 meters across the lobby space at the center of the project, creating a dramatic, four-story-high room surfaced on three sides by exposed timber. Diagonal steel rods provide added stability. Junctions between steel elements are concealed within the GLT members (see Figure 2.6.11).

▲ Figure 2.6.3. Sara Kulturhus is the new symbol for the northern Swedish city of Skellefteå, which is amidst a regenerative transition from mining to a more sustainable economy. © Åke Eson Lindman

▲ Figure 2.6.4. GLT columns and beams seen during construction on a level in the low-rise podium. © Martinsons I Jonas Westling

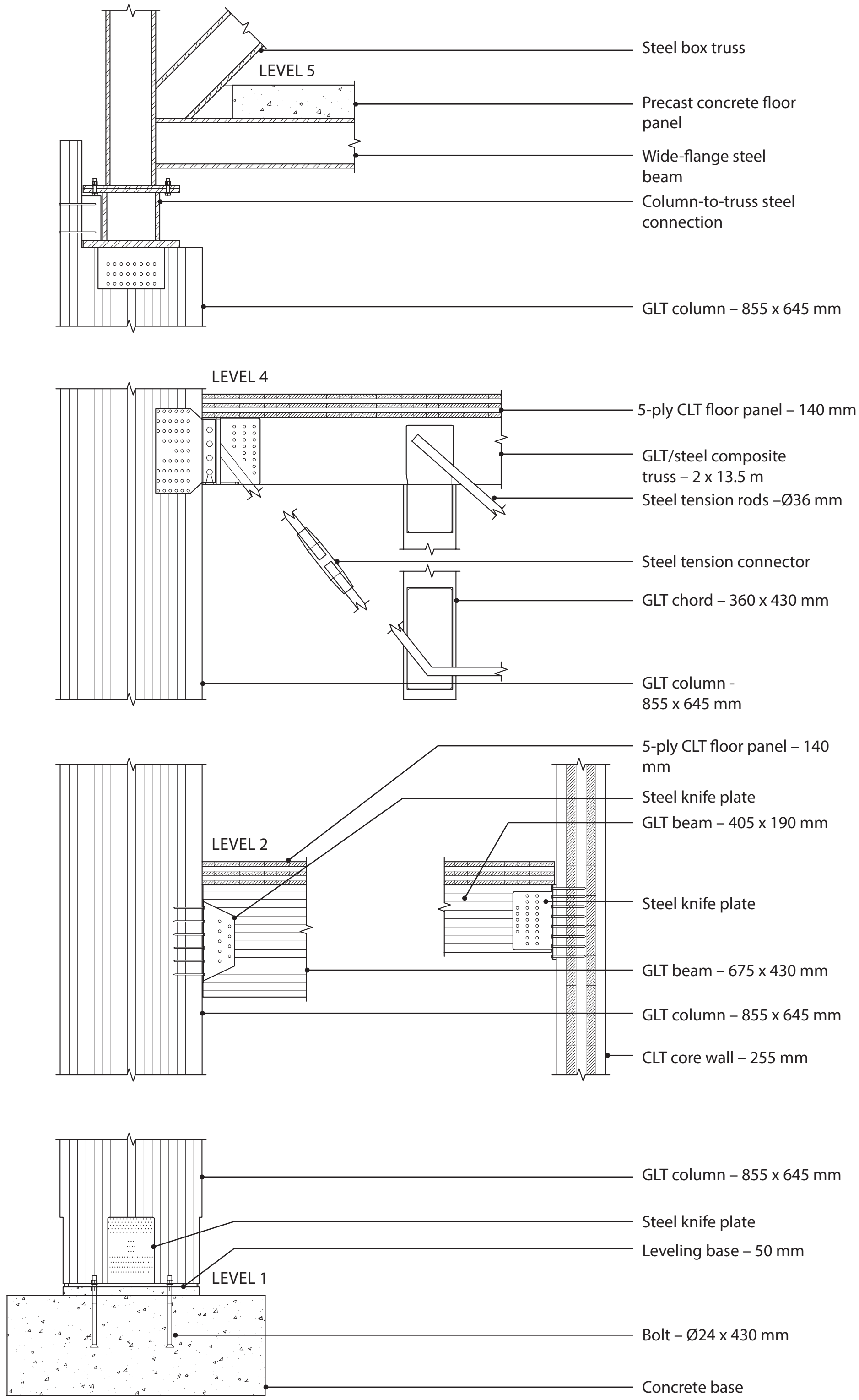
▲ Figure 2.6.5. A prefabricated CLT module, which will form one of the hotel rooms, is lifted into place. © Martinsons I Jonas Westling

▲ Figure 2.6.6. Detail of the connection between the steel box truss and the GLT column below. © Martinsons I Jonas Westling

▲ Figure 2.6.7. Detail of the steel-timber truss used for the long spans of the cultural space. © Martinsons I Jonas Westling

▲ Figure 2.6.8. Detail of the column-beam-platform system used on the lower floors. © Martinsons I Jonas Westling

▲ Figure 2.6.9. Detail of the connection between the knife plate embedded in the concrete floor at level 1 and the GLT column. © Martinsons I Jonas Westling



▲ Figure 2.6.10. Typical connection details for levels 1 to 5. © White Arkitekter, redrawn by CTBUH

In the cultural center, GLT trusses achieve the long-span roofs over the performing arts spaces below, augmented by horizontal steel H-section stiffeners between diagonal braces.

The longest timber span in the project is 24.3 meters, and the greatest height of any room is 20.8 meters. The typical floor-to-floor height is 3.2 meters.

Level 5 is caged within a large steel truss composed of H-sections for the beams and multiple dimensions of square sections for the columns and diagonal braces. This massive truss rests on GLT columns extending to the ground. The floor is poured concrete on a CLT deck. This built-up region uses heavier materials in order to hold the building's physical plant and other technical equipment. It also transfers some of the vertical loads from the tower above to the perimeter columns and walls (see Table 2.6.2 for steel quantity information).

Levels 6 through 18 contain premanufactured, self-supporting hotel modules made of CLT set among GLT columns and beams and two CLT elevator cores (see figures 2.6.12–2.6.15). Levels 19 and 20 use both steel and GLT columns, with CLT shear walls and concrete floors. From level 6 to 20, lateral support is provided by the CLT elevator cores.

Levels 19 and 20 accommodate the hotel's restaurant and spa, and as such

General Mass Timber/Structural Information			
Structural Systems			
Steel-Timber Hybrid Building		Core system	CLT
		Floors	Levels -1 to 1, 5, 19 to 20: concrete floors Levels 2 to 4, 6 to 18: CLT floors
		Columns	Levels 1, 5, 19 to 20: steel columns Levels 1 to 4, 19 to 20: GLT columns
		Beams	Levels 1 to 4, 19 to 20: GLT beams Level 5: steel box truss Levels 19 to 20: steel beams
		Prefabricated modules	Levels 6 to 18: GLT and CLT modules
		Lateral system	Two CLT cores
		Building envelope	Double-skin façade with an exterior aluminum mullion and glass curtain wall protecting the interior layer of exposed GLT and CLT
Engineered Mass Timber Products			
General		Species	Spruce
		Density	430 kg/m³
Glued Laminated Timber (GLT)	Columns	Grid spacing	Hotel: 3.6 x 6.3 m
		Number of columns per typical level	Hotel: 66 columns
		Column height	3.2 m
		Typical column dimensions	Hotel: 215 x 400 mm
		Total volume	1,092 m³
		Total weight	469,560 kg
	Beams	Total volume	847 m³
		Total weight	364,210 kg
		Total volume	84 m³
		Total weight	36,120 kg
Cross-Laminated Timber (CLT)	Floors and Roofs	Panel thickness	Cultural Center floors: 140 mm Hotel ceiling: 5-ply CLT 100 mm Hotel floors: 5-ply 140 mm Roofs: 5-ply 160 mm
		Total volume	2,788 m³
		Total weight	1,198,840 kg
	Walls	Panel thickness	Core: 5-ply CLT 255 mm; Hotel: 5-ply CLT 120 mm
		Total volume	7,211 m³
		Total weight	3,100,730 kg
Mass Timber		**Total volume**	**12,022 m³**
		Total weight	**5,169,460 kg**

▲ Table 2.6.1. General structural information for Sara Kulturhus.

use GLT and steel columns, rather than the GLT/CLT modules, to accommodate the greater open areas.

Code Considerations

Swedish code is neutral as to the type of materials used in a building, and only states performance requirements and fire loads for occupancy levels, which focus only on the fire to which structural members are exposed.

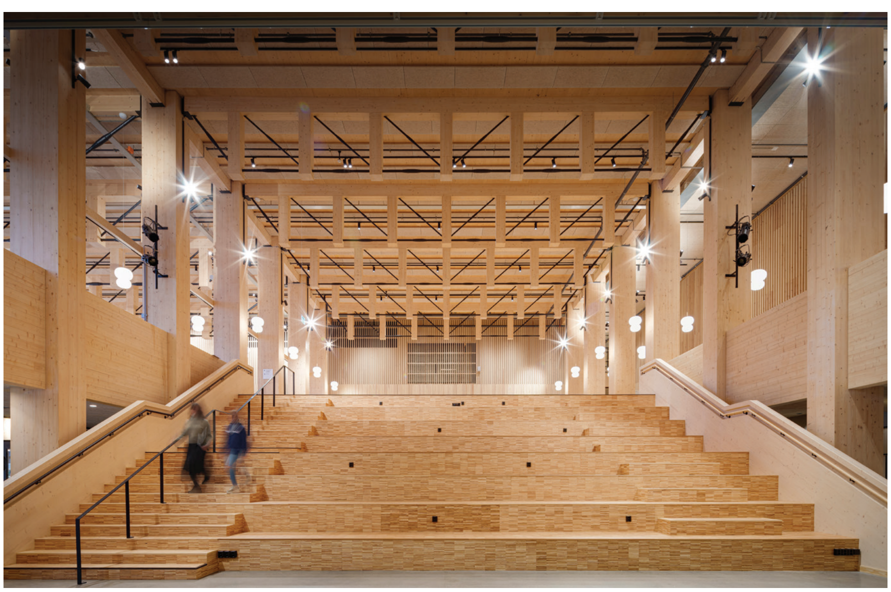
Fire Engineering

The building was required to meet the standards of the BR0 Swedish system, which meant high-rise areas needed 90

▲ Figure 2.6.12. The top two floors house a restaurant and hotel amenities, and as such required a column-and-beam structural system. © Martinsons I Jonas Westling

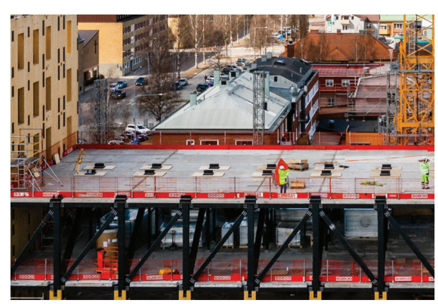
Steel Products		
Category	**Volume (m³)**	**Weight (kg)**
Color coated steel sheets and coils	1.5	11,775
Cut and Bent Rebar	63.7	500,000
Steel connections for concrete elements	0.4	3,510
Steel Reinforced Profile	0.1	956
Steel Beam Profiles	20.8	163,339
Total	**86.5**	**679,580**

▲ Table 2.6.2. General steel information for Sara Kulturhus.

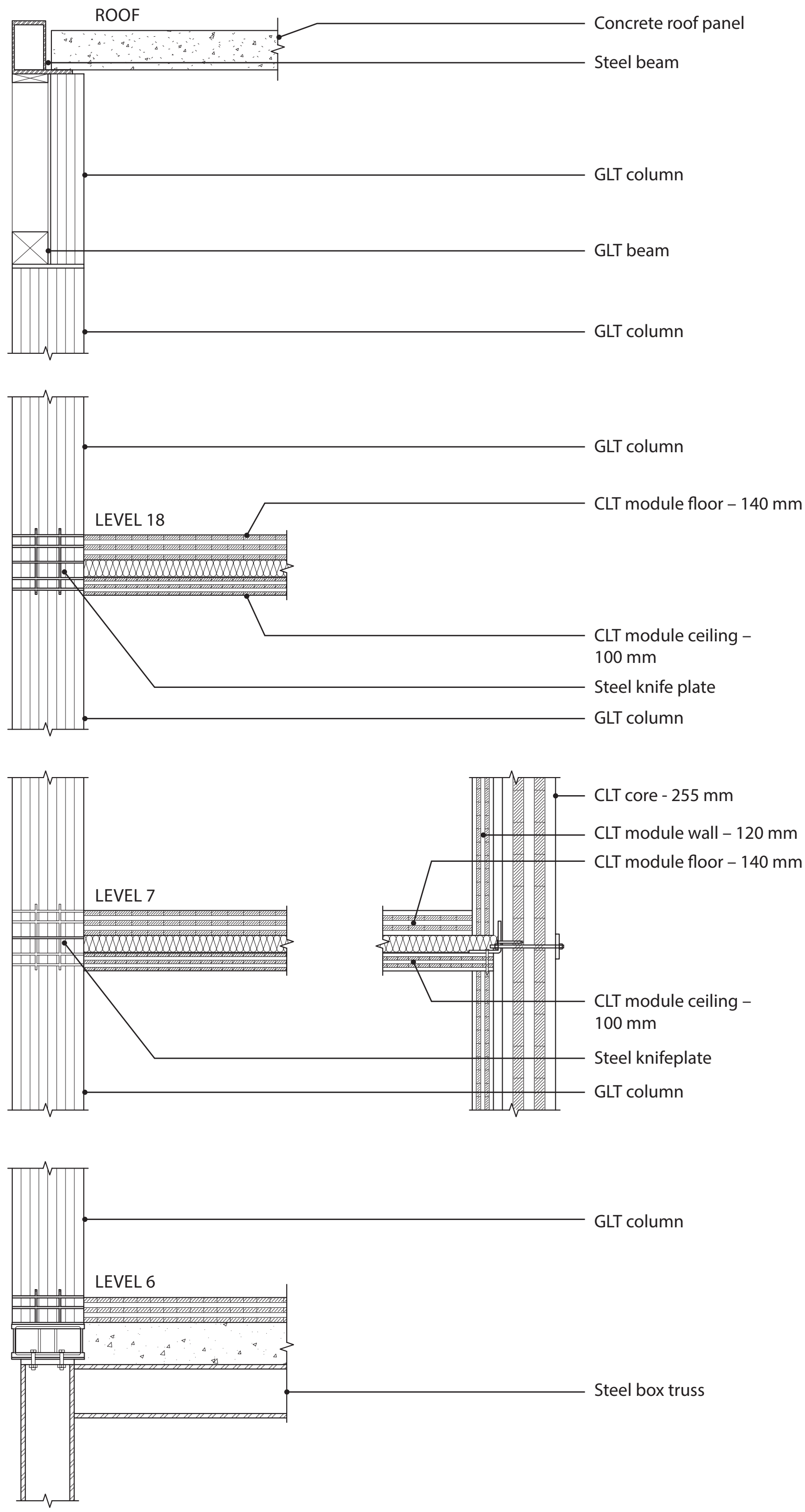


▲ Figure 2.6.11. GLT chorded trusses, augmented by steel tension rods, allow long spans over an amphitheater-style seating area on Level 1. © Martinsons I Jonas Westling

▲ Figure 2.6.13. Detail image of the installation of the individual hotel modules, showing how each module sits on the module below. © Martinsons I Jonas Westling



▲ Figure 2.6.14. The top of the steel truss at level 6, with knife plates integrated for easy connection to the GLT columns above. © Martinsons I Jonas Westling



▲ **Figure 2.6.15. Typical connection details for levels 6 to 19.** © White Arkitekter, redrawn by CTBUH

minutes of resistance for load-bearing elements and 60 minutes for non-load-bearing material. The requirements in the low-rise section were 60 and 30 minutes, respectively. Stair flights within otherwise protected stairwells, as well as smaller structural members with limited local consequences in a collapse, could be designed in timber with 30 minutes of resistance. In most cases the method of fire resistance was a combination of surface treatment with flame retardant and the char depth of the elements themselves.

The fire safety strategy, to a great extent, was executed via performance-based design. A full automatic sprinkler protection system (in accordance with SS-EN 12845 and with amendments in accordance with Swedish standard SBF 110:8) is an integral part of the fire safety strategy for the building (see Figure 2.6.16). To some extent, the sprinkler system is used to meet the fire-resistance durations for both the requirements of the structural systems (in general R 60 or R 90) and for unprotected wooden surfaces, including internal walls and the façade. The wooden structure is generally designed without external protection, i.e., it is protected by over-designing the structure to allow for charring in case of fire. Unprotected wood is allowed on walls in non-public areas and in smaller details, as on columns, etc., where the cladding has been deemed to have little or no effect on the safety of the occupants. To meet the general requirement for surfaces, exposed wood has either protective paint or protective cladding (see Table 2.6.3).

MEP Systems

As with many other timber buildings, the main consideration around MEP systems at Sara Kulturhus was around coordinating penetrations through beams. One challenge that emerged was that structural strength calculations were sometimes being carried out while the MEP system routing was also being designed, which sometimes resulted in larger-than-ideal beams that then had to be redesigned or required the MEP elements to be relocated (see Figure 2.6.17).

In other areas, predrilled holes allowed for MEP services to be run through beams.

Building Envelope

The building's glass exterior is one of its most significant features (see Figure 2.6.18). Laminated safety glass is held away from the inner façade by glue-laminated lamellas extending 200 millimeters, creating an air gap. Hotel rooms have triple-glazed, aluminum-framed windows. Within the air gap, scrolling sunscreens are mounted to the underside of the floor above. On center with the partition walls between hotel rooms, a self-closing pivot-action lamella made from a 32-millimeter CLT panel allows air to circulate within the gap.

▲ **Figure 2.6.16. The automatic sprinkler system is discreetly hung from the underside of the CLT floor panels above the multipurpose room on Level 2.** © Martinsons / Jonas Westling

Fire and Acoustic Performance Ratings	
Fire Performance/Protection	
Resistance Rating	High-rise areas: 90 min for load-bearing elements Low-rise areas: 60 min for load-bearing elements
Resistance Method	Designed for char depth; all timber element surfaces are treated with flame retardant
Acoustic Performance/Sound Transmission	
Sound Transmission Class, Walls	52 dB between hotel rooms

▲ Table 2.6.3. Performance ratings listed to meet the requirements for fire resistance and acoustic performance.

The solid parts of the façade are faced with Superwood, a brand of preservative-impregnated spruce sourced from Denmark, 22 millimeters thick. The wood is lightly pressure-treated, so that it will naturally turn gray over time with solar exposure.

Construction Process

Sourcing and Supply Chain

The wood used in the project was sourced from managed forests in the region and processed in Bygdsiljum, Sweden (see Table 2.6.4), about 60 kilometers from Skellefteå. The GLT

▲ Figure 2.6.17. In many public areas of the podium, high ceilings made hanging MEP ducts and pipes an unobtrusive proposition. © Åke Eson Lindman

▲ Figure 2.6.18. The building's glass exterior has an air gap, in which sun screens are mounted to the underside of the floor above. © Åke Eson Lindman

Transportation Distance and Method			
Material Element	Source	Distance from Factory to Site	Transportation Method
GLT	Martinsons Såg AB, Bygdsiljum, Sweden	60 km	Truck
CLT	Martinsons Såg AB, Bygdsiljum, Sweden	60 km	Truck
Steel - Rebar	Tibnor AB, Köping, Sweden	778 km	Truck
Steel – Connecting Parts	Peikko Group, Lahti, Finland	886 km	Truck
Steel – Reinforced Steel Profile	Norgips Norge AS, Drammen, Sweden	1,057 km	Truck

▲ Table 2.6.4. Travel distances, modes, and materials delivered during the construction of Sara Kulturhus.

used was GL28 C grade, from C25 lumber, with an average moisture content of 13 percent.

The nearly 700,000 kilograms of steel was produced in several locations in Sweden and Finland, all by truck. The largest constituent volume, some 500,000 kilograms, is substantiated by rebar.

Prefabrication

The CLT panels were produced by Martinsons Såg AB in Bygdsiljum and could be delivered in lengths up to 26 meters for the building cores and shear walls. The panels used polyurethane glue.

Approximately 30 percent of the steel connectors were installed in the factory. The most common types were slotted knife plates, fastened with steel dowels or screws. Most holes were precut in the factory.

The prefabricated modules consist of four GLT columns, and a floor, ceiling and three walls made of CLT. The floor assembly, from bottom to top, consists of 140 millimeters of CLT panel; two layers of 20-millimeter-thick mineral wool for sound protection; two layers of 13-millimeter-thick gypsum for fire protection; 22 millimeters of particle board, and 8 millimeters of carpeting or hardwood flooring. The ceilings consist of 100 millimeters of insulation on top of 100 millimeters of CLT.

Site Delivery
About 100 to 200 square meters of storage or laydown space was needed for each crew. In certain instances, the project required up to 400 square meters, such as when a wall section for the theater with an area of 180 square meters had to be prepared for lifting it into place.

On-Site Construction
Between one and three cranes worked on-site at once, with the relatively light weight of timber elements helping to speed up assembly. Between six and 15 workers were on the site at a time. Among the first timber elements to be raised on the site were the CLT shear walls. These were connected to the concrete base via steel knife plates embedded in the concrete base (see Figure 2.6.19).

The main structure installation began with the four-story theater space, consisting of CLT walls topped by a long-spanning GLT truss system. This was then followed by the column-beam structural system of the lower floors (see Figure 2.6.20). The steel box truss at Level 5 was installed next, providing space for mechanical equipment, as well as a base for the stack of pre-assembled modules that would constitute the hotel tower. A row of twin column heads penetrates through the concrete floor slab of Level 6. These columns are topped by knife plates, onto which the GLT

"Overall, the project is complex structurally, due to the variety of program and the need to support the hotel structure on top of a long-span roof over the conference and performing arts center."

▲ **Figure 2.6.19. The CLT wall shown here was kept wrapped until placement and installation of surrounding walls, to protect it from the weather.** © Martinsons I Jonas Westling columns embedded in the corners of the prefabricated modules were connected (see Figure 2.6.21).

The modules were placed in sequence, from the interior (north) CLT core towards the outer (south) core, on levels 6 to 18 (see Figure 2.6.22). The exterior-facing side of each prefabricated module is left open, as this later receives a double-skin façade.

Levels 19 and 20 were constructed with a hybrid column-and-beam system, with both GLT and steel columns. This was done to allow for wider, more open spaces for the restaurant and spa, breaking with the cellular program of the hotel rooms below.

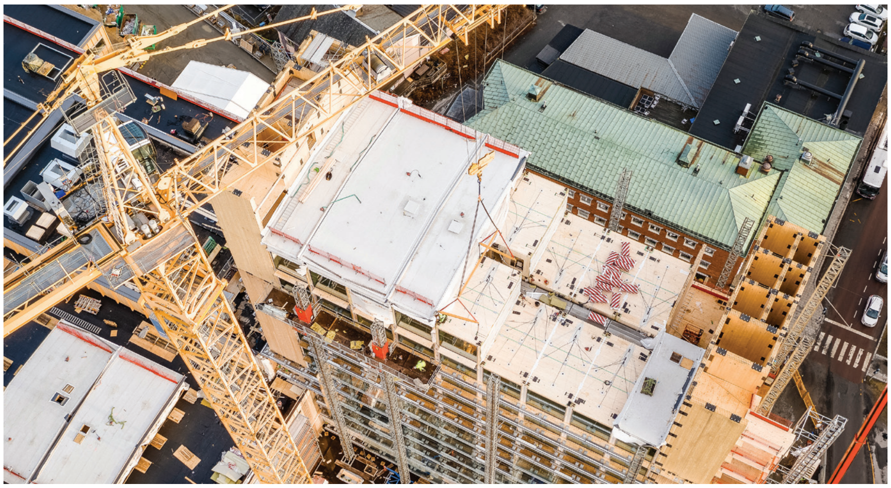
The double-skin façade was constructed near the end of the process (see Figure 2.6.23).

The last element to be constructed was the outdoor canopy on Level 4, consisting of GLT beams and columns with a CLT roof.

Tolerances and Accuracy Testing
The high-rise was designed to shrink 127 millimeters vertically, accounting for the natural properties of the timber used in its construction. Due to the use of Tekla software and processing with CNC machines, tolerances were generally kept within a few millimeters.

▲ Figure 2.6.20. The installation of the steel box truss on level 5, surrounded by construction on the lower floors. © Martinsons / Jonas Westling

▲ Figure 2.6.21. Modules arrived on-site wrapped in plastic, which was removed once they were set into place. © Martinsons I Jonas Westling



▲ Figure 2.6.22. The installation of the pre-assembled modules for each floor started at the interior CLT core and worked outward, with each module stacking directly on top of the module below. © Martinsons I Jonas Westling

Carbon/Sustainability Overview

The total carbon footprint of Sara Kulthurhus is 4,827,903 kg CO_2 eq, from manufacturing to end of life. This number is offset by the 8,017,188 kg CO_2 eq that is sequestered in the structural timber, allowing the building to be embodied-carbon negative.

Overall, Sara Kulturhus is estimated to have 51 percent less of a climate impact than a comparable reference project constructed in concrete (see tables 2.6.5 and 2.6.6, and Figure 2.6.24). This is

▲ Figure 2.6.23. The nearly finished project shows the impact of the double-skin façade, as installed. The final construction was a canopy on the exterior deck. © Patrick Degerman

> "Much of the exterior visible timber is technically 'displayed,' rather than 'exposed,' behind a glass curtain wall that encases most of the tower, providing weather protection and a unique, dynamic way of showcasing the material."

Total Embodied Carbon (kg CO_2 eq), based on EBD (Environmental Building Declaration) Modules						
Stages	**Phases**	**Sara Kulturhus**		**Concrete Reference Scenario**		**% Difference**
		Estimated GHG emissions (kg CO_2 eq)	Normalized to floor area (kg CO_2 eq / m^2)	Estimated GHG emissions (kg CO_2 eq)	Normalized to floor area (kg CO_2 eq/m_2)	Difference normalized to floor area
Manufacturing and Construction	A1 Raw material supply A2 Transport A3 Manufacturing	3,546,701	126.7	8,108,734	289.6	43.7%
	A4 Transport	24,437	0.9	187,845	6.7	13%
	A5 Construction Installation process	513,629	18.3	513,629	18.3	0%
Use	B1 Use and application B2 Maintenance B3 Repair B4 Replacement B5 Refurbishment	14,820	0.5	1,176	0.1	1,260.2%
End of Life	C1 Deconstruction C2 Transport C3 Waste processing C4 Disposal	728,316	26	609,445	21.8	119.5%
Results	**Total estimated GHG emissions**	**4,827,903**	**172.4**	**9,420,829**	**336.5**	**51.2%**

▲ Table 2.9.6. Total embodied carbon estimates for Sara Kulturhus, Skellefteå, based on life cycle analysis modules. Estimated carbon emissions were normalized to the total gross floor area of 28,000 m^2 for both scenarios.

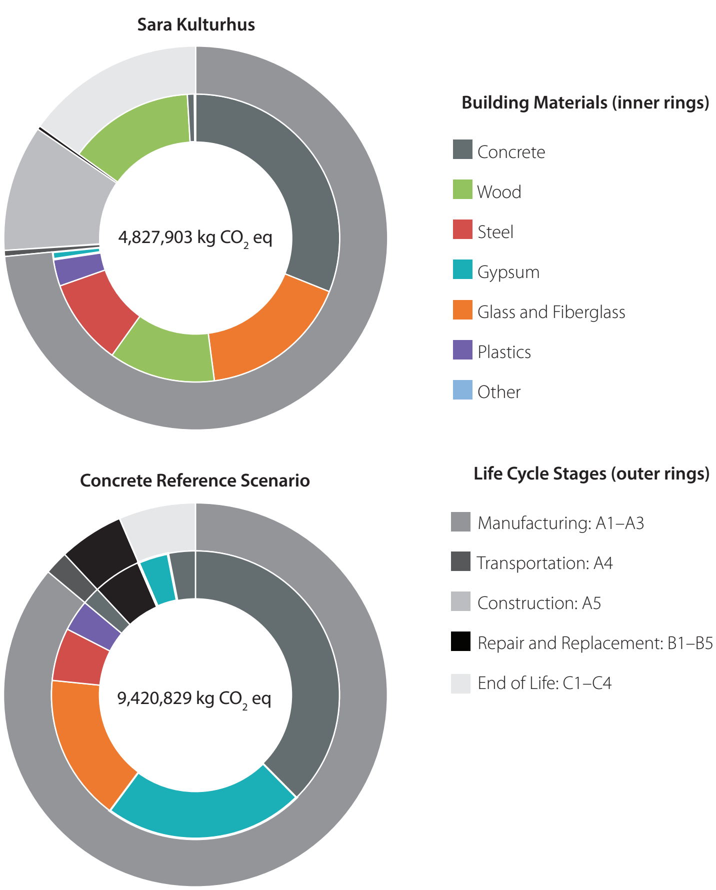
Sara Kulturhus' Carbon Storage	
Total carbon sequestered within structural timber	8,017,188 kg CO_2 eq
Net carbon emissions of the structure (total emissions minus sequestration)	-3,189,285 kg CO_2 eq
Total carbon emissions avoided by using timber over conventional materials	4,592,926 kg CO_2 eq

▲ Table 2.6.5. Carbon stored by using timber as compared to other, conventional building materials.

despite the higher carbon impacts in the B "use" and C "end of life" stages attributed to the project as built, versus a reference concrete structure of the same scale. It may seem surprising to some that the later stages record a higher assumed GHG emission for the steel-timber building as constructed. There are differences in required maintenance for the materials, as reflected in the use stage.

Project Team

Owner/Developer: Skellefteå Municipality
Architect: White Arkitekter
Structural Engineers: WSP (Concrete); TK Botnia (Timber)
MEP Engineer: Incoord
Project Manager: Hent AB
Main Contractor: Hent AB
Timber Planning and Coordination: DIFK; TK Botnia
Acoustics: BrekkeStrand
Fire & Life Safety: Brandskyddslaget
Software: Tekla
Sustainability/Environmental: Hent AB and White Arkitekter
Other Consultants: NORDKONSULT (landscape); AIX, AV-Consultants, Artifon (theater); WSP (traffic); Rulltek (vertical transportation)
Engineered Mass Timber Suppliers: Derome (hotel modules); Martinsons Såg (main structure)
Other Material Suppliers: Frapont (acoustics panels); Skellefteå Snickericentral (doors)



▲ Figure 2.9.24. An analysis of the embodied carbon associated with Sara Kulturhus and a similar concrete reference scenario. The inner rings indicate material type and the outer rings indicate life cycle phase. © CTBUH

3.0 Conclusions, Limitations & Recommendations

Case Study Comparisons

This section collects the findings of the individual case study buildings, subjecting them to a broader analysis and commentary.

The case studies were selected from a wider pool of steel-timber hybrid and concrete-steel-timber hybrid buildings being tracked and monitored by CTBUH (see Chapter 1.3 on page 23). To investigate multiple typologies of this structural type, case studies were selected from different regions, cover a broad range of structural types and solutions, and focus on different building heights—ranging from several two-story buildings to the 20-floor Sara Kulturhus.

For the purposes of this evaluation and comparison, as 55 Southbank, Melbourne, is a vertical extension atop an existing building—it adds a 10-floor, steel-timber hybrid hotel on top of an existing nine-story office building—the below evaluations will indicate when the data is representative of the entire building vs. just the new steel-timber hybrid floors.

Building Heights

In order to assess a broad range of project types, buildings in different height classes were selected (see Table 3.1). Often steel-timber hybrid buildings are classified by the number of floors instead of height, particularly in code considerations. There are three buildings that are 10 floors or greater, one building between four and nine floors, and two buildings of three floors or less. On average, all case studies include on average 10.3 above-ground floors, including the ground floor itself, and significant mezzanine floors and major mechanical plant floors. The average number of steel-timber hybrid floors per case study is lower (5.5 floors), due to concrete podia seen in 55 Southbank, 843 North Spring Street, and Lighthouse Joensuu, as well as the unique structural solutions used in Sara Kulturhus (see Chapter 2.6 on page 68).

Building Characteristics

Region
Three case studies are located in North America, with three projects, and the remainder are located in Europe (two projects) and Oceania (one project). As mentioned in chapters 1.1 and 1.2, multistory mass timber hybrid buildings were largely first popularized in Europe, so it follows that two of the three buildings 10 stories or higher are located in Europe: Lighthouse Joensuu and Sara Kulturhus (see Table 3.2).

Function
Three case studies are single-function projects, or buildings where 85 percent or more of the total height is dedicated to a single function (see Table 3.2). The single-function projects include a residential building (Lighthouse Joensuu), an office building (Houston Endowment Headquarters), and an institutional building (Billie Jean King Main Library). This also leaves three mixed-use projects remaining in the case studies, or buildings containing two or more functions, where each of the functions occupies a significant proportion of the tower's total space. This "significant proportion" can be judged as 15 percent or greater of either: (1) the total floor area, or (2) the total building height, in terms of number of floors occupied for the function. Support areas, such as car parks and mechanical plant space, do not constitute mixed-use functions.

Within the mixed-use functions, additional office space is included in 843 North Spring Street, but this building also features retail space on floors 1 and 2. 55 Southbank is a bit of a unique case, as although it is specified as a mixed-use building, the new construction was almost exclusively hotel, and the hotel space was built atop the existing office space (in fact, some of the office space was still operational during the construction of the upper floors) (see Table 3.2).

Although no case studies are exclusively a hotel, the hotel space constitutes the greatest proportion across all case study above-ground floors, with 29 total floors split across the two mixed-use projects10 floors or greater in height: 55 Southbank (12 hotel floors) and Sara Kulturhus (17 hotel floors) (see Table 3.3).

Construction Timeline As steel-timber hybrid buildings are in their relative infancy, most of the case studies selected are recent completions, with the oldest

Name	Height (m)	Floors Above	Floors Below	Steel-Timber Hybrid Floors	GFA (m²)	GFA (m²)/Floor
55 Southbank	69.7	19	1	10	15,977	840.9
843 North Spring Street	29.4	5	1	3	13,471	2,694.2
Billie Jean King Main Library	14.0	2	1	2	8,686	4,343.0
Houston Endowment HQ	13.8	2	1	2	9,662	4,831.0
Lighthouse Joensuu	48.0	14	0	13	5,935	423.9
Sara Kulturhus	72.8	20	1	3	28,000	1,400.0

▲ Table 3.1: Inventory of steel-timber hybrid case studies, including project heights and floor areas.

Name	Region	Country	Function	Function Details
55 Southbank	Oceania	Australia	Hotel over Office	*Hotel*: Floors 2 (Lobby), 9 (Amenities), and 10–19 (Rooms) *Office*: Floor 1 (Lobby) and Floor 3–8 (Offices)
843 North Spring Street	North America	United States	Office over Retail	*Hotel*: Floors 2 (Lobby), 9 (Amenities), and 10–19 (Rooms) *Office*: Floor 1 (Lobby) and Floor 3-8 (Offices)
Billie Jean King Main Library	North America	United States	Institutional	*Institutional*: Floor 1-2 (Library Space)
Houston Endowment HQ	North America	United States	Office	*Office*: Floor 1-2 (Offices)
Lighthouse Joensuu	Europe	Finland	Residential	*Residential*: Floor 1-14 (University Dormitories)
Sara Kulturhus	Europe	Sweden	Hotel over Exhibition	*Hotel*: Floor 1 (Lobby and Amenities), Floor 5 (Services), Floor 6–18 (Rooms), and 19–20 (Additional Amenities) *Exhibition*: Floor 1 (Cultural Center Entrance), Floor 2–3 (Exhibition Space and Theatres), and Floor 4 (Conference Center)

▲ Table 3.2: Location and function of each case study cited in this publication.

Function	Total Floors	Function Details
Hotel	29	12 Floors (55 Southbank) and 17 Floors (Sara Kulturhus)
Office	14	7 Floors (55 Southbank), 5 Floors (843 Spring Street), and 2 Floors (Houston Endowment HQ)
Residential	14	14 Floors (Lighthouse Joensuu)
Public (Exhibition, Institutional, Retail)	8	2 Floors (843 Spring Street), 2 Floors (Billie Jean King Main Library), and 4 Floors (Sara Kulturhus)

▲ Table 3.3: Breakdown of building functions across all case studies cited in this publication.

Name	Construction Start	Construction End	Construction Period (Months)
55 Southbank	2019	2020	-
843 North Spring Street	Apr 2021	Nov 2023	31
Billie Jean King Main Library	2017	2019	-
Houston Endowment HQ	Mar 2021	Sep 2022	18
Lighthouse Joensuu	2018	2019	-
Sara Kulturhus	Nov 2018	Oct 2021	36

▲ Table 3.4: Construction periods for each case study cited in this publication.

Name	Structure Type
55 Southbank	Steel-Timber Hybrid over Concrete
843 North Spring Street	Concrete-Steel-Timber Hybrid over Concrete-Steel Hybrid
Billie Jean King Main Library	Steel-Timber Hybrid
Houston Endowment HQ	Steel-Timber Hybrid
Lighthouse Joensuu	Steel-Timber Hybrid over Concrete
Sara Kulturhus	Steel-Timber Hybrid over All-Timber over Steel-Timber Hybrid

▲ Table 3.5: Structural configurations of each case study.

building being the Billie Jean King Main Library, completed in 2019, and the most recent, 843 North Spring Street, completing as recently as November 2023 (see Table 3.5). The constructability of steel-timber hybrid projects is reinforced by the projects' short construction time. None of the steel-timber hybrid buildings surpassed three years (36 months) of construction time. In fact, for those case studies that specified specific months for the start and end of the construction period, the average period for the case studies in this publication was only 28.3 months. Comparing these rates to conventional structural assemblies, timber hybrid projects can reduce construction time by 20 percent and the number of crew workers per level by up to 80 percent (Wood et al. 2023).

Structural Configurations

See Chapter 1.1 or the definition of structural material types and configurations. Of the six projects, two include an all-concrete podium (55 Southbank and Lighthouse Joensuu), while two utilize steel-timber hybrid structures for the entirety of their height (Billie Jean King Main Library and Houston Endowment HQ). 843 North Spring Street includes a concrete-steel-timber hybrid structure atop a podium with steel framing and concrete cores and floors. Also, Sara Kulturhus features all-timber modules between floors 6 and 18, and features steel-timber hybrid structural solutions below and above (see Table 3.5).

Carbon Data from Case Studies

These numbers stated below only consider structural materials (steel framing, CLT panels, etc.), and more specifics about carbon sequestration and emissions can be found in each respective case study.

Of the case studies that reported the total amount of CO_2 sequestered within the structural system, an average of 3,009 metric tons are sequestered, with Sara Kulturhus sequestering over 8,000 metric tons in one project. These high numbers for Sara Kulturhus are in part due to its status as the tallest of all the case studies, and the one with the most steel-timber hybrid flooring. But when compared against total gross floor area, it still comes out on top. Compared to the case-study-wide average of 0.199 metric tons of sequestered CO_2 per square meter, Sara Kulturhus has 0.286 t CO_2/m^2. On a per-floor basis, however, the Billie Jean King Library has the greatest amount of sequestered carbon, with a total of 1,700 metric tons of sequestered CO_2 across two floors, netting approximately 850 metric tons of sequestered CO_2 per floor on average (see Table 3.6).

Note that figures for requested carbon are calculated by the project team

Name	CO_2 Sequestered (metric tons)	Floors (Above Ground)	CO_2 Sequestered per Floor	GFA (m^2)	CO_2 Sequestered per m^2 (of GFA)
55 Southbank	2,800	19	147.4	15,977	0.1753
843 North Spring Street	930	5	186.0	13,471	0.0690
Billie Jean King Main Library	1,700	2	850.0	8,686	0.1957
Lighthouse Joensuu	1,600	14	114.3	5,935	0.2696
Sara Kulturhus	8,017	20	400.9	28,000	0.2863

▲ Table 3.6: Amount of carbon sequestered in reporting case study projects. Note that Houston Endowment HQ did not provide carbon sequestration figures.

Name	Project Costs (USD, in millions)
55 Southbank	35
Billie Jean King Main Library	48
Houston Endowment HQ	21.5

▲ Table 3.7: Overall project costs for 55 Southbank, Billie Jean King Library, and Houston Endowment HQ. Note that 843 North Spring Street, Lighthouse Joensuu, and Sara Kulturhus did not supply cost information.

and stakeholders of the respective case studies, and thus, may not be directly comparable; each likely uses the carbon reporting methodologies of the specific region and jurisdiction the case study is located.

Cost Data from Case Studies

As with the calculation of Life Cycle Assessment (LCA) values and comparison of total carbon emissions, amount of sequestered carbon, etc., comparing costs of multiple projects, especially those located in different jurisdictions and of different structural and functional classifications, can be difficult. Especially when considering projects that commence and complete construction at different times, the ability to accurately compare building costs can be challenged by the regular fluctuation of exchange rates, inflation rates, and the costs of the raw materials. Further, approximate costs of the project will be developed by the quantity surveyors and cost consultants during the design process; for instance, are the total available project costs reflective of these initial estimates, or are they a post-construction assessment?

In addition to these factors, the problems are compounded by different elements of the construction being considered, and one must clarify whether the total project costs include: material costs for just the core and shell of the building or interiors as well; insurance costs (both builder's risk insurance and standard property insurance); labor and workforce involved in the project's assembly; preliminary testing and research; etc. For these reasons, it is difficult to compare costs and determine averages per floor, or averages by GFA, but the case study projects that did report total project costs are summarized in Table 3.7.

Limitations & Recommendations

This project was undertaken to showcase the cutting edge of innovation in steel-timber hybrid buildings, particularly those that would take timber into new territories of scale and program. The approach has limitations that must be acknowledged, but it provides an illustrative example set.

The pioneering nature of many of the case studies comes with some obvious drawbacks. The practice of combining engineered mass timber and steel in large-scale structures is growing but not yet commonplace. Most of these are not "typical" buildings, in their use of the materials, the level of exposure given to the structure in some cases, and their configurations in others. For various reasons, many also lack consistent information about cost and carbon impact, which are among the primary factors in the decision to erect steel-timber hybrid structures in the first place. This was mostly because many projects did not prioritize a detailed accounting of their carbon footprint from the outset and were thus unable to report accurate statistics after construction. Others may have had large proportions of concrete and other carbon-intensive materials that would have produced unfavorable comparisons.

We also note that there is a trade-off that comes with the carbon reductions implied by the introduction of mass timber and steel into the structure. Both may need additional fire-protection materials. These are not typically accounted for in "structure-only" life cycle assessments (LCAs), but for the sake of accuracy, there is a case that they should be. When the structural optimizations are described in terms of their overall embodied carbon, there is inconsistent accounting for the additional environmental impact of fire protection, acoustical, and vibration control materials, which would not have been required if traditional concrete or concrete-encased steel construction had been pursued.

Carbon and cost information was provided whenever it could be found, but in most cases, it is an incomplete picture that complements the anecdotal narratives of the project conception, design, and construction.

Several aspects of this report's development prevented the full execution of this goal at the highest level of detail; these can be regarded as points for improvement in future research and in practice.

As mentioned in the previous Tall Timber guide (Wood et al. 2023), a lack of transparency around both cost and carbon emissions continues to be an obstacle to a comprehensive understanding of steel-timber hybrid buildings' full potential. The researchers undertook an online survey approach with this effort, which was more concise and user-friendly than previous questionnaire-based methodologies used in the prior project, but the response rate was still very uneven.

Few parties had access to a single source of truth for all relevant information; therefore, many consultants pointed the researchers at other consultants for fragments of data, which was very time-consuming to collect. This suggests that the evolving guidance to "coordinate early and intensely" has not yet truly become standard practice, as project data seemed to fade away over time and was scattered amongst stakeholders. Worse, institutional knowledge sometimes disappeared with the departure of key practitioners from their firms.

While the narratives found in the case studies produced for this guide are illuminating and useful, the relative lack of standardized cost and carbon data—and a willingness to share it—will continue to restrict steel-timber hybrid buildings' potential unless the construction industry collectively decides to improve this condition.

Increased government and industry research funding into material properties and construction techniques, as well as harmonization of reporting methods and standardization of environmental product declarations (EPDs), with a consequent requirement to transparently communicate the results, could help ameliorate the knowledge gaps.

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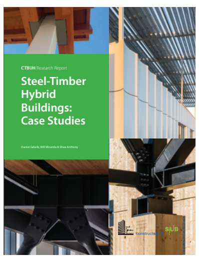

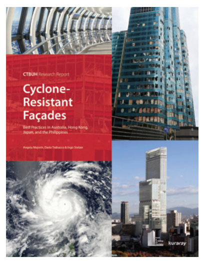

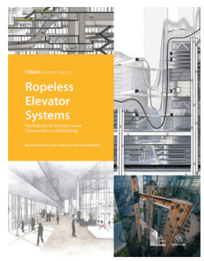

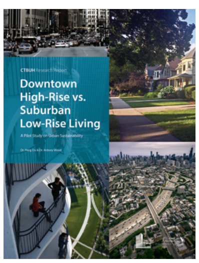

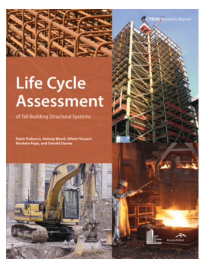

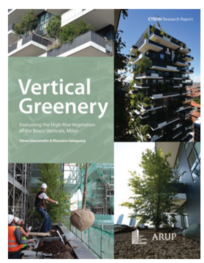

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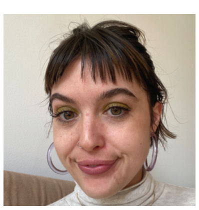

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Turner & Townsend alinea
Turner Construction Company
WSP

Gold+
Dar
Gensler
KLCC (Holdings) Sdn Bhd
Pelli Clarke & Partners
Tishman Speyer

Gold
Adrian Smith + Gordon Gill Architecture
Aedas
Aqualand
Arcadis/IBI Group
Aspect Studios
Aurecon Pty Ltd
Beca
Brandston Partnership, Inc.
chapmanbdsp
CityGroup Design Collective CO., LTD
Corgan
DCI Engineers
Drees und Sommer SE
E.Rogovin Ltd.
East China Architectural Design & Research Institute (ECADI)
Emaar Properties, PJSC
Fujitec

FXCollaborative Architects
gad
GCL Builds
Giarratana, LLC
Goettsch Partners
GVA Lighting
Hongkong Land
IMEG Corp
Leviat GmbH
Magnusson Klemencic Associates
McNamara ? Salvia
Motioneering, Inc.
Mott MacDonald
NORR Group Consultants International Limited
Nucor Corporation
PDW Architects
Perkins & Will
Permasteelisa Group
Pickard Chilton Architects, Inc.
Ping An Real Estate Co Ltd
PNB Merdeka Ventures Sdn. Berhad (PMVSB)
Quan Dat Trading & Production Co., Ltd
Ramboll
Rider Levett Bucknall
Rise Global LLC
S+B Gruppe AG
Severud Associates Consulting Engineers, PC
Shanghai Institute of Architectural Design & Research (Co., Ltd.)
Simpson Strong-Tie
Think Wood
Tide Construction
Tongji Architectural Design (Group) Co., Ltd.
Windtech Consultants
Zaha Hadid Architects

Silver+

A&H Tuned Mass Dampers
AI PlanetWorks
Allford Hall Monaghan Morris
AMSYSCO
ArcelorMittal
Architects Hawaii Limited - AHL
architectsAlliance
Architectural Design and Research Institute of South China Univ. of Technology
Architectus
Arney Fender Katsalidis
Bates Smart
BDP Quadrangle
Beijing Institute of Architectural Design - BIAD
Beijing Tsinghua Tongheng Urban Planning & Design Institute
Benoy
BG&E
bKL Architecture
Bosa Properties Inc.
Boundary Layer Wind Tunnel Laboratory (BLWTL)
Bouygues Bâtiment International
Broadway Malyan
CCDI Group
Cerami & Associates, Inc.
CetraRuddy
Charles Russell Speechlys
China Architecture Design & Research Group (CADI)
CNP Dong Yang
Code Consultants, Inc.
COIMA
Cox Architecture
CPP Wind Engineering Consultants
D2E International VT Consultants Ltd
Davy Sukamta & Partners Structural Engineers
DCA Architects Pte Ltd
Degenkolb Engineers
Dextra Manufacturing Co Ltd
DIALOG
Doka GmbH
Elevating Studio
Enclos Corp.
enstruct
Environmental Systems Design, Inc. Now Stantec
Envision Engineering Consultants
Epstein
Eric Parry Architects
Fender Katsalidis
Fisher Marantz Stone
Fletcher Priest Architects
Foster + Partners
GEI Consultants
GERB Vibration Control Systems
GGLO
Gilsanz Murray Steficek
gmp · Architekten von Gerkan, Marg und Partner
Gradient Wind Engineering Inc.
Graziani + Corazza Architects Inc.
Grimshaw Architects
Group GSA
Hariri Pontarini Architects
Hartshorne Plunkard Architecture
Hassell
Henning Larsen Architects
Hill International
HKA Elevator Consulting, Inc
IDOM
Israeli Association of Construction and Infrastructure Engineers - IACIE
Jahn/
JB&B
Jensen Hughes
JLL - Jones Lang LaSalle Property Consultants Pte Ltd
Killa Design
Larsen & Toubro, Ltd.
Laurie & Brennan LLP
LeMessurier
Lendlease
LERA Consulting Structural Engineers
Lerch Bates, Inc.
LIFTbuild LLC
LWK + PARTNERS
M Moser Associates
Maeda Corporation
MAURER SE
Metal Yapi Holding
Mirvac Construction
Murphy Facade Studio Limited (MFS)
MVRDV
Nabih Youssef & Associates
OFR Consultants Limited
Ornamental Metal Institute of New York
Palafox Associates
Pei Cobb Freed & Partners
PLP Architecture
Rene Lagos Engineers
Rhode Partners
RJC Engineers
Robert A.M. Stern Architects
RSHP
Safdie Architects
Schüco
Securistyle
SENER MOBILITY S.A.
setec tpi
Shui On Management Limited
Sika Services AG
Skyline Robotics
Solomon Cordwell Buenz - SCB
Stanley D. Lindsey and Associates, Ltd.
Steel Institute of New York
Studio Gang Architects
Surface Design
Takenaka Corporation
Terracon
TÜV SÜD Dunbar Boardman
UNStudio
V&A Waterfront
VDA Elevator and Escalator Consulting
Walter P Moore
Walters Inc
wh-p Ingenieure
Williams & Russell CDC
Woods Bagot
Yashar Architects

Silver

10 Design (part of Egis Group)
360 Chicago
3MIX
3XN Architects
A. J. Pericleous LLC
Abu Dhabi Investment Council
ACC Glass and Facade Consulting
Access Advisors
ACPV ARCHITECTS Antonio Citterio Patricia Viel
Acro Real Estate
Adamson Associates
ADG Engineers (Aust) Pty Ltd
AET Flexible Space
AF Buildings Denmark
Aidea, Inc.
AIT Solutions
AKAIA Architecture
Akitek Jururancang Malaysia
AKT II Limited
Alderson Engineering, LLC.
Alfa Sustainable Projects Limited
Alimak
Alison Brooks Architects
Allied REIT
Allies and Morrison Architects
ALT Limited
Aluminum Construction Group
Amexon Development Corporation
Amot Investments and Gav-Yam J.V.
Andrew Lee King Fun & Associates Architects Ltd.
ARC Studio Architecture + Urbanism Pte. Ltd.
Archetype Group
Architecture by Belova
ARCO Architecture Company
Aria Property Group
Arrowstreet
AsheMorgan
Ashtrom Group Ltd
ASL
Atelier Ping Jiang | EID Arch
Atelier Ten
Aviv Group
Azrieli Group Ltd.
B+H Architects
BA Ingenieria
BALA Engineers

(List continued on next page)

Baldridge & Associates Structural Engineering
Barker Mohandas, LLC
Barre Levie Architects & Urban Planners
Battersea Power Station Development Company
BauMont Real Estate Capital
Bedrock Detroit
Billbergia Pty Ltd
Billings Design Associates, Ltd.
Bjarke Ingels Group
BluEnt
BOA
Bollinger + Grohmann Ingenieure
Boston Properties, Inc.
Bouygues Immobilier
Broad Sustainable Building Co., Ltd.
Brookfield Properties
BuildWind
Bureau Cube Partners
Bureau d`etudes Greisch
bureau^proberts
Büro Ole Scheeren
BVN
C.F. Moller
C.Y. Lee & Partners Architects/Planners
Canaan Shenhav Architects
Canada Israel
Canary Wharf Group, PLC
CapitaLand Development Pte Ltd
Carazo Architecture
Carlo Ratti Associati S.R.L.
Carrier Johnson + Culture
Cary Kopczynski & Company
Cast Connex
CB Engineers
Cbus Property
CCL
CDC Curtain Wall Design & Consulting, Inc.
Chang Minwoo Structural Consultants
ChartierDalix
Cheng Chung Design
China Academy of Building Research
China Southwest Architectural Design and Research Institute Corp. LTD
China Vanke Co.
Choice Properties
CIMET Arquitectos
City Developments Limited
City of Gold Coast
Cityzen Development Group
Civil and Structural Engineering Consultants (Pvt.) Ltd
Concord Adex
COR
Core Architects, Inc.
Core Five
Cosentini Associates
Coughlin Porter Lundeen
CoxGomyl
CREE GmbH
Cro&Co Architecture
CS&P Architects Inc
Cubic Architects
Cundall Johnston & Partners LLP
Daewoo E&C
Dam & Partners Architecten
David Engineers Ltd.
DBI
Deerns Nederland B.V.
Degraeuwe Consulting NV
Design Box
Dexus
Diar Consult
Dietrich | Untertrifaller Architekten ZT GmbH
Discount Bank Group
DLR Group
Domis
DP9
Dubai Multi Commodities Centre
Duo Projects
Dusit Thani Public Company Limited
Eckersley O'Callaghan
EDGE Technologies
Edgett Williams Consulting Group, Inc.
EFC Engineering Consulting Company, Ltd
Eli Attia architect PC
Entuitive Corporation
Eric Owen Moss Architects
Ethos Urban
Evergreen Consulting Engineering
Expo City Dubai LLC
Extell Development
Far East Facade (Hong Kong) Limited
Farrells
Fast + Epp Structural Engineers Inc.
FG Empreendimentos
Fitzpatrick + Partners
FORCITIS Architectural Technology Co., Ltd
Francis-Jones Carpenter Studio
FSD Active Limited
Fubon Life Insurance Co., Ltd.
FullStack Modular LLC
Furtado Sullivan
Galaxy Industry Group
Gallagher
Generate Property Group
GENx Design & Technology
GEO Global Engineering Consultants
Glacier Northwest, Inc. DBA CalPortland
Glotman Simpson Consulting Engineers
Glumac
GOA (Group of Architects)
Greenaway Architects
Greenland Group
Guangzhou Jianke Citiexpo Co.,Ltd
Guardian Glass
Halls Lane Studio
Haptic Architects
Hatfield Group
HD Hyundai
HDA
Hearst
Heatherwick Studio
Heintges Consulting Architects & Engineers
Hera Engineering Pty Ltd
HEWITT Architecture
Hilson Moran
Hines
Hitachi, Ltd.
Hiten Sethi Architects
HKS
Hong Kong Huayi Design Consultants (Shenzhen) Co., Ltd
Høpfner Projects ApS
Housing & Development Board
HPP Architekten GmbH
HYPRLIFT, Inc.
I. Shani Engineers
IECA Internacional S.A.
Infra Group Co., Ltd.
ingenhoven associates gmbh
Inhabit Group
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Israel Towers Group - Urban Renewal Corporation
J. Roger Preston Limited
Jackson Clements Burrows Architects
Jaspers-Eyers Architects
Jay Paul Company
JCE Structural Engineering Group
JDS Development Group
JPW
JQZ Group Pty Ltd
JRMI
JW Consultants LLP
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Kalpataru Limited
KCL Group Ltd
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Kengo Kuma and Associates
Kerstin Thompson Architects
Kerzner International
Kettle Collective
KieranTimberlake
Kinemetrics
Kinetica Dynamics
Kingold Group Companies LTD.
Koichi Takada Architects
Koltay Façades
Kor Structural
Korb + Associates Architects
KPMB Architects
Kreysler & Associates
Kroonenberg Groep
Krueck Sexton Partners
KTP Consultants Pte Ltd
L&L Holding Company, LLC
Laing O'Rourke
Lamda Development SA
LCI Consultants
Lead8
Lee Herzog Facade Access Consulting Inc
Leigh & Orange Limited
Lipa-innovation
Lodha Group
Lotte Property & Development
LYT Architecture (Pty) Ltd.
MAA - MELIKE ALTINISIK ARCHITECTS
Magellan Development Group
Magnom Properties
Make
Manntech
Mario Cucinella Architects
Martin/Martin
Maybourne Hotel Group
McHugh Construction
McKinsey & Company
MEC Margolin Bros. Ltd.
Meinhardt (Thailand)
Melco Resorts & Entertainment
Metropolis
MEYERS+ ENGINEERS
Michael Blades & Associates
Michael Graves Architecture & Design
Microclimate Ice & Snow Inc.
Mithun
Mitsubishi Jisho Design
MJH Structural Engineers
MoA Design
Mobtakeron Realty
Mochly-Eldar Architects
Moelven Limtre

Mori Building Co., Ltd.
Moriyama Teshima Architects
Morph
Mueser Rutledge Consulting Engineers PLLC
Multistudio
National Real Estate Development
NBBJ
NCI Estructurales
New Development Bank
New Land Enterprises
New World Development Company Limited
Nikken Sekkei Ltd
Nordic Office of Architecture
Norman Disney & Young
Nouvelle AOM (Franklin Azzi, ChartierDalix, Hardel Le Bihan)
OAC Services, Inc.
OC&C Strategy Consultants
ODA
O'Donnell & Naccarato
OJB Landscape Architecture
OLYMPIQUE Façade Access Consulting
Omnium International
One Za'abeel LLC
Optima Inc.
Ortiz Leon Arquitectos
Pappageorge Haymes Partners
Pavarini McGovern
PEI Architects
Peikko
Pell Frischmann Consultants
Pierce Engineers, Inc.
PILA Studio IKE
PISSA Capital
POHL Facade Division
Pool Re
Portafolio Inmobiliario
Precinct Properties NZ Limited
Profica
Protect Tadeusz Cisek i Wspolnicy Sp. J.
PT Anggara Architeam
PT Design Global Indonesia
PT Gistama Intisemesta
PT Quadratura Indonesia
PT Total Bangun Persada Tbk
PTW Architects
RATIO I smdp
RAW Design Inc.
RDH Building Science Inc.
RED Fire Engineers Pty Ltd
REGENBE
Renzo Piano Building Workshop
Residential Construction Council of Ontario
RIOS
Riverside Investment & Development
Robert Bird Group
Rocco Design Architects Associates Ltd
Rockefeller Group
Rogers Real Estate Development
Roland Berger GmbH
Rothelowman
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Royal HaskoningDHV
Royal Institution of Chartered Surveyors (RICS)
RSP
SAA Architects
Saguez & Partners
Sami Engineering AB
Sauerbruch Hutton
Schmidt Hammer Lassen Architects
Semper Fire Engineering
Shanghai Yaohua Pilkington Glass Group Co.,Ltd.(SYP Glass)
Shimao Group
Shimizu Corporation
SickKids
Sigmund Soudack & Associates Inc.
SimpsonHaugh
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Sitowise
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SRA ARCHITECTES
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Stefano Boeri Architetti
STEMS CONSULTANTS (PVT) LTD
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SZ DJI Technology Co., Ltd.
Taisei Corporation
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Terrell Group
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Transsolar Energietechnik GmbH
TTW (NSW) Pty Ltd
Unibail-Rodamco-Westfield
Unipol Group
UOL Group Ltd
URAL Engineering Inc.
Urban Capital
Urban Dashboard
Urban Maglev
Valor-Byron Real Estate
Vanderweil Engineers
Vidal Arquitectos
VIGUIER architecture urbanisme paysage
Wacker Ingenieure GmbH
Walker Group Holdings PTY LTD
Waxman Govrin Geva Engineering LTD. (WXG)
WE - Wolansky Engineering
Werner Sobek AG
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Whitby Wood Mills
White Arkitekter
Wiese Architects
WilkinsonEyre
Wilo SE
WOHA Architects
World Class Land Pte Ltd
WT Partnership
WTM Engineers International GmbH
Yangtze Optical Fibre and Cable Joint Stock Limited
YKK AP Facade Pte. Ltd.
Zeidler Architecture Inc.
ZEN Architects
Zhejiang Dadaoqiyun Group Co., Ltd.
Zurcher Arquitectos

Nonprofit/Governmental
Aarhus University
Boston University
Canadian Wood Council
Cardiff University
CCHRB (Chicago Committee on High-Rise Buildings)
Chalmers University of Technology
DAM Deutsches Architekturmuseum
École Polytechnique Fédérale de Lausanne
Institute of Building Technology
Jerusalem Municipality
Karelia University of Applied Sciences
Max-Planck-Institut of Geoanthropology
New York University
Northwestern University
Pontificia Universidad Javeriana
Post-Tensioning Institute
Pratt Institute
Rutgers University
Thakur School of Architecture & Planning
The Skyscraper Museum
Thomas Jefferson University
Toronto Metropolitan University
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The global building industry is now at a turning point, where increasing pressure towards more sustainable construction methods is driving great interest in engineered mass timber—not only because of its perceived lower carbon footprint in production, but because of timber's ability to sequester carbon from the atmosphere as it grows and produces. However, the adoption of mass timber is still in its relative infancy, with heights in the 15–20 floor count typically being achieved so far. Timber will need to act in symbiosis with other materials, such as steel, to achieve greater heights for these buildings in the future.

This publication, the outcome of a grant from constructsteel and the Softwood Lumber Board, is a key step forward in understanding the full potential of steel-timber hybrid structures in high-rise buildings, globally, as a means of clarifying the benefits of steel-timber hybrid construction for the tall building industry. The detailed case studies of completed examples of steel-timber hybrid buildings make this the definitive guide for understanding of the design, cost, environmental, and market benefits of specifying steel-timber composite structures.

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