YRKESHÖGSKOLAN NOVIA

Structural Performance of Prefabricated CLT Wooden Modules

Fereshteh Qorbani

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Author: Fereshteh Qorbani
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Abstract

This thesis focused on the study of prefabricated modular houses made from cross-laminated timber (CLT), with a specific emphasis on their connection systems and environmental performance. The aim was to review the use of CLT in modular construction, examine typical joint types, explore innovations in connections, and assess the life cycle impact (LCA) of CLT-based systems.

The research was conducted through a literature review and the analysis of recent European case studies: one multi-unit residential project. Methods included examining project documentation, technical articles, and academic sources.

The study reviewed the structural use of CLT panels and common fasteners such as metal brackets and dowels, along with newer joint technologies like interlocking connections. Environmental aspects, including material efficiency and life cycle assessment data, were also considered.

The results indicated that CLT modular construction provides good structural integrity, efficient construction processes, and a reduced environmental footprint. The findings support the growing relevance of CLT modular systems as a practical and sustainable choice for residential construction.

Language: English
Key Words: CLT, Modular, LCA, Environmental Footprint

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1 Introduction

As the global population continues to grow and urban areas become more densely populated, the demand for efficient, sustainable, and affordable housing solutions is increasing. At the same time, the construction industry faces major challenges related to time, labor shortages, material waste, and environmental impacts. In response, modern construction methods such as modular building systems have gained attention for their ability to improve speed, quality, and sustainability.

Modular construction refers to the process of assembling buildings from prefabricated components that are manufactured off-site and then transported to the building site for final installation. When this approach is combined with engineered timber products, especially cross-laminated timber (CLT), it offers a promising alternative to traditional steel or concrete structures. Timber modular buildings not only reduce construction time but also lower the carbon footprint of the built environment, as timber is a renewable and carbon-storing material.

This thesis explores the technical, architectural, and environmental aspects of prefabricated timber modular buildings, focusing particularly on CLT systems. It investigates how this construction method works, the benefits and challenges it presents, and its potential role in the transition toward more sustainable and circular construction practices. The research also examines connection techniques, design flexibility, and life cycle considerations, providing a comprehensive understanding of modular timber construction in the context of today’s building industry.

1.1 Background and Motivation

In recent years, the construction industry has been seeking faster, more sustainable, and cost-effective methods of delivering buildings. Modular construction, which involves assembling structures from prefabricated components, has gained popularity due to its potential to reduce time, labor, and environmental impact compared to traditional construction methods. At the same time, timber—especially engineered wood products like cross-laminated timber (CLT)—has emerged as a renewable and low-carbon building material suitable for both structural and architectural use.

Timber modular buildings combine these two innovations, offering benefits such as reduced site disruption, faster building times, and lower embodied carbon. This construction approach is increasingly being explored for housing, schools, and even high-rise buildings. However, the widespread adoption of modular timber systems still faces challenges in areas such as connection detailing, acoustic and fire performance, and regulatory acceptance. Understanding the characteristics and limitations of this construction method is essential for architects, engineers, and policymakers seeking sustainable alternatives in the built environment.

1.2 Problem Statement

Despite the growing interest in modular timber construction, several issues limit its broader application. These include uncertainties regarding long-term performance, such as the durability of joints and connections, the structural behavior of modules under lateral loads, and concerns about moisture and fire resistance. In addition, standardization across manufacturers is limited, leading to variations in connection design, which can complicate design integration and on-site assembly.

There is also a gap in understanding how the environmental benefits, such as reduced embodied carbon and improved life cycle performance, compare with those of conventional concrete or steel buildings. Without clearer performance data and design strategies, decision-makers may hesitate to adopt modular timber construction despite its advantages.

1.3 Research Aims

The aim of this thesis is to investigate the architectural, structural, and environmental aspects of prefabricated modular buildings constructed from timber, especially cross-laminated timber (CLT). The study focuses on identifying and analysing:

- The structural properties and environmental performance of CLT in modular construction.
- The types, functions, and mechanical behavior of modular joints and connection systems.
- Architectural considerations such as space utilization and aesthetic flexibility in modular timber design.
- Life cycle assessment and sustainability outcomes compared to other construction materials.

By synthesizing recent case studies, standards, and technical literature, this thesis intends to provide practical insights and recommendations for more efficient and sustainable modular timber construction.

1.4 Scope and Limitations

This research is limited to modular buildings constructed from timber, with a primary focus on CLT-based systems. While other types of prefabrication and materials (e.g., steel or hybrid concrete systems) are briefly mentioned for comparison, they are not the main subject of study. The technical focus is on mid-rise residential or institutional buildings, typically up to 10 stories, where timber modules are most feasible with current design codes.

The study relies on published literature, case studies, product data, and design guidelines from manufacturers. It does not include full-scale experimental testing but may refer to such studies from other researchers. Additionally, the research is centered on projects and technologies from 2010 onward, with an emphasis on the period after 2020, reflecting current innovations and practices in the modular timber construction sector.

2. Definition and characteristics of Modular building

Modular construction is a building method in which a structure is assembled in whole or in part from prefabricated components that are produced off-site and then transported to the construction site for final assembly. In practice, this typically involves manufacturing modules or panels in a factory setting, with each module often being a three-dimensional section of the building (e.g. a room or volumetric unit) complete with interior finishes and fixtures (often called volumetric modules), or a two-dimensional panelized element (such as a wall or floor panel) that will form part of the building envelope. In either case, these prefabricated units conform to the same building standards as conventional construction and are designed to fit together as a complete structure on-site (Filion et al., 2024). Modular buildings, therefore, are assembled from such factory-made modules or panels, as opposed to being entirely constructed piece-by-piece on-site (Winter et al., 2017). This approach to construction is a subset of off-site construction or prefabrication, characterized by a high degree of completion in the factory before components arrive at the site (Smith, 2010).

A key characteristic of modular buildings is the range of modularization levels and system types available. Modules can range from 1D elements (like prefabricated linear components), 2D panelized systems (factory-built wall, floor, or roof panels) (Figure 1), to 3D volumetric modules (complete room-sized units).Often, a building will use a hybrid modular approach, combining volumetric modules with panelized or traditional elements to meet design and structural requirements, for example, a high-rise modular building might use a steel or concrete podium at ground level and a rigid core for stability, while stacking 3D modular units for the upper residential floors – a hybrid technique that leverages the benefits of module speed while handling the structural demands on lower levels (Lawson et al., 2014). In other cases, open-panel systems (2D panels assembled on-site) are blended with modular pod modules (like bathroom or kitchen pods) in one project – another form of hybrid modular construction (Pan & Sidwell, 2011). Essentially, modular construction is flexible: volumetric modules provide maximum factory completion (including interior finishes and services), whereas panelized systems offer more adaptability in configuration, and hybrid systems combine elements to optimize both factory fabrication and on-site assembly (Filion et al., 2024).

Figure 1. CLT prefabricated panel house (WIGO Group,2025)

Volumetric modular construction (3D modules): In this method, the building is made up of repeating room-sized units. Each module is typically a fully fitted three-dimensional section of the structure, often including interior walls, flooring, ceilings, plumbing, electrical, and finishes, produced under factory conditions, (Figure 2), (Yuan et al., 2018). These modules are transported to site and stacked or arranged to form the complete building. A common example is in the hotel or multifamily housing sector, where each module might correspond to a fully finished hotel room or apartment unit. For instance, a basic hotel design often fits well into a series of factory-made room modules (Filion et al., 2024).

Figure 2. Volumetric modular construction (Pbctoday, 2023)

One notable example of volumetric modular technique is the construction of the 30-story T30 Hotel in China (Figure 3), which was built by assembling factory-made modules – this 99.9-meter-tall hotel in Changsha was erected in only 15 days. This project, developed by the Broad Group, dramatically demonstrated volumetric modular speed by using modules that came with all interior components pre-installed, allowing floors to be stacked rapidly on-site (Generalova et al., 2016). Such volumetric modular buildings capitalize on fast on-site assembly, since as much as 80–90% of the building work (including finishes) can be completed off-site in advance (Chen et al., 2010).

Figure 3. Volumetric modular construction T30 hotel in China (Skyscrapercenter, 2023)

The modular units are designed to fit together precisely; they may be steel or timber-framed boxes that connect to one another when stacked. Transportation and lifting constraints play an important role in volumetric modular design – modules must be sized to legal road transport limits and engineered to endure lifting by crane without damage (Filion et al., 2024). Despite these constraints, volumetric modular methods have been used successfully in many permanent buildings, from low-rise homes to multi-story apartments and hotels, by firms seeking rapid construction timelines and high-quality control.

Panelized modular construction (2D panels): In this approach, the emphasis is on prefabricating flat building elements (panels) which are then assembled on-site into the structural frame of the building. Typical panelized components include wall panels (with windows/doors pre-installed or openings left), floor panels, and roof trusses or roof panels. These are often referred to as open panels if they are basic framing with perhaps sheathing, or closed panels if they come with insulation, internal finishes, and even services pre-installed. For example, cross-laminated timber (CLT) panels have emerged as a popular panelized system for tall timber buildings, enabling rapid assembly of floors and walls that are manufactured with precision off-site (Younis & Dodoo, 2022). Panelized systems generally offer greater flexibility in design than fully volumetric modules, because the building shape is not constrained by the size of 3D boxes. Instead, panels can be arranged and connected to form various layouts on-site, more akin to traditional stick-built construction but with large sections assembled in one go, (Figure 4).

In contemporary practice, panelized timber construction was used in the eight-story Puukuokka Housing Block in Finland (2015), where CLT wall and floor panels were assembled into a mid-rise apartment building, demonstrating the capability of panel systems to achieve height and performance (Li et al., 2023). Panelized modular construction maintains the benefit of factory quality control and weather-protected fabrication, while allowing more freedom in customizing building dimensions. However, it requires more on-site labor for assembly than volumetric modules, and additional work to finish the joints between panels and complete any on-site insulation or finishes that weren’t pre-installed.

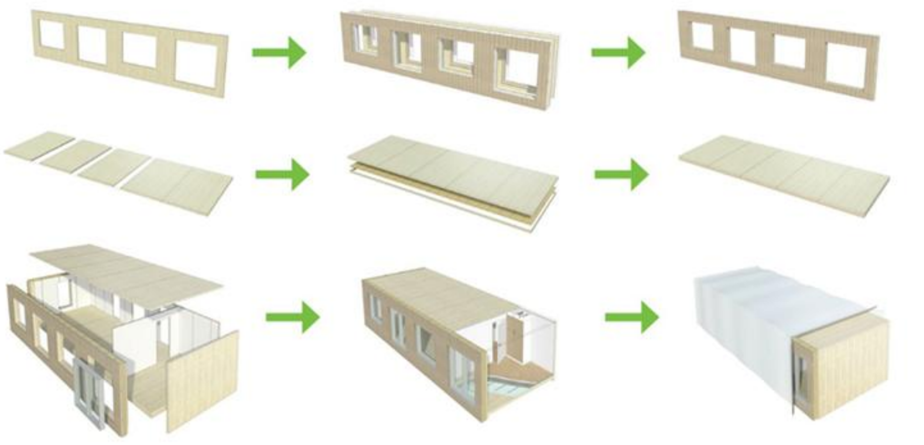


Figure 4. Stora Enso modular building systems proposes a CLT-backed subassembly for volumetric modular production (Masstimberconference, 2025)

Hybrid modular construction: Many projects combine both volumetric modules and panelized elements to leverage the benefits of each. Hybrid strategies can also mix modular construction with conventional construction. A common hybrid approach is the podium technique for multi-story buildings: the lower floors (or a core) are built with a traditional system (e.g., concrete or steel frame) to provide a robust base and open space for lobbies or retail, while the upper floors are made of repetitive modular units. This was the case in the 44-story, Ten Degrees, at 101 George Street in Croydon (UK),(Figure 5), where a concrete core was used alongside modules for the apartments – at the time of completion, this was one of the world’s tallest modular buildings (Gbadamosi, 2020).

Figure 5. Ten Degree Croydon, 101 George Street, George Street Modular Tower, 101 George Street (Skyscrapercenter, 2025)

Another hybrid example is the “Treet” tower in Norway, (Figure 6), a 14-storey timber apartment building completed in 2015 that combined volumetric wooden modules with an external glulam beam-and-column frame for structural support. In Treet, the modules (each 4 stories high stack of apartments) were inserted into the timber frame structure, illustrating how a hybrid system can achieve both height and module reusability. Generally, hybrid modular construction is chosen to address limitations of pure modular systems – for instance, using a steel frame or shear walls to handle lateral loads (wind or earthquake) in a tall building, while modular units handle gravity loads and provide finished interiors (Lawson, 2012). The characteristics of hybrid modular buildings include careful interface design between the modules and the traditional elements, and a need for precise coordination in engineering and assembly. By combining systems, hybrids can achieve greater architectural complexity or height than modules alone, albeit with somewhat longer construction times than an all-modular approach (since part of the structure is built conventionally).

Figure 6. Treet tower in Norway (Woodhouse, 2025)

Beyond the core structural approaches (volumetric, panelized, hybrid), modular buildings share several general characteristics and benefits. Speed and efficiency are a hallmark of modular construction. Because site preparation and foundation work can occur in parallel with module fabrication in the factory, overall project duration is significantly reduced. Studies show that using modular methods can shorten construction schedules by 30–50% compared to traditional builds. Likewise, on-site labor requirements are much lower – roughly 50% less on-site labor – since a large portion of work (framing, MEP installation, finishes) is done off-site (J. Li et al., 2023). This translates into cost savings in some cases: for example, site management costs can drop by 8–15% when using modular construction, due to the reduced time and crew size on-site.

Furthermore, the controlled factory environment improves construction quality and precision (components are built with jigs and tooling, with consistent supervision and testing) and can yield better workmanship than unpredictable field conditions (Goodier & Gibb, 2007). Weather delays are minimized, and material waste is typically reduced, since leftover materials can be recycled or reused more easily in a factory.

Modular buildings also often exhibit improved safety and less disruption on the construction site – with fewer workers and shorter time on-site, there are fewer accidents and less impact on neighboring properties (Kamali & Hewage, 2017). These characteristics make modular construction attractive for projects where speed, quality, or working in constrained urban sites are critical considerations.

However, modular buildings also come with specific challenges and design considerations. Because modules must be transported from factory to site, their dimensions are limited by road or rail shipping regulations (typically, width and height limits mean modules often max out around 3 to 4 meters wide and tall). This constraint can influence the layout of rooms and the structural design (engineers may need to design splices or connections where modules join). Additionally, the need to withstand lifting by cranes means modules usually have additional framing or reinforcement, sometimes resulting in higher material usage in the module edges or corners (to prevent damage or distortion during hoisting) (Zhang et al., 2020).

Coordination among disciplines is crucial: since so much of the project is completed off-site, the design phase must resolve all details early – plumbing, electrical, HVAC, and structural systems are integrated into the modules upfront, so late design changes can be costly (Filion et al., 2024). This necessitates a high level of collaboration between architects, engineers, and manufacturers from the beginning of the project (Mao et al., 2015). Furthermore, contractors must plan for logistics like storage and cranage on the job site; sufficient space is needed to stage modules as they arrive and a robust crane strategy must be in place to lift modules into position efficiently (usually one module can be set in minutes, but the sequence and site access are critical) (Ji et al., 2022).

Despite these challenges, modern modular construction techniques have advanced to the point that nearly any building type – from schools and hospitals to offices and high-rise apartments – can be partially or wholly built using modular methods, given proper planning (Yuan et al., 2018). The variety of real-world examples across different sectors, such as modular classrooms for rapid school expansion, pop-up medical clinics, and even modular data centers, underscores the versatility of this construction approach (Lawson et al., 2014).

Overall, modular buildings are defined by their prefabricated nature and characterized by speed, efficiency, and a need for precise integration – offering a fundamentally different process compared to conventional construction while delivering buildings that meet the same performance standards (Kamali & Hewage, 2017).

2.1 Historical Context and Evolution of Modular Techniques

The concept of constructing buildings from pre-made components has a long history, with early examples of prefabrication appearing well before the 20th century. In the 17th and 18th centuries, European colonizers used prefabricated building kits to quickly erect shelters in distant lands. One of the first documented instances was in 1624, when panels for a wooden house were reportedly shipped from England to the American colonies for assembly on-site (Herbert, 1984; Davies, 2005). By the early 19th century, the idea had advanced – notably, in 1837, a London carpenter named Henry Manning designed a portable wooden cottage that was pre-cut in England and shipped to Australia, where it was reassembled by immigrants (Davies, 2005). These early examples were essentially panelized buildings delivered in kit form, demonstrating the appeal of transporting *ready-to-build* houses to areas lacking skilled labor or materials.

The mass production techniques of the Industrial Revolution further enabled prefabrication: by the mid-1800s, components like iron beams, wall panels, and even entire modules (e.g. the cast-iron structural pieces of the Crystal Palace exhibition hall in 1851) were being fabricated off-site and assembled rapidly on-site (Smith, 2010). Although these 19th-century efforts were not called “modular construction” in modern terms, they established the precedent for speedy construction using off-site manufacturing, a core principle that would later define modular techniques.

The early 20th century saw prefabrication and modular concepts gain broader traction, particularly in housing. Factory-produced “kit homes” became popular in the United States and elsewhere: companies like Sears, Roebuck and Co. sold tens of thousands of mail-order houses between 1908 and 1940, providing customers all the parts needed (lumber cut to size, wall panels, hardware, etc.) to assemble a house on their lot (Smith, 2010). While these kit houses still required on-site assembly by local labor, they introduced a generation of homeowners to the idea of a partially pre-made dwelling and proved that standardized designs could be replicated efficiently (Smith, 2010). During the same era, architects and inventors explored more radical prefab structures – for example, Buckminster Fuller's Dymaxion House (1920s) was a prototype for a lightweight aluminum modular home that could be mass-produced (Smith, 2010). Though Fuller's concept did not go into mass production, it reflected the growing fascination with industrialized housing (Smith, 2010).

World events significantly accelerated the development of modular construction techniques in the mid-20th century. The urgent need to rebuild cities after World War II and to provide quick, affordable housing for veterans led to a surge in prefabrication in the late 1940s and 1950s (Davies, 2005). In the UK, for instance, the government deployed thousands of "prefab" temporary houses – small bungalows manufactured in factories (often from steel or timber panels) and assembled on bombed-out sites to address housing shortages. These post-WWII prefabs were meant to last 5–10 years, though a number survived far longer, illustrating both the promise and limitations of early modular housing (some had durability issues, but they were delivered and erected with unprecedented speed) (Herbert, 1984). Around the same time in the United States, the concept of manufactured homes took root: the 1950s saw the evolution of the mobile home (trailer) industry into larger, more permanent trailer homes, which were essentially volumetric modules on wheels. By the 1960s, these had given rise to the idea of modular homes (without wheels) that could be built in a factory and placed on a permanent foundation – an early form of volumetric modular housing governed by new building codes (Smith, 2010).

Meanwhile, architects experimented with modular concepts in avant-garde projects: the famous Habitat '67 housing complex in Montreal (figure 7), designed by Moshe Safdie for Expo 67, stacked 354 precast concrete boxes to create a striking apartment complex, capturing global attention for modular architecture. Each box was a module cast on site (in this case) but assembled in a Lego-like fashion to create terraced housing; Habitat '67 demonstrated the potential for modular units to provide both structure and living space, though the complexity and cost of that project also highlighted challenges in modular construction. (Gili Merin, 2023).

Figure 7. Habitat ’67 housing complex in Montreal (archdaily,2023)

By the 1970s and 1980s, modular construction continued to evolve amid fluctuating interest. The oil crisis and economic conditions of the 1970s initially dampened some enthusiasm for experimental architecture, yet modular building found steady application in certain sectors. Notably, Japan embraced prefabrication in housing on a large scale: companies like Sekisui House and Panasonic Homes developed sophisticated panelized and modular home factories, delivering thousands of standardized houses annually (Gibb, 1999). In the West, the late 70s and 80s saw incremental improvements in factory-built housing and commercial modular units (such as site offices, classroom pods, etc.), but also a growing stigma – some viewed modular or “prefab” buildings as cheap, temporary solutions, associating them with the uninspired post-war prefabs or mobile homes of earlier decades (Smith, 2010).

Nevertheless, important technical advances were made. For example, Kisho Kurokawa’s Nakagin Capsule Tower in Tokyo (completed 1972), (Figure 8), introduced the idea of replaceable modular units attached to a core: it consisted of 140 small, prefabricated capsules (volumetric units) clipped onto a concrete shaft. This was a landmark in the Metabolist movement, envisioning that capsules could be removed and replaced over time. Although Nakagin’s capsules were never actually swapped out and the building eventually faced demolition due to degradation, it provided a pioneering example of modular flexibility – an architectural vision of buildings as dynamic collections of factory-made units

(Kurokawa, 1977). Similarly, in the 1980s, architects like Nicholas Grimshaw in the UK experimented with prefabricated panels and service-integrated modules in projects such as the Factory Record Building and serviced apartments, pushing the boundaries of what could be prefabricated.

Figure 8. Kisho Kurokawa's Nakagin Capsule Tower in Tokyo (Kakidai,2023)

The late 20th century and early 21st century marked a renaissance for modular construction, driven by improved technologies, materials, and a pressing need for faster, more sustainable building methods. By the 1990s, computer-aided design and manufacturing (CAD/CAM) became more prevalent, enabling greater precision in prefabrication. Cross-Laminated Timber (CLT) was developed in the 1990s in Europe, revolutionizing timber construction by allowing large-format wood panels to serve as structural walls and floors (Younis & Dodoo, 2022). The advent of CLT and other engineered wood products opened new possibilities for modular and panelized buildings using sustainable materials, and by the 2000s several pioneering projects demonstrated mass-timber modular systems. For example, the Murray Grove (Stadthaus) in London (2009) was a nine-story residential building made from CLT panels – a largely panelized prefab project that showed timber's viability in urban construction.

In recent years (2020s), modular construction has been further propelled by goals of sustainability and efficiency. The construction industry’s focus on reducing carbon emissions has favored modular approaches because of their potential for less waste and integration with circular economy principles – for instance, designing modules for disassembly and reuse. Research into reusable modular buildings (e.g., modules that can be disassembled at end-of-life and reconfigured elsewhere) has gained momentum (J. Li et al., 2023). One state-of-the-art example is the Mobi-Space system in Germany, (Figure 9), a reusable timber modular system developed for temporary school and office buildings: its 54 m² room modules can be assembled, disassembled, and reassembled multiple times, demonstrating a high degree of design for disassembly and adaptability.

Figure 9. Mobi-Space on the grounds of the Ludwig Weber School in Frankfurt Sindlingen. (Winter, Jacob-Freitag, & Köhler, 2017)

At the same time, digital technology (Building Information Modelling, automation in factories, and even robotics) is making modular production more precise and cost-effective. Factories are now able to incorporate advanced mechanical systems, high-performance materials, and custom finishes into modules with greater ease, broadening the appeal of modular buildings even for luxury developments and architecturally complex designs (Goulding et al., 2015).

3. Cross-Laminated Timber (CLT) in Construction

Cross-laminated timber (CLT) (Figure 10) is a modern engineered wood product that has emerged as a viable structural material for building construction. It consists of several layers of solid wood boards (typically spruce or pine) stacked crosswise at 90° angles and bonded together with structural adhesives to form large, rigid panels (KLH Massivholz, 2021). This cross-lamination technique imparts dimensional stability and enables the panels to carry loads in two directions. Developed in the 1990s in Austria as Kreuzlagenholz (KLH) and now produced by various manufacturers, CLT has quickly gained popularity in Europe and globally as an alternative to construction materials like concrete and steel (Swedish Wood, 2019).

Figure 10. Cross laminated timber, CLT (Holz, 2021)

CLT panels can be produced in very large formats (e.g. up to around 3–4 meters in width and over 15 meters in length), allowing entire wall or floor sections to be prefabricated as single pieces (Swedish Wood, 2019). These prefabricated panels are precisely cut (often with CNC technology) to include openings for doors, windows, and service channels, and are then transported to site for rapid assembly.

In construction, CLT elements are used for a building’s walls, floors, roofs, and cores, assembled typically with metal connectors and screws. Because the panels are stiff and load bearing immediately upon installation, they enable fast, dry construction with minimal on-site wet work. Many buildings up to mid-rise and high-rise scale have been built with

CLT structures, demonstrating that tall timber buildings are now feasible by assembling CLT panels as part of a robust structural system (Swedish Wood, 2019).

In summary, CLT has introduced a new paradigm of mass timber construction – using large, engineered wood panels to achieve structural performance comparable to steel or concrete frames, while offering the benefits of prefabrication and sustainability.

4. Material Properties of CLT

As a wood-based material, CLT inherits many of the characteristics of lumber, but its cross-laminated configuration gives it unique properties.

4.1 Structural Strength and Stiffness

CLT panels have a high load-bearing capacity relative to their weight. The wood lamellae (boards) in the outer layers (aligned with the panel's strong axis) provide excellent bending and tensile strength along the grain, while the crosswise layers provide stability and enable the panel to carry loads out-of-plane and in-plane in both directions (Swedish Wood, 2019). In engineering terms, wood is an orthotropic material – it is much stronger and stiffer parallel to the grain than perpendicular to it. By arranging layers perpendicularly, CLT panels even out some of this directional disparity. The result is a plate-like structural element that can act like a reinforced concrete slab or wall, capable of spanning significant distances and supporting multi-story loads. Although the elastic modulus of wood is lower than that of steel or concrete, the thickness and composite action of multiple layers give CLT adequate stiffness for many applications. CLT panels can be designed to resist bending, shear, and axial forces; for example, a sufficiently thick CLT floor panel can span several meters without intermediate support, and CLT shear walls can stabilize multi-story buildings. However, it is noted that CLT's effective stiffness in its major load-bearing direction may be a bit lower than an equivalent solid timber section (because of the interrupted cross-layers), and the rolling shear strength in the cross-layers can govern certain failure modes (Swedish Wood, 2019). Engineers account for these factors in design, often using published characteristic strength values for panels made from a given timber grade.

4.2 Density and Weight

CLT is a lightweight material compared to concrete. With a typical density on the order of 400–500 kg/m³ (depending on wood species and moisture content), a CLT floor slab weighs only a fraction of an equivalent concrete slab of the same size. This low self-weight reduces foundation loads and is advantageous for transport and handling. Despite being five times lighter than concrete, CLT's strength-to-weight ratio is high – meaning it delivers considerable load-bearing capacity per unit weight (Swedish Wood, 2019). This attribute is one reason CLT can compete with more massive materials in construction.

4.3 Dimensional Stability

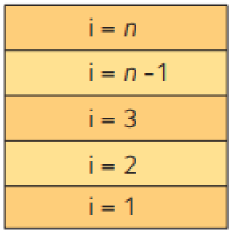
One of the notable material properties of CLT is its dimensional stability across changing climates. Wood typically swells and shrinks with moisture variation – mostly across the grain. In a CLT panel, each layer's grain is oriented orthogonally to the next, which restrains movements and splits. The cross-laminating significantly reduces swelling and shrinkage in the plane of the panel, resulting in minimal dimensional change with humidity fluctuations (KLH Massivholz, 2021). For example, KLH reports that the perpendicular layer arrangement cuts wood's natural swelling/shrinkage effects "to an insignificant minimum," as the layers hold each other in check (KLH Massivholz, 2021). This stability is beneficial during construction and over the building's life, as CLT components are less prone to warp or crack compared to traditional sawn lumber assemblies. That said, designers still aim to keep the wood's moisture content in service below about 12–18 %. If CLT panels are exposed to high humidity or liquid water for prolonged periods, they can still experience dimensional changes or biodeterioration (rot or mold) like any wood product. Manufacturers supply CLT at a controlled moisture content (often ~12 % at production), and it's important to prevent excessive wetting of the panels on site. With proper detailing (cladding, membranes, sealants) to keep moisture out, CLT elements can remain dimensionally stable and durable for many decades.

4.4 Thermal properties

Like solid wood, CLT has advantageous thermal insulation properties. Wood has a much lower thermal conductivity than materials like concrete, masonry, or steel. For instance, softwood in the radial/tangential direction has a thermal conductivity around 0.11–0.13 W/(m·K) (Swedish Wood, 2019). This means a CLT panel provides some insulation value and has relatively few thermal bridges, contributing to energy efficiency. In practice, CLT exterior walls are usually combined with additional insulation layers to meet strict thermal requirements, but the wood itself adds to the overall R-value of the assembly. CLT also has a high specific heat capacity (around 1600 J/(kg·K)), meaning the panels can absorb and store heat, which helps moderate indoor temperature fluctuations (Swedish Wood, 2019). This thermal mass effect, while less than concrete due to wood's lower density, can still improve comfort by damping swings in temperature and humidity inside the building.

4.5 Fire Performance

Although wood is a combustible material, large timber sections like CLT exhibit predictable fire performance. In the event of fire, the exposed surface of a CLT panel will char at a known rate (approximately 0.6–0.8 mm per minute for softwood) and that char layer insulates and protects the core of the panel, (Figure 11), (Swedish Wood, 2019). As a result, a sufficiently thick CLT element can maintain structural integrity for a considerable time under fire exposure. For example, panels can be designed to achieve fire resistance ratings such as 1-hour or 2-hour by accounting for sacrificial charring thickness in engineering calculations. CLT does not deform or collapse suddenly in fire; it tends to retain its load-bearing capacity until the char front progresses deep into the section. This performance is recognized in building codes – fire safety designs for CLT involve either using thick panels that can char and still support loads or adding protective non-combustible layers (e.g. gypsum board) to achieve the required fire rating. It is worth noting that adhesives used in CLT are now typically high-temperature-resistant (e.g. polyurethane PUR adhesives that do not emit formaldehyde), so they remain effective during fire and do not cause early delamination (KLH Massivholz, 2021). Overall, while wood burns, a CLT structure can be designed to meet fire regulations by balancing charring rates and protective measures.



a) Cross-section at normal temperature.

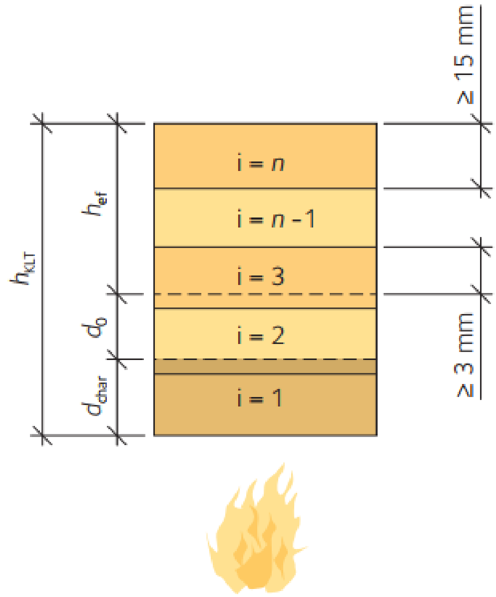


Figure 11. CLT layer in fire situation (CLT handbook, 2019)

4.6 Acoustic Performance

Solid timber panels like CLT have characteristics of a single-leaf wall, which means that by themselves they are not as effective at blocking airborne sound as heavier or multi-layer construction. The relatively high stiffness of a CLT panel can lead to lower sound attenuation at certain frequencies (compared to, say, a limp partition of the same surface weight). In practice, achieving good sound insulation with CLT often requires construction of double-shell assemblies, for example two CLT layers separated by an air gap and insulation or adding other materials (like resilient channels and drywall) to increase damping and reduce sound transmission. Studies have shown that a single CLT wall, especially if thin, will struggle to meet typical apartment separation sound ratings on its own (Swedish Wood, 2019).

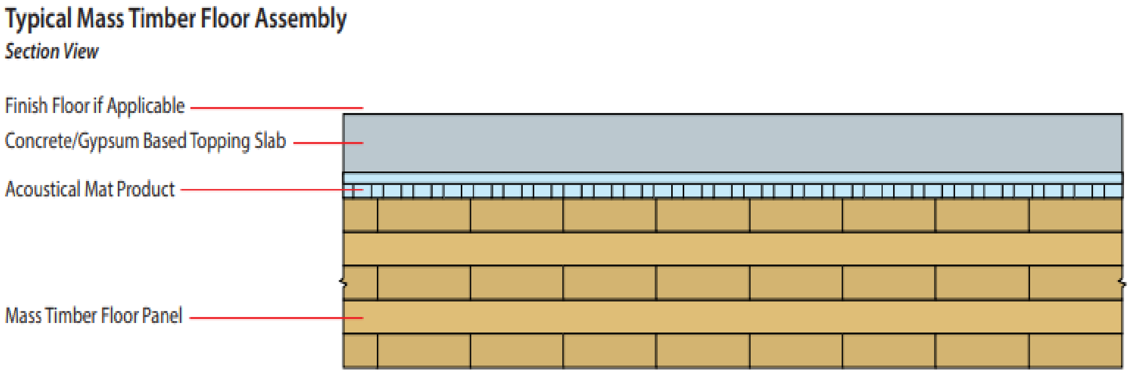


Figure 12. Acoustic solution for CLT floor (Woodworks, 2018)

However, when used in combination with insulation and secondary layers, CLT buildings can be designed to provide excellent acoustic performance. The floor systems often include concrete toppings or floating floors to add mass and prevent footstep noise (figure 12), while wall systems may use split panels or additional insulation like Batt insulation (Figure 13).

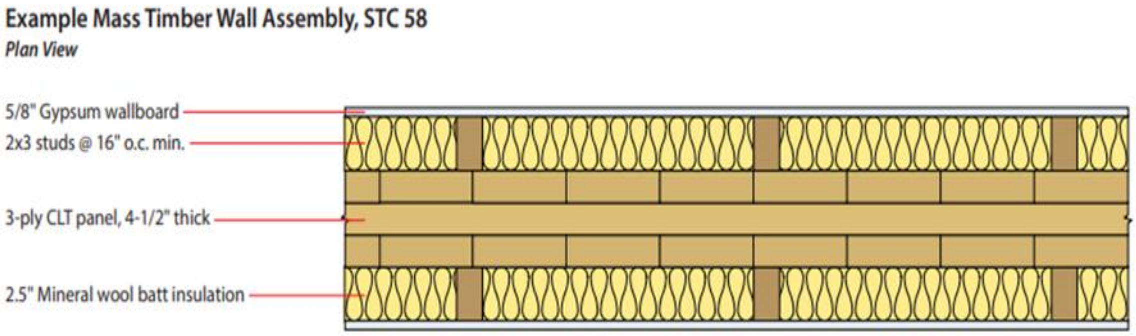


Figure 13. Batt insulation for noise barrier for CLT wall (Woodworks, 2018)

For reducing flanking path in connections and joints, one suggestion is to use resilient connection isolation and sealant strips, (Figure 14), (R McLain, Woodworks, 2018). Thus, while acoustics is sometimes viewed as a challenge for CLT construction, it can be addressed through thoughtful assembly design (and is an active area of development in mass timber research).

Figure 14. Acoustic insulation stripe in connection and joints (Woodwork, 2018)

4.7 Other Properties

CLT panels are generally durable and long-lasting when kept dry and protected. Wood does not corrode like steel and can last for centuries (there are wooden buildings still standing after hundreds of years). The surface of CLT can be specified in appearance grades: many manufacturers offer an "industrial" grade for hidden structural uses and a higher "architectural" grade with visually appealing wood surfaces for exposed use. In an architectural application, the interior face of a CLT panel can serve as the finished ceiling or wall, showcasing the natural wood texture, (Figure 15), (Swedish Wood, 2019). This dual structural-and-finish function is a unique property of timber construction. Additionally, because CLT is made of relatively small lumber boards finger-jointed into layers, it makes efficient use of forest resources, including boards of varying quality (the cross-lamination can compensate for some natural wood defects by distributing them). From a fabrication perspective, CLT panels are precision-engineered: factories implement strict quality control, ensuring each board is strength-graded and each panel is manufactured to spec. The result is a high degree of dimensional accuracy (often within a few millimeters) in the delivered product (KLH Massivholz, 2021). This precision contributes to the tight tolerance and solid feel of CLT buildings.

In summary, the material properties of CLT - combining high strength-to-weight, dimensional stability, thermal efficiency and predictable performance under load - support its growing use in construction. At the same time, designers must consider the nature of wood (moisture sensitivity, acoustics, etc.) to take full advantage of CLT in a building.

Figure 15. Natural wood texture (Storaenso, 2025)

5. Advantage of CLT

CLT offers numerous advantages that make it an attractive choice for sustainable modern construction. Some of the key benefits include:

Sustainability: CLT is made from a renewable resource – wood – and has a much lower embodied energy and carbon footprint than steel or concrete. Using timber from responsibly managed forests can result in a net reduction of CO_2 in the atmosphere, as the wood sequesters carbon during tree growth (Swedish Wood, 2019). For example, wood products store carbon for the life of the building, and the production of CLT panels emits significantly less CO_2 compared to producing cement or steel. These qualities make CLT a centerpiece of green building strategies aiming to reduce greenhouse gas emissions.

High Strength-to-Weight Ratio: Despite its light weight, CLT has excellent structural capacity. CLT panels can support heavy loads and long spans while being much lighter than concrete elements (Swedish Wood, 2019). This reduces foundation loads and is especially advantageous for adding stories to existing structures or building on weaker soils. The impressive strength-to-weight ratio of CLT enables the construction of multi-story buildings; several projects have demonstrated buildings of 8–10+ stories using predominantly CLT structures.

Dimensional Stability and Precision: The cross-laminated construction of CLT gives it superior dimensional stability. It is less prone to warp, twist, or shrink compared to traditional lumber because the crosswise layers balance the wood's natural movements (KLH Massivholz, 2021). Additionally, CLT panels are factory-made under strict quality control, resulting in precise, true panels that fit together with minimal tolerances. This precision means walls and floors come out exceptionally straight and plumb, simplifying later finish work.

Speed of Construction: Building with CLT elements or modular can be significantly faster than with regular materials. The panels arrive at the site prefabricated and often include pre-cut openings, which reduces on-site labor for framing or forming. Assembly is rapid – large sections (entire wall or floor panels) can be craned into place in one go. Dry construction (no curing time needed, unlike concrete) means a CLT structure can be erected in a matter of days or weeks rather than months (KLH Massivholz, 2021). This speed can translate into cost savings in terms of labor and financing, and it reduces the disruption at the construction site and surrounding area.

Reduced Site Impact: Construction using prefabricated CLT panels tends to be cleaner and quieter. Since major cutting and fabrication are done off-site, there is less noise and waste generated at the site (KLH Massivholz, 2021). CLT panels only need to be fixed in place with screws or brackets, so the process is relatively low noise compared to heavy concrete work. Smaller construction crews are required for assembly (often a crew of 4–5 can assemble a house-sized CLT structure with a crane), improving site safety and potentially lowering labor costs (KLH Massivholz, 2021). Fewer deliveries to site are needed as well (panels arrive in batches), which can ease logistics, especially in urban projects.

Flexibility in Design: CLT elements or modular provide design flexibility to architects and engineers. They can be used as structural walls, floors, roofs, and even shear diaphragms or elevator cores. Openings can be cut into panels for stairs, service shafts, or later modifications. This allows for creative architectural designs – including cantilevers, sculptural forms, and exposed wood interiors – that still benefit from the efficient, flat-pack panel construction method. Unlike stick framing, CLT doesn’t impose a repetitive grid of studs or beams, so interior spaces can be configured more freely (KLH Massivholz, 2021). The panels also combine well with other materials; hybrid structures are possible where CLT is used alongside steel or concrete to optimize performance or aesthetics (Swedish Wood, 2019).

Good Fire Performance: As discussed, heavy timber like CLT chars at a predictable rate and maintains strength for a long duration in fire. This inherent fire resistance (when properly accounted for) is considered an advantage, as it can meet safety standards without needing as much applied fireproofing as steel would. Many building codes now recognize mass timber elements for fire-resistant construction, making CLT a permissible and safe option even for larger buildings (Swedish Wood, 2019).

Thermal Efficiency: Wood’s natural thermal insulating properties mean that CLT buildings can be energy efficient. The panels help reduce thermal bridging and can contribute to meeting insulation requirements. The high wood mass can also regulate indoor temperatures and humidity, creating a comfortable living environment. Residents often report that CLT buildings feel warm and “cozy,” thanks to the wood surfaces moderating the indoor climate (Swedish Wood, 2019).

Aesthetic and Biophilic Appeal: CLT allows for exposed wood finishes that many find visually and tactically appealing. Interiors with exposed CLT have a natural look, with warm wood tones and grain visible on walls or ceilings. In addition to aesthetics, there is evidence that wood interiors can have positive effects on occupants’ well-being – for instance, promoting lower stress levels and even improving sleep quality (Swedish Wood, 2019). This gives CLT an advantage not only structurally, but also from an architectural and occupant experience perspective.

Ductility and Seismic Performance: Timber structures have a degree of flexibility and ductility, especially at the connections, which can be beneficial in seismic regions. The lighter weight of CLT reduces seismic forces (which are proportional to mass), and engineered wood systems can dissipate energy through controlled connection yielding. CLT buildings in earthquake-prone areas have shown good performance when properly designed, making it a viable material for seismic design (KLH Massivholz, 2021).

6. Disadvantage of CLT

Alongside its advantages, CLT has certain limitations and challenges that must be considered in design and construction:

Moisture Sensitivity: Wood is vulnerable to moisture and must be protected from prolonged wetting. A major limitation of CLT construction is ensuring adequate weather protection during construction and in the building envelope design. If CLT panels are improperly exposed to rain or high humidity, they can absorb water, leading to swelling, mold growth, or decay over time, (Figure 16), (Swedish Wood, 2019). Builders must take care to keep panels dry (often using temporary covers or rapid enclosure strategies) and architects must detail the finished building to prevent water ingress (through cladding systems, membranes, overhangs, etc.). In climates with significant rainfall, this can be a challenge compared to concrete or masonry which are more water-tolerant during construction.

Figure 16. Moisture damage in CLT (Vaproshield, 2020)

Fire Regulations and Char Depth: While CLT can be designed for fire resistance, it is still a combustible material, and building codes impose strict requirements on timber buildings (especially for heights beyond a certain limit) (Gagnon & Pirvu, 2011). One limitation is that to achieve high fire ratings, CLT panels may need to be quite thick or protected by gypsum board layers, which can add cost or weight (Karacebeyli & Douglas, 2013). There is also ongoing research into the behavior of CLT in severe fires – for instance, if the char layer falls off, fresh wood can reignite, a phenomenon observed with certain adhesive types (Frangi et al., 2009). Thus, designers must use approved, fire-tested products and details, and additional sprinkler protection is often mandated for tall timber buildings as a precaution (ANSI/AWC, 2022). In summary, CLT can meet fire code, but it requires careful engineering and sometimes additional safeguards, whereas non-combustible materials like concrete inherently satisfy some fire code provisions more easily (Buchanan & Abu, 2017).

Acoustic Performance: As noted earlier, a single CLT panel by itself does not always provide sufficient sound insulation, especially for party walls or floors in multi-family housing. Consequently, acoustic design is a known limitation – it often necessitates additional construction such as floating floors, resilient ceiling hangers, double-stud walls, or other solutions to achieve acceptable sound transmission class (STC) ratings (Swedish Wood, 2019). These additional layers can partially offset the simplicity and thinness advantages of CLT and can make dismantling more difficult and produce more waste in the environment. If not addressed properly, poor acoustics could be a complaint in timber buildings. Acoustic design for CLT is improving, but it remains a technical consideration that designers must account for (unlike the mass of concrete which naturally provides good sound insulation in many cases).

Cost and Availability: In some regions, CLT panels are still a specialty product and can be more expensive than traditional building systems on a direct cost basis (Espinoza et al., 2016). The manufacturing process for CLT is capital-intensive—requiring large presses, CNC machinery, and strict quality control—which adds to initial production costs (Gagnon & Pirvu, 2011). There may also be limited regional suppliers, resulting in longer lead times or higher transport costs if panels must be shipped long distances (Karacebeyli & Douglas, 2013). While the overall construction speed and reduced on-site labor can yield cost savings, the material unit cost of CLT may still be higher than conventional systems like light-frame timber or cast-in-place concrete (Smith, 2010). In addition, contractors unfamiliar with CLT may include contingency costs due to uncertainty in handling or sequencing (Jones et al., 2021). However, as production expands and more manufacturers enter the market, competition and economies of scale are gradually helping to reduce prices and improve availability (Li et al., 2023).

Building Height Limits: Although CLT has enabled mid-rise timber buildings, going extremely tall in wood poses challenges. There are practical and code-related limits on timber buildings – for example, some building codes cap the allowable height or number of stories for wood structures unless special approvals are obtained (Buchanan & Abu, 2017). Issues like lateral stability, connection performance, and construction sequencing become more complex as buildings get taller (Gagnon & Pirvu, 2011). As a result, hybrid solutions are often used in taller timber buildings, such as concrete or steel cores combined with CLT panels for floors or walls (Green, 2012). While CLT can form the backbone of high-rise projects, it currently cannot fully replace concrete or steel in the tallest structures due to code restrictions and performance limits (Karacebeyli & Douglas, 2013).

Connections and Structural Detailing: Joining CLT panels to each other or to foundations requires custom engineered connections – typically involving long self-tapping screws, steel plates, brackets, and bolts (Gagnon & Pirvu, 2011). These connections are critical to the building's performance and must be designed for both strength and stiffness. One key limitation is that connection design in CLT is complex and differs significantly from steel or concrete systems, requiring specialized knowledge and high precision during installation (Smith, 2010). If improperly designed or executed, issues such as squeaking, deflection, or reduced load transfer can occur (Jones et al., 2021). In seismic zones, connections serve as ductile fuses that absorb energy during an earthquake, which adds another layer of engineering complexity (Popovski et al., 2010). Thus, achieving reliable performance demands high-quality detailing and skilled labor.

Experience and Supply Chain: Because CLT is still an emerging material in many regions, the industry is facing a learning curve. Not all contractors are familiar with handling and installing large-format timber panels, which can lead to slower construction, coordination errors, or the need for retraining (Espinoza et al., 2016). Additionally, some local building officials and insurers are unfamiliar with mass timber systems, leading to extra review steps, testing requirements, or increased insurance costs (Li et al., 2023). These hurdles are gradually being addressed as the use of CLT grows globally, but in areas where mass timber is just beginning to emerge, limited experience can still pose a barrier to adoption (Kamali & Hewage, 2017).

Durability Considerations*:* While wood structures can be very durable, they are susceptible to certain hazards that differ from concrete or steel. Besides moisture and fire, one must consider insect attack (such as termites or beetles) in some climates – protection or treatment may be necessary in those areas, adding maintenance requirements (Karacebeyli & Douglas, 2013). Also, unlike concrete, wood can't be left exposed to weather indefinitely; exterior CLT must be protected by facade materials (Gagnon & Pirvu, 2011). If part of the panel does get damaged or begins to rot, repairs can be more involved, since a CLT panel is a single large component rather than discrete studs that can be easily swapped (Espinoza et al., 2016). These factors mean the long-term durability of CLT structures hinges on good design, construction, and maintenance to keep the timber dry and covered (Swedish Wood, 2019).

7. Architectural Aspects of Wooden Modular Houses

Modular wooden houses have gained prominence due to their adaptability, environmental benefits, and aesthetic possibilities. These structures utilize prefabricated components assembled off-site, significantly reducing construction times and enhancing quality control (Li, Andersen, & Hudert, 2023).

7.1 Design Flexibility and Aesthetic Considerations

A critical benefit of modular wooden houses is their design flexibility. The modular approach enables customization of buildings according to specific needs and preferences. Modules can be rearranged or expanded, allowing structures to adapt over time to changing functional requirements or user preferences (Marza, Corsiuc, & Graur, 2019). For instance, the Mobi-Space system demonstrates how modular units initially intended for temporary school facilities were later successfully adapted as office spaces, highlighting their versatile use across different functions (Winter, Jacob-Freitag, & Köhler, 2017).

Aesthetic considerations are also effectively addressed through modular wooden systems. Unlike traditional prefabricated structures perceived as monotonous or repetitive, modern modular wooden buildings emphasize architectural quality. They offer varied façade treatments such as wooden sidings, metal panels, and other contemporary materials, providing pleasing visual outcomes that can blend naturally with diverse landscapes (Marza et al., 2019). Additionally, modular timber structures often feature clean, minimalist aesthetics, leveraging wood's inherent visual warmth and texture, thus enhancing user experience and visual integration with natural environments (Li et al., 2023).

7.2 Modular Layouts and Space Utilization

Space utilization is significantly optimized in modular wooden homes through careful design and efficient layouts. Modules are typically standardized to specific dimensions, ensuring ease of transportation, rapid assembly, and efficient use of interior spaces. Standard module dimensions, such as 5.80 m by 2.55 m, allow for versatile configurations, facilitating diverse arrangements including compact dwellings and more expansive residential units (Marza et al., 2019).

Effective space management is evident in the flexible interior layouts possible with modular designs. Interior spaces can be quickly reconfigured by relocating partitions or combining modules, which accommodates evolving residential or institutional needs without extensive structural modifications (Winter et al., 2017). This ability to reorganize space is particularly beneficial in urban settings or disaster relief scenarios, where rapid and adaptable housing solutions are essential.

Moreover, wooden modular units have very good insulation abilities because of their layered walls, which greatly help in making buildings comfortable and saving energy, especially in small spaces. Materials such as polyurethane foam and rockwool are used because they offer effective insulation even when used in thin layers, allowing better use of space without losing thermal performance (Marza et al., 2019). However, insulation must be examined from various angles, not just thermal performance.

Rockwool, also known as stone wool (Figure 17), is a high-performance insulation material made by spinning molten rock and recycled slag into fibers (ROCKWOOL, n.d., 2025). Polyurethane foam is a versatile polymer produced by the reaction of polyols and isocyanates, forming a cellular structure that can be either rigid (Figure 18), or flexible like spray foam (Figure 19) depending on its formulation. (Polyurethane Foam Association, n.d., 2025). From an environmental point of view, polyurethane foam is excellent for insulation, but its production uses chemicals that can significantly contribute to global warming, making it less environmentally friendly (Blengini & Di Carlo, 2010). On the other hand, rockwool is made from natural materials, which makes it more environmentally friendly because it can be recycled and uses less energy to produce (Papadopoulos, 2005).

Figure 17. Rockwool (Optimera, 2025)

Regarding fire safety, rockwool is better because it does not burn easily and can withstand high temperatures, making wooden modular buildings safer during fires (Hull & Stec, 2009). Polyurethane foam, although good for insulation, can be dangerous in fires unless treated with special chemicals. These chemicals can sometimes release harmful gases, causing additional safety and environmental concerns (Mouritz & Gibson, 2006).

Figure 18. Rigid polyurethane (Acoustafoam, 2021)

Moisture control is also important. While wooden modular buildings use insulation layers effectively to keep the inside comfortable, poor installation or inadequate moisture barriers can cause moisture problems inside the walls. Polyurethane foam generally handles moisture better than rockwool, reducing the risk of mold and damage to the building structure (Straube & Burnett, 2005). However, this benefit requires careful installation.

Figure 19. Polyurethane spray foam (Gnsgroup, 2025)

Therefore, a complete analysis shows that although polyurethane foam and rockwool greatly improve insulation and energy efficiency in modular wooden buildings, their selection should balance thermal efficiency with considerations of environmental impacts, fire safety, and moisture management to ensure good overall performance.

8. Joints and Connections in Prefabricated CLT Modulars

Prefabricated wooden modular buildings rely on specialized joints and connections to ensure structural integrity during assembly, transport, and service life. These connections must accommodate repeated assembly/disassembly, tolerate manufacturing tolerances, and resist various forces (compression, tension, shear, etc.). Key connection strategies include traditional timber joinery and modern metal fasteners or hybrid systems, each offering distinct advantages in modular construction. In this section, we discuss common connection types, their structural/mechanical performance, and emerging joint technologies in modular timber design.

8.1 Structural and Mechanical Performance of Connections

The mechanical performance of modular connections is crucial for overall building stability. Key aspects include load-bearing capacity (under vertical loads), lateral resistance (under wind or seismic forces), stiffness, and tolerance for repeated assembly.

Load Transfer and Strength: Connections in modular timber buildings must effectively carry vertical loads from upper modules to lower ones and transfer horizontal forces across the modules (Auclair, 2023; Filion et al., 2024). Metal brackets and plate connectors typically exhibit high strength in shear and tension, enabling them to safely transfer various loads between units. For example, screws utilized with hook-in profiles, a specific type of metal connector, are effective at absorbing uplift forces, while angle brackets placed at joint ends can secure shear transfer between modules (Auclair, 2023). Timber dowel joints, on the other hand, are highly effective at carrying significant shear and compressive loads due to their inherent form-fit characteristics. However, they offer minimal resistance to uplift or tensile forces unless additional fasteners or reinforcements are incorporated (Auclair, 2023). Similarly, traditional carpentry joints, such as dovetails or mortise-and-tenon joints, excel in compression and shear due to their interlocking geometries, which primarily utilize gravity and friction to handle vertical and in-plane loads (Auclair, 2023; Filion et al., 2024). Yet, without supplementary reinforcement, carpentry joints have limited tension capacity and risk loosening under repeated cyclic or uplift loading conditions (Auclair, 2023).

Stiffness and Structural Behaviour: Connection stiffness influences how a modular building responds to loads (e.g., wind causing racking). Rigid connections (like screwed steel brackets or rod ties) create stiffer module integration, meaning the modules act more monolithically. This improves the building's lateral stability but can concentrate stresses at connection points. Semi-rigid or flexible connections (like some timber cleats or sliding hook connectors) allow slight movement, which can dissipate energy (useful in seismic conditions) but may require supplementary bracing to control drift. (Yousefi et al., 2020, as cited in Auclair, 2023). Recent experimental studies indicate that inter-module connection stiffness significantly affects the global shear resistance of modular timber buildings (Koskimies, 2022). Therefore, designers often fine-tune connection design: stiff enough for stability, yet with some ductility for dynamic loads. Connections are usually placed at the module corners or along edges, since these locations align structural elements like columns and beams. Indeed, literature notes that *"modular connections are generally made in the corners of the modules"* to effectively tie the structural frames together. Corner connections often combine vertical load transfer (through bearing pads or posts) and horizontal tying (through brackets or tension ties).

Repeatability and Tolerances: Prefabricated modules must fit accurately when assembled on-site; thus, their connections are deliberately designed with allowances for minor misalignments. High manufacturing precision, commonly achieved through CNC-machined joint slots, allows modular elements to fit together within millimetres-scale tolerances (Auclair, 2023; Filion, Ménard, Carbone, & Bader Eddin, 2024). Despite this precision, slight gaps or offsets may occur during actual assembly. To address such discrepancies, elastomeric bearings or pads can be installed between modules, helping to level surfaces, and additionally improve acoustic and fire insulation performance (Auclair, 2023). However, this method is not universally compatible; joints such as dowels that depend on direct physical contact between timber elements may not adequately accommodate these elastomeric layers without compromising their structural integrity or acoustic properties (Auclair, 2023).

Mechanically, modular connections must also remain reliable and robust across multiple cycles of assembly and disassembly. Reusable fasteners like screws and bolted plates are effective at maintaining their structural integrity if handled correctly. Nonetheless, improper handling or excessive force during disassembly can damage surrounding timber, adversely affecting future performance (Auclair, 2023). Notably, fully plug-in connections, which interlock securely without additional screws or nails, tend to offer greater convenience and durability for repeated use, promoting efficient assembly and disassembly cycles (Auclair, 2023; Filion et al., 2024). Overall, successful modular connections carefully balance structural strength, stiffness, and construction tolerances to ensure modules are quickly, safely, and repeatedly connected and disconnected with minimal structural degradation (Auclair, 2023).

8.2 Common Connection Types

Metal Brackets and Plates: Metal connectors (e.g., steel angles, brackets, plates) are widely used in modular timber construction for their strength and ease of installation (Gagnon & Pirvu, 2011). Standard steel angle brackets reinforce corners and splice points between modules, providing strong anchorage against uplift and shear forces (Karacebeyli & Douglas, 2013). Perforated metal plates and hooked plates can also join timber panels or frame elements, often secured using screws or bolts. These metal connectors typically ensure rigid and repeatable connections and can often be pre-installed off-site, which speeds up assembly on-site (Rothoblaas, n.d.). The use of screws through the bracket into timber can help absorb uplift tension, while the addition of side angles increases lateral and shear strength (Rothoblaas, 2022). Metal brackets are valued for their high load resistance, accessibility, and compatibility with Eurocode design calculations, making them a standard and reliable choice in modular timber joints (Smith, 2010).

Timber Dowel Joints: Dowel-type connections involve inserting wooden or steel dowels between stacked modules. In a common dowel joint, a dowel fixed in the lower module’s ceiling fits into a recess in the module above, creating a form-fit link that resists lateral movement. Wooden dowels (Figure 20), (or similar interlocking timber lugs) can carry horizontal pressure and shear by their shape and rely on gravity to engage. However, a limitation is that dowel joints do not resist tension (uplift) forces well, so they often must be paired with supplemental screws or brackets for full structural performance. In practice, dowel connections enable rapid alignment between modules and can be deconstructed easily (since they are not permanently bonded). Challenges include ensuring dowels fully seat into the upper module (their own weight can hinder complete insertion) and accommodating any gap adjustments between modules (large gaps reduce dowel effectiveness). Despite these challenges, dowel joints are valued for creating pin-type connections that are reversible and material-efficient, aligning with sustainable construction goals (Spax, n.d., as cited in Auclair, 2023).

Figure 20. Timber Dowel joint (NuernbergMesse, 2024)

Traditional Timber Carpentry Joints*:* Modular construction sometimes adapts classic wood joinery techniques such as cleats, dovetails, and mortise-and-tenon joints to connect modules (Figure 21), (Auclair, 2023). For example, a mortise-and-tenon joint can be enlarged to effectively join wall or floor elements between modules, providing a tight fit that resists movement due to its form-fit nature (Auclair, 2023). These joints are typically cut with high precision—often using CNC machinery—to ensure a snug and accurate fit (Auclair, 2023; Filion et al., 2024). Traditional joints mainly depend on wood-to-wood contact (form-fit) to resist compressive and shear loads. However, without additional metal reinforcement, purely wooden joints generally cannot sustain significant tensile loads, and thus might separate if modules are lifted or subjected to uplift forces (Auclair, 2023).

To overcome this limitation, hybrid designs are frequently employed, incorporating screws or steel pins through carpentry joints (e.g., pinned mortise-and-tenon connections) to securely lock modules in place (Auclair, 2023; Filion et al., 2024). While traditional carpentry joints preserve an aesthetically pleasing all-timber appearance and can exhibit significant stiffness under compression and shear forces, they require tight manufacturing tolerances and careful on-site alignment. Consequently, their application in modular systems is often limited to specific interfaces or is combined with modern fasteners to ensure comprehensive structural stability (Auclair, 2023; Filion et al., 2024).

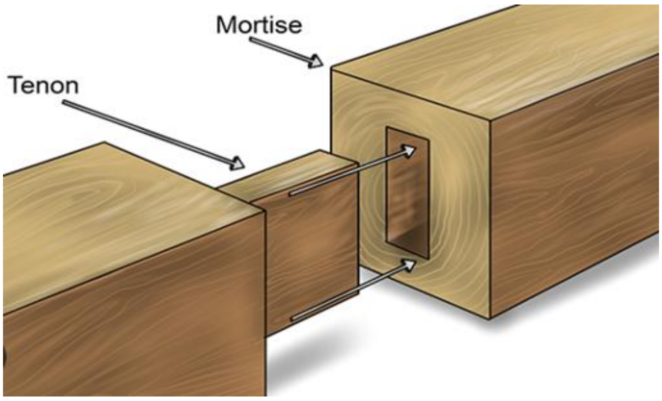


Figure 21. Mortise-and-Tenon joint (Kaltimber, 2017)

Screws and Rod Fasteners: Simple wood screws remain fundamental in timber modular connections (Figure 22). Screws are used both independently (to directly fasten modules) and in conjunction with other connectors, such as securing brackets or metal plates (Auclair, 2023). Angled screw techniques, such as toe-screwing modules together at approximately 30° angles, can enhance load transfer by effectively engaging multiple wood fibers, which is a recommended practice in CLT construction guidelines (Swedish Wood, 2019). Threaded rods or hangers are another connection method, in which long bolts run vertically through stacked modules—often located at corner posts—and are tightened to clamp modules securely together. These rods provide strong tensile capacity, effectively bolting modules into one cohesive structural unit, and can typically be concealed within wall cavities or corner columns (Auclair, 2023). Although threaded rod connections offer both rigidity and ductility, they require precise alignment of pre-drilled holes and sufficient access to tighten nuts during assembly. Importantly, both screws and rods facilitate disassembly by simply unscrewing, making them suitable for modular designs intended for future relocation or reconfiguration. Design and selection of these fasteners can follow structural demands outlined clearly in engineering standards, such as the Eurocode guidelines provided for timber joint calculations (Auclair, 2023; Swedish Wood, 2019).

Figure 22. Screws and Rod Fasteners (Essentracomponents, 2025)

High-Capacity Angle Brackets: Heavy steel angle brackets remain a straightforward way to connect modules (Figure 23), for example, fixing a CLT wall to a floor. These L-shaped brackets are mechanically fastened with screws or bolts to transfer shear and hold modules together. They are effective for horizontal shear loads and uplift restraint. Recent models such as the Rothoblaas "NINO" universal angle bracket offer improved shear and tension capacity for multi-story modular stacks (Rothoblaas, n.d.-a). Though proven and cost-effective, their installation requires on-site alignment and screwing, which may slow the assembly process. These brackets allow for some onsite tolerance, accommodating minor misalignments during installation. They are reliable and cost-effective but typically need to be installed onsite during module stacking, which can slow down the process. Their visibility may also disrupt interior or exterior finishes if not carefully detailed (Hilti Deutschland AG, 2022; Kekki, 2022; Rothoblaas, n.d.-b).

Figure 23. NINO, Universal angle bracket for shear and tensile loads (Rothoblaas, 2025)

Interlocking Hook Connectors: A newer class of connectors uses concealed hook plates that interlock between modules. For instance, the Rothoblaas UV–T (Figure 24), is a two-part aluminium connector designed for modular timber construction. One plate is mounted to each module; when modules are pushed together, they hook into one another forming a rigid connection (Rothoblaas, n.d.-b). These connectors can carry forces in all directions and provide high certified strength (over 60 kN for the UV–T). CNC precision machining is essential to ensure proper placement and tight fit. Once installed, they are hidden within the timber for improved fire protection and aesthetics. They are also fully demountable and have been used in wall-to-wall or beam-to-beam applications.

Figure 24. Concealed hook timber-to-timber connector (UV-T), (Rothoblaas,2025)

Joint Profile Connectors for Panels*:* Manufacturers have also introduced interlocking metal profiles to connect large CLT surfaces, such as floor slabs. An example is the Rothoblaas "Lock Floor" system (Figure 25), which features aluminium profiles pre-mounted on CLT panel edges that hook together on-site (Rothoblaas, n.d.-c). These profiles align modules, carry vertical loads, and can resist shear when used with screws or side angles. The Lock Floor profile supports both timber-to-timber and timber-to-concrete joints, making it suitable for reconfigurable or relocatable buildings. These connectors are fast to install and demountable, supporting design for disassembly. However, their cost is higher, and they demand precise fabrication to ensure perfect alignment (Rothoblaas, n.d.-b).

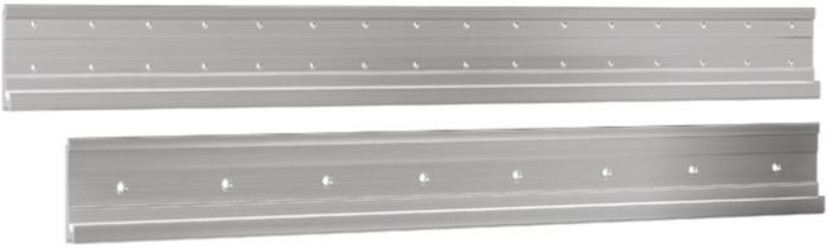


Figure 25. Lock floor, Joint profile for CLT panels (Rothoblaas, 2025)

Steel Dowel alignment connectors: Dowels are advantageous for rapid assembly and reuse, although challenges such as friction misalignment or spacing due to acoustic pads may affect performance (Figure 26). These connectors rely on gravity and precise positioning. A metal dowel is inserted into the top of a lower module and fits into a corresponding recess in the module above. This creates an automatic alignment and shear lock without the need for screws. While this makes assembly quick and clean, these joints have no resistance to vertical uplift and may not fully engage if tolerances are not exact or padding is used for acoustics. Additionally, they can disengage if modules shift, making them best suited for use in combination with tension-resistant fasteners (Fritz Kathe & Sohn GmbH, 2023; Spax, n.d.).

Figure 26. Dowel Connectors (KitegroupLtd, 2025)

Self-Locking Stack Connectors: The Hilti HCW system (Figure 27), introduced in 2021–2022, represents a significant innovation in vertical stacking. The Hilti HCW system consists of a threaded bolt installed in the lower module and a spring-loaded clamp in the upper one. When stacked, the clamp automatically locks onto the bolt, creating a secure, concealed joint that resists uplift and lateral forces. This tool-free solution speeds up assembly and protects the steel parts from fire by encasing them in timber. The main drawback is its lack of removability, which limits reuse. Also, penetration of airtight barriers may occur where the connector passes through insulation layers (Hilti Deutschland AG, 2022). These connectors are recessed in the timber, supporting fire safety and clean design. The HCW has seen growing adoption in European CLT modular construction.

Figure 27. Hilti HCW system (Hilti, 2025)

Concealed Hook Plate Connectors: These are precision-made, interlocking metal connectors that sit within timber elements. Products like the Rothoblaas Lock T Midi (Figure 28) allow two wall panels to hook into each other invisibly. This creates a clean look with good fire resistance and enables module separation without damage. However, they require highly accurate factory machining, and installation is less forgiving than with bracketed joints (Rothoblaas, n.d.-b).

Figure 28. Concealed timber-to-timber connector (LOCK T Midi) (Rothoblaas,2025)

Self-Tapping Screw Tie-ins: These involve driving long screws diagonally between adjacent modules to stitch them together. This method is simple and doesn't require additional metal hardware. Screws are often flush or hidden, maintaining clean aesthetics. The connection depends on proper installation, and long screws may compromise fire or acoustic barriers unless detailing addresses thermal bridges or noise transfer (Auclair, 2023; Rothoblaas, n.d.-b).

Traditional Timber Joints (Lap, Spline, Tongue-and-Groove): Simple wood-based solutions such as lap or spline joints still have widespread use (Figure 29), especially in small or single-module applications. These joints are structurally sound for many uses and are cost-effective. However, they lack removability and do not carry high tension or dynamic loads without reinforcement. Their use is more limited in large modular assemblies (Binderholz GmbH, 2021).

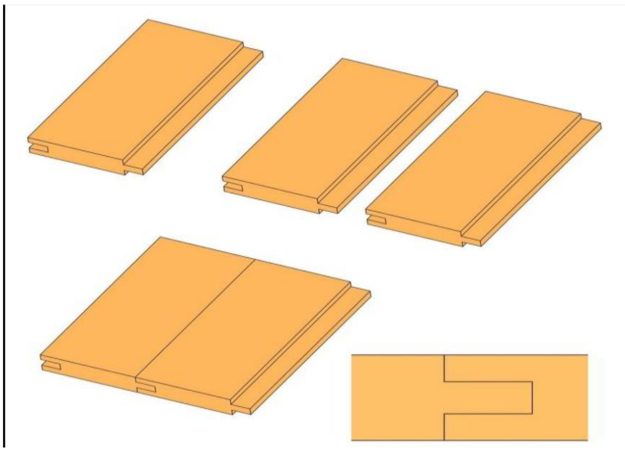


Figure 29. Tongue and groove joint with bead (Craftsmanspace,2025)

9. HeimdalsPorten Modular Building Case Study

HeimdalsPorten is a modular housing development in Trondheim, Norway (Figure 30), consisting of four multi-story residential towers (Unihouse SA, 2019). Two of the buildings are seven stories high and the other two are eight stories, making HeimdalsPorten one of the tallest modular timber building projects completed by a Norwegian developer (Unihouse SA, 2019; Ergodomus, 2021). The project provides approximately 200 apartments in total, all constructed using factory-fabricated volumetric timber modules (Unihouse SA, 2019). Construction began in 2019, and the first buildings were completed by the end of 2020, demonstrating a rapid project timeline compared to conventional construction (Unihouse SA, 2019; EurobuildCEE, 2021).

Figure 30. HeimdalsPorten (Ergodomus, 2025)

As a hybrid structure, each tower has a robust reinforced concrete core that houses elevators and staircases, anchored to a concrete foundation. The timber modules were assembled around these central cores, combining the strength of the concrete spine with the speed and sustainability of wood construction. This design approach leverages the benefits of both materials, using concrete for stability and fire safety in the core, and timber for the modular units to achieve quicker assembly and lower environmental impact. Modular construction is celebrated as a sustainable solution for reducing carbon footprint and meeting housing demand; in this case the use of timber for the modules further enhanced the project's sustainability profile (Ergodomus, 2021).

9.1. Design and Engineering

Each prefabricated module, arrived on site nearly complete, already outfitted with interior finishes and systems. Modules width can vary between 1.4 meter to 5.4 meter and their length can be between 3 to 16.5 meter. Larger apartment can consist of 1.5 or 2 modules that are connected (figure 31), (Unihouse,2025). The modules were delivered with bathroom fixtures, kitchen installations, flooring, electrical wiring, and plumbing all pre-installed. Walls were painted and mechanical systems were in place, making each unit almost ready for immediate occupancy upon installation (Ergodomus, 2021). This high level of pre-assembly significantly reduced on-site labor and construction time, while also improving quality control by shifting work to the factory environment. The construction process is not complete once all modules have been connected; the aesthetic façade must also be completed in line with the design.

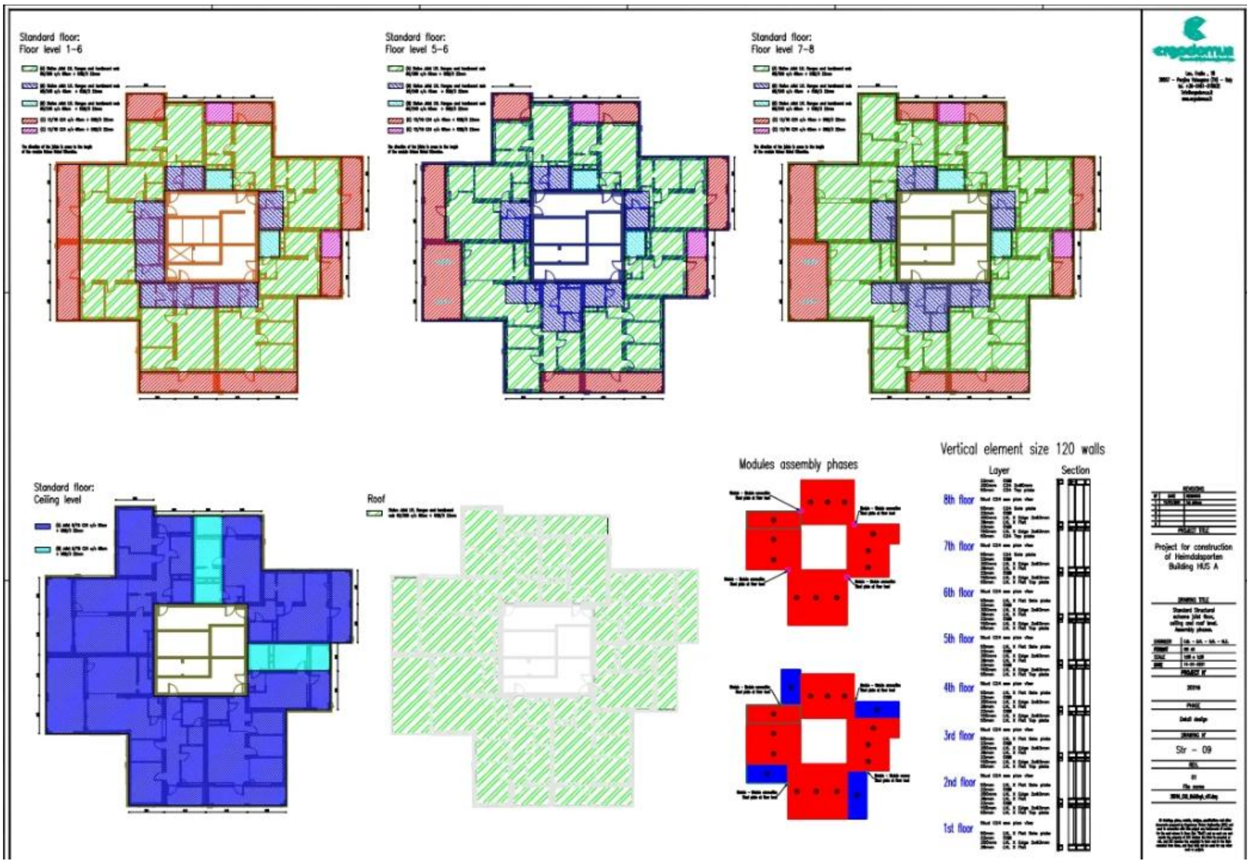


Figure 31. HeimdalsPorten floorplans (Ergodomus, 2025)

Norwegian winter conditions—with harsh weather and very limited daylight—made a strong case for choosing volumetric modular construction for this project (Ergodomus, 2021). Building modules indoors in a controlled factory setting ensured that weather did not delay the construction schedule and workers were not exposed to freezing outdoor conditions more than necessary. The completed modules only needed to be stacked and fastened on site, a process that can be performed relatively quickly even during short daylight hours. This strategic choice of construction method highlights how modular building can mitigate climate and weather challenges on difficult sites (Ergodomus, 2021).

Another key innovation in the HeimdalsPorten project was the development of custom steel connection hardware to facilitate swift and precise assembly. The engineering team at Unihouse designed bespoke steel connectors that guide each module into place, essentially self-aligning like a rail system for the module being placed above (Ergodomus, 2021). These tailor-made connections meant that workers did not need to spend extra time adjusting and checking the alignment of each unit; there was essentially only one correct way each module could fit. These bespoke connectors typically consist of heavy steel plates or boxed sections embedded at the tops/bottoms of modules. In this example (from a similar Ergodomus project), see (figure 32), we see grey steel plates bolted at the module corners to transfer forces between units. On Heimdalsporten, the connectors were engineered as custom cold-formed or welded steel parts (likely high-strength structural steel) that bolt into the cross-beams of each timber module. This was especially advantageous given the extreme cold during installation—workers could assemble modules quickly without fine adjustments, which helped maintain speed on site (Ergodomus, 2021).

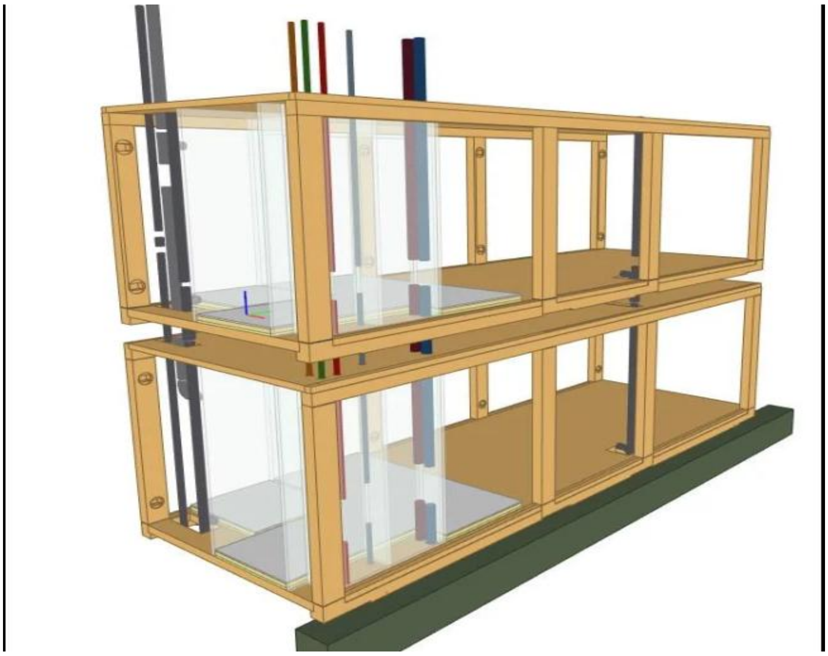


Figure 32. Tilor-made connectors (Ergodomus, 2025)

The connectors were also engineered to address the challenges of wood as a material. Timber elements can shrink or swell with moisture changes and compress under load, which could affect the building's geometry over time. To anticipate these effects, the designers created a detailed three-dimensional finite element model (FEM) of the structure (Ergodomus, 2021). The FEM analysis allowed the team to predict movements, deformations, and internal stresses as the timber modules respond to moisture and loads. Using this analysis, the connector design was refined to both securely tie modules together and permit slight movements of the wood without causing damage (Ergodomus, 2021). The connections transfer horizontal forces (e.g. wind or seismic loads) through the structure while accommodating the natural behaviour of the timber, preventing undue stress build-up. The development and testing of these connection systems—including trials on a full-scale 1:1 mock-up module in the factory—were crucial for the successful execution of the high-rise modular design (Figure 33), (Ergodomus, 2021).

Figure 33. HeimdalsPorten, adding wool insulation (Unibep, 2025)

9.2 Logistics and Assembly

Logistical planning was a major component of the HeimdalsPorten project's success. The modular units were manufactured in Poland by Unihouse, then transported by sea to Norway, which required careful coordination (Ergodomus, 2021). Approximately 110–120 modules were loaded onto a specialized cargo ship per shipment in a specific sequence dictated by the assembly order (Ergodomus, 2021). The first module loaded at the factory would be the last module needed on site, ensuring that when the ship was unloaded in Trondheim, the modules could be erected directly in the correct order. This just-in-time delivery sequence minimized on-site storage needs and enabled a continuous assembly flow once installation began (Ergodomus, 2021). Upon arrival in Norway, additional local regulations required that oversized module deliveries occur at night, which was accommodated in the planning (Figure 34), (Ergodomus, 2021).

On site, the assembly of the towers was remarkably fast. The first seven-story tower was initially scheduled to be assembled in about three weeks, but the construction team managed to complete it in only 10 days. The assembly crew developed an efficient rhythm, and buoyed by their success, they erected the second tower at an even faster pace—averaging 12 to 14 modules set per day. This rate was roughly 30% faster than the first tower's assembly speed, showcasing the learning curve and efficiency gains inherent in modular construction (Ergodomus, 2021). The ability to stack dozens of fully finished apartments in a matter of days is a clear advantage of the modular approach. It not only reduces the total construction schedule but also means that the buildings can be occupied sooner, allowing the developer to realize returns faster and residents to move in earlier than with conventional construction methods.

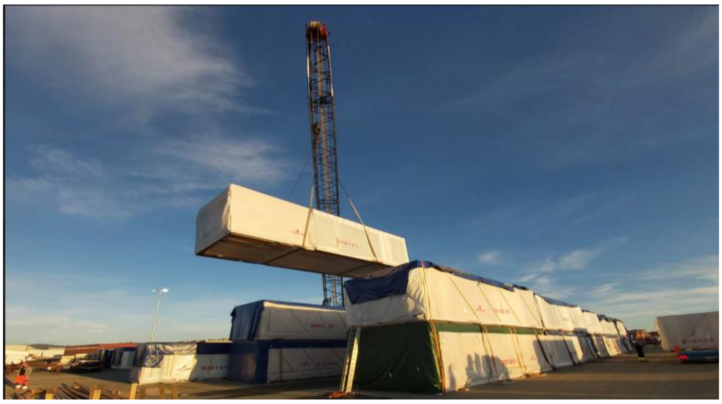


Figure 34. HeimdalsPorten, modular transportations (Ergodomus, 2025)

10. Environmental Considerations in Modular Construction

As the world continues to face environmental challenges like climate change and resource depletion, the construction industry is under pressure to adopt more sustainable practices. One area getting a lot of attention is modular construction using Cross-Laminated Timber (CLT). This method combines the efficiency of off-site construction with the environmental benefits of timber. In this section, I'll explore the key environmental aspects of CLT modular buildings: life cycle assessment (LCA)

10.1 Life Cycle Assessment of CLT

Life Cycle Assessment (LCA) is the method used to evaluate the environmental impact of materials and buildings throughout their entire life span—from the extraction of raw materials all the way to demolition or recycling. Studies have shown that CLT performs better environmentally than other construction materials like concrete or steel (Younis & Dodoo, 2022). Wood stores carbon throughout its lifespan, which helps reduce the amount of carbon dioxide in the atmosphere and contributes to reducing climate change. Studies show that using CLT in buildings can cut the carbon footprint by around 40% compared to concrete structures. CLT production requires less energy and emits fewer greenhouse gases than concrete and steel. Prefabricating components off-site improves quality control, reduces waste, and makes construction more efficient. CLT's recyclable nature allows for reuse and repurposing, extending its life and avoiding the environmental cost of making new materials (Younis & Dodoo, 2022). Some LCA studies use advanced models that consider how much carbon is stored in the timber over a long period—up to 100 or even 300 years—which shows even greater environmental benefits (Younis & Dodoo, 2022). However, there are still some challenges. For example, LCAs vary significantly depending on the country where they are conducted due to differences in data, assumptions, and end-of-life scenarios. Although EN 15978:2011 provides a standardized framework for assessing the environmental performance of buildings, including those using CLT, many existing studies apply varying methods, system boundaries, and assumptions. This inconsistency makes it difficult to compare results across different life-cycle assessments. (Younis & Dodoo, 2022).

10.2 LCA and Sustainability Factors of CLT Modular Houses

LCA analysis is the most effective way to assess contribution to climate change, as it focuses exclusively on greenhouse gas emissions. Modular houses made from CLT have a much smaller carbon footprint than those built with concrete or steel. A study in Indonesia found that most of the emissions from a CLT modular house came from the raw materials, with transportation accounting for only about 2.5 % of the total (Hatmoko et al., 2023). This resolves the common concern that modular construction increases emissions because of transporting materials. Modular CLT construction is a great solution that supports circular economic principles. This means the materials can be reused or recycled instead of being thrown away. If the building is ever taken down, the timber panels can potentially be repurposed. However, in today's construction industry, materials are usually demolished and thrown away rather than reused, because recycling or repurposing is often seen as expensive or difficult. Therefore, the industry needs to change its habits and adopt practices that make reuse and recycling of materials easier and more common. This would further reduce waste and save energy compared to producing new materials (Auclair et al., 2023; Ghaffar, Burman, & Braimah, 2020).

Modular construction with CLT is the key to reducing the time and energy needed on-site. The parts are made in a factory and then assembled quickly, so construction takes less time, in fact, one study definitively found that construction time could be reduced by up to 30 % compared to regular concrete buildings (Younis & Dodoo, 2022).

Using wood, the key to reducing emissions in the construction sector. The Production of cement and steel is responsible for a large percentage of global CO2 emissions — about 8 % and 7–9 %, respectively — while timber stores carbon instead of releasing it (Abed et al., 2022). CLT is the ideal material for sustainable building, especially in cities where demand for new housing is high. CLT is not perfect, it still faces challenges like sound insulation and fire resistance. In taller buildings, designers use hybrid systems combining CLT with concrete to meet safety and performance standards (Auclair et al., 2023). But as research continues, these issues are being addressed, and new innovations are making CLT more practical for a wider range of buildings.

11 Summary

The present study examined the structural performance and environmental aspects of prefabricated modular houses constructed using cross-laminated timber (CLT). The research concentrated on the understanding of CLT's performance as a construction material, with reference to its use in modular systems. Key elements studied included joint types, architectural flexibility, and sustainability performance.

The primary section of the thesis focused on the principles and evolution of modular construction. The findings indicated that modular methods have the capacity to reduce the time taken for construction, enhance quality, and minimise environmental impacts in comparison with traditional construction methods.

The material analysis indicated that CLT is a resilient and stable timber product that allows for large-format prefabrication. The benefits of CLT include a high strength-to-weight ratio, dimensional stability, good fire resistance when designed correctly, and thermal efficiency. Nevertheless, challenges persist, including sensitivity to moisture, acoustic performance, and connection detailing requirements that are subject to exacting standards.

The architectural review demonstrated that modular wooden buildings exhibit a high degree of adaptability in design, thereby enabling them to meet both functional and aesthetic goals. Modular layouts allow for the flexible use of space, while CLT contributes to the creation of natural and comfortable interiors.

A detailed study of the connection systems was performed. The findings demonstrate that both traditional timber joints and current metal fasteners can be used effectively, but each has its limits. Metal brackets and screws are widely used for their strength and ease of installation, while dowels and carpentry joints offer the benefit of being reversible and suitable for repeated use. The importance of reusability in the context of circular construction should be noted.

The Heimdalsporten case study provided practical insight into the application of CLT modular systems in real projects. The study demonstrated that, with adequate design and planning, these systems have the capacity to meet the demands of modern multi-unit housing projects.

Lastly, the environmental section shows that CLT modular buildings have a lower carbon footprint than conventional buildings, especially when timber is sourced responsibly. Life cycle assessment data supports the claim that CLT can reduce emissions and waste in construction.

The research questions:

- **How does CLT perform structurally in modular building?**

  CLT shows high strength, stiffness, and stability, making it suitable for structural walls, floors, and roofs. However, connection detailing is critical to maintain performance.

- **What type of joints are commonly used and how do they behave?**

  Common joints include metal brackets, screws, dowels, and mortise-and-tenon types. Metal joints provide strength and stiffness, while dowel and carpentry joints support reuse but require precision.

- **What are the architectural advantages of CLT of modular houses?**

  They offer flexible, customizable designs with efficient space use. The exposed wood provides a warm aesthetic and supports well-being.

- **What is the environmental impact of using CLT in modular buildings?**

  CLT has a lower environmental footprint than concrete or steel. It supports circularity through prefabrication, reduced waste, and potential for reuse.

In conclusion, prefabricated CLT modular systems offer a promising approach to sustainable construction. While technical challenges remain, especially with connections and acoustics, the benefits in terms of speed, design, and sustainability make this system a valuable choice for future building projects.

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