



Floor Design for Taller Timber Buildings

Joonas Jaaranen¹(✉), Sebastian Krug², Vlatka Rajcic³, Martina Sciomenta⁴,
and Chiara Bedon⁵

¹ Department of Civil Engineering, School of Engineering, Aalto University, Espoo, Finland
joonas.jaaranen@aalto.fi

² Institute for Timber Design, University of Applied Sciences Biberach, Biberach, Germany

³ Department of Structures, University of Zagreb, Zagreb, Croatia

⁴ Department of Civil, Architectural and Building and Environmental Engineering, University
of L'Aquila, L'Aquila, Italy

⁵ Department of Engineering and Architecture, University of Trieste, Trieste, Italy

Abstract. Floors have two fundamental structural functions in buildings: (i) transferring the vertical loads (that they are subjected to) to the vertical load bearing structures, and (ii) acting as diaphragms in the overall lateral load resisting system. In this Chapter the focus is on the former function, concentrating especially on their out-of-plane behaviour. To this aim, there are in fact various floor systems that can be used in taller timber buildings (TTBs). Among other aspects, the choice of the suitable floor system for a particular timber building depends widely on several influencing parameters, such as the span, the assigned loads, the requirements of the floor for the intended use, and the floor layout. The floors are subjected to various loads, and their design is very often governed by serviceability aspects, such as static deflections and dynamic responses (e.g., vibrations). A robust assessment of the serviceability performance requires the evaluation response of the floor system to the imposed loads, and the application of corresponding design criteria (in the region the building is situated in). In this section, aspects such as different floor systems, relevant loads, mechanical behaviour and serviceability criteria in different regions shall be discussed.

Keywords: Timber floor systems · Taller timber buildings (TTBs) · Hybrid floor systems · Serviceability performance · Vibration and deflection criteria

1 Floor Systems in TTBs

Floors usually consist of multiple components, such as the load-bearing structural systems and the non-load-bearing layers (e.g., flooring on top and ceiling underneath the floor structure). In the following, commonly encountered options for both are shortly presented as the basis for further discussion.

1.1 Load-Bearing Systems

The load-bearing system transfers vertical loads to the supporting structures and is mainly responsible for the structural performance of the floor. The structural systems can be

differentiated by (i) their materials into timber-only and hybrid systems and (ii) their geometrical arrangement into joist- and slab-based systems, as illustrated in Fig. 1.

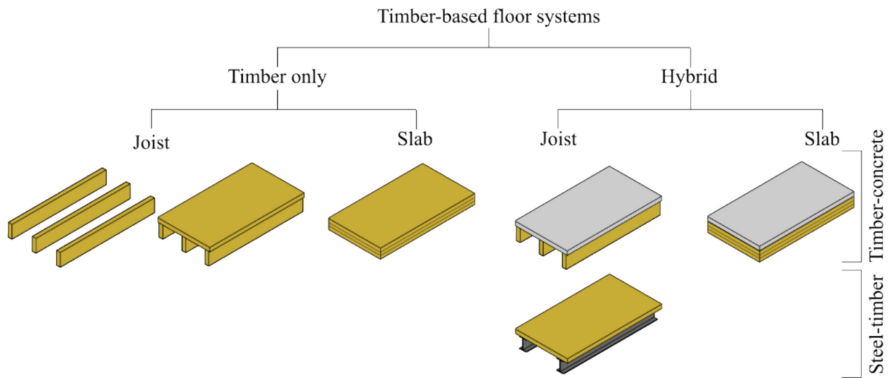


Fig. 1. Schematic illustrations of different timber-based floor systems categorized by materials and geometries.

The traditional structure is a joisted floor, in which the structure consists of parallel joists spanning from one support to another. These joists can be made of sawn timber, laminated veneer lumber (LVL), glued-laminated timber (GLT) or prefabricated I-joists. However, pure joisted floors are less common in TTBs, due to limited performances. Especially sawn timber joists are normally used for short spans only, around 3–5 m [1], due to the small available cross-sections.

Modern timber constructions often use wood-based composite elements that consist of timber joists (webs) connected to timber-based top and/or bottom plates (flanges). Typical examples are ribbed-panels (joists and top plate) and hollow-box systems (joists, top and bottom plates). The elements are usually prefabricated utilizing structural glueing between the basic components, although mechanical connections (such as inclined screws) can be also used, if they provide adequate composite action between the components. The main benefit of composite systems is that – due to the high structural efficiency – they allow to reach significantly longer spans, compared to conventional joisted floors with relatively low material volume. Further discussion can be found for example in [2, 3].

An alternative that has recently become very popular is the use of mass timber panels for the load-bearing structure. The most common panel type is the cross-laminated timber (CLT), which is made of an odd number of glued layers of timber boards, rotated 90° with respect to adjacent ones [4]. Due to their intrinsic structure, CLT panels exhibit also plate-like biaxial bending behaviour. Recently, there has been interest providing connections between CLT panels that can ensure effective biaxial behaviour for whole floors [5–7] and significantly improve their efficiency. Other suitable mass timber products are nail-laminated timber (NLT) elements, in which timber boards are laminated horizontally by nailing [8], and dowel-laminated timber (DLT), see for example [9]. The latter is an adhesive-free alternative to CLT laminated vertically using wooden dowels.

In hybrid systems, the structure combines timber with other materials to achieve the preferable mechanical behaviour. Among the most prevalent hybrid systems in timber buildings, are timber-concrete composite (TCC) floors. In the floor applications, TCC structures typically consist of timber components, a concrete slab placed on top, and the shear connection between them (Fig. 1). This configuration seeks to combine the advantages of timber and reinforced concrete construction. Depending on design requirements and construction methods, various types of shear connectors can be employed, such as notched connectors, screws, or metal plates. At the European level, the Technical Specification CEN/TS 19103:2022 [10] was published as a guideline for designing TCC floors. It is expected to be integrated into Eurocode 5 as EN 1995-3 by 2028. Currently, CEN/TS 19103:2022 regulates shear connectors, including (i) dowel-type fasteners, (ii) steel reinforcement bars embedded in timber perpendicular to the shear plane, and (iii) notched connections (see Fig. 2). However, alternative connection systems may also be employed, provided that their characteristic load-bearing capacity and stiffness are known. Given the increasing adoption of CLT-concrete composite floors in hybrid timber buildings, it is important to account for the influence of cross-layers in CLT panels on the stiffness of notched connections. The stiffness reduction caused by these cross-layers should be considered in the design process, as suggested in DIN CEN/TS 19103/NA:2024 [11]. These additional provisions are currently being discussed as part of the process of converting CEN/TS 19103:2022 into EN 1995-3 and are expected to be incorporated. Moreover, it should be noted that the design of TCC floors is often governed by serviceability requirements related to deformation. One strategy to enhance deformation serviceability is the design of continuous TCC floor systems [12]. Precast TCC systems represent an important advancement in the dissemination of TCC technology. These elements are often supplied with pre-determined structural capacities, simplifying the design process and fostering adoption. Several companies have demonstrated how the use of precast elements supports rapid construction, which is particularly valued in TTb where investors often prioritize short construction times [13]. In conclusion, TCC plays an important role in the transition from conventional concrete construction to more sustainable building methods and materials. By combining the strengths of timber and concrete, TCC systems contribute to reducing the environmental footprint of modern construction while meeting high performance standards.

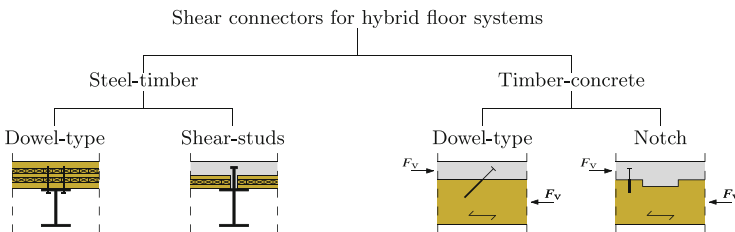


Fig. 2. Schematic illustrations of common shear connectors used in hybrid floor systems, including steel-timber and timber-concrete configurations.

The hybrid steel-timber systems allow for the combination of high strength and ductility of steel with high stiffness and light weight of timber. However, currently hybrid steel-timber structures are built usually with hot-rolled steel elements and timber diaphragms. In hybrid steel-timber systems, connection plays the key role in their seismic performance [14]. Well-known hybrid solutions are the steel-timber flooring and wall systems. The combination of steel, particularly cold-formed steel (CFS) members, and timber plate materials enable lightweight construction with structural, cost, and environmental benefits for low- and high-rise construction [15]. CFS sections can outperform most alternative construction materials due to their cost, strength-to weight ratio, and ease of erection. However, the sections are slender, thin-walled, and susceptible to different types of buckling, such as lateral torsional, local, distortional, crippling, and bearing failure [16]. These failures are mostly due to the thin plate elements of CFS section beams, which can be avoided or delayed by using timber plate acting as stiffeners [17] or by prestressing of the CFS members [18]. These structural elements are of low mass and beneficial in terms of earthquake resistance, while resistance to uplift loading due to high wind loads can be ensured by massive panels, and high-capacity connectors, which connect the panels to the vertical structural components at regular intervals. However, very limited information exists on the influence of timber plate and demountable shear connections on other forms of buckling in CFS floor systems using prestressed CFS sections [19, 20]. Hybrid CFS-timber structural designs are based on traditional standards and regulation [21]. As this construction adopts unconventional connections, thus, the safety factors and design tool specified in the traditional design standards, EN1993-1-1:2005 [22] and EN1995-1-1:2004 [23] may lead to uncertainty in the robustness of the design, building stability and structural performance under loading conditions. Therefore, more reliable design tools are required which can be developed through experimental testing and numerical analysis. Connecting the timber plates and even boards to the CFS beams can result with the systems with significant load bearing capacity. The performance of these systems is strongly related to the resistance, slip modulus and spacing of the shear connectors (see Fig. 2). Existing research has demonstrated significant improvements to the floor flexural performance if the composite action between CFS and timber boards is optimised and exploited [20]. Such composite action relies on the efficacy of connection (slip modulus and shear stiffness), to enable the two components to work together as a composite system, to resist flexural loads [17]. The flexural performance of the CFS-timber flooring systems in terms of stiffness and load-carrying capacity can be significantly improved by introducing prestressed CFS sections, novel shear connectors with timber embedment resistance and improved connector bending performance [24].

1.2 Non-Load-Bearing Layers

Non-load-bearing layers in floors of taller timber buildings fulfil essential functions such as acoustic and thermal insulation, fire protection, and moisture control. Raised floors are particularly relevant in TTBs, as these structures are often used as office buildings, allowing technical installations to be efficiently integrated beneath the floor. Additionally, the mass of screed or similar materials enhances the vibration behaviour of floor systems, improving comfort for occupants. In purely timber floors, mass-increasing

fill materials such as gravel or sand are frequently used to improve acoustic performance and dynamic behaviour. Other techniques to improve the impact sound insulation on timber floors were proposed in [25] that included the increase in mass or damping and the addition of a ceiling that could improve the sound insulation at low frequencies.

Concerning fire, the addition of gypsum board layers is widespread, in accordance with the encapsulation technique. When floors are constructed with open void spaces—such as those using engineered joists or counter battens beneath traditional solid joists—the risk of fire spreading through the floor void increases significantly. While the cavities of timber frame assemblies are completely filled with insulation materials in addition to the protective effect of cladding, the charring of a timber member is strongly dependent on the type of insulation used [26]. Any penetrations through the plasterboard, including downlighters, soil vent pipes, or ventilation duct heads, introduce vulnerabilities in the ceiling. These must be properly fire-stopped using fire collars, fire hoods, or other fire-rated products to maintain the integrity of the fire barrier.

A key aspect concerns the integration of Mechanical, Electrical, and Plumbing (MEP) services into mass timber high-rise buildings without compromising structural performance or aesthetics. The principal challenges related to the correct conception of MEP system concern the early design collaboration to minimize interferences (i.e. with sound-proofing material), the use of integrated vertical and horizontal MEP zones to keep systems organized and the use of non-combustible enclosures for some systems and/or intumescent coating.

2 Loads on Floors

In taller timber buildings, long-span floors are subject to various actions that can significantly affect their performance. According to EN 1991-1-1 [27], loads are classified as “permanent” and “imposed”. For floors, the first category of loads includes the combined self-weight of structural and non-structural elements acting permanently on the floors, while the second category includes variable actions (i.e., occupancy, furniture, partitions and machinery).

Both, the permanent and imposed loads can induce significant short- and long-term (creep) out-of-plane deformations on long-span floors. Those are also susceptible to “indirect actions” caused by fluctuations in environmental conditions (particularly changes in moisture and temperature), which can lead to differential vertical movements and affect the long-term performance. The fluctuations of moisture conditions have different sources as seasonal variations or indoor climate, which is influenced by human occupancy and their activities. Concerning the sources of thermal variations, this aspect is linked to the seasonal changes and sunlight exposure as to the type of ventilation, heating and cooling systems (i.e. underfloor heating) and the presence of adequate of the building’s envelope.

Further imposed loads (e.g. wind, earthquake, or machinery actions) generate horizontal global deformations that can lead to floor drift and vibrations, potentially impacting serviceability and occupant comfort. Together, these indirect actions highlight the importance of considering time-dependent behaviours in the design of long-span timber floors, to ensure durability and keep comfort and functionality over the building’s lifespan.

It is also worth mentioning the walking-induced loads, which cause floor vibrations. Vibration levels at floor surfaces could be perceptible by humans depending on motion frequency contents and the types of activities being performed by observers or other people occupying a floor [28]. If the vibrations exceed certain limits, it can lead to discomfort and dissatisfaction among the occupants.

3 Short- and Long-Term Response to the Loads

In terms of serviceability, the most significant load-induced deformation is vertical deflection, which can be quasi-static (and occurs slowly, without the involvement of inertial effects) or dynamic (which occurs fast and involves inertial effects). The latter is often experienced by the users as vibrations. Furthermore, quasi-static deflection consists of instantaneous (elastic) and delayed (creep) responses to the loads. The detailed mechanical response of a floor depends significantly on the type of load and on the structural system.

3.1 Timber-Only Floors Systems

The conventional timber floors are designed as one-way systems, i.e., the loads are transferred by uniaxial bending and shear along the strong axis (span direction). However, even the simple joisted floors possess some lateral stiffness, and they are more accurately described as rib-stiffened plates [29], displaying biaxial bending and lateral load distribution between the joists. The amount of load distribution depends on the ratio between the lateral and longitudinal bending stiffness of the floor structure. In conventional floor, where the lateral stiffness is provided only by the subfloor and other non-structural layers, the lateral stiffness is low, and the lateral load distribution is limited. In composite systems, where the flanges are built of biaxial timber panels, load distribution between the joists can be clearly higher. In slab type floors, especially when biaxial panels, such as CLT, are used, the transverse stiffness is significant, leading to stronger biaxial behaviour.

Hygrothermal variations, i.e., variations of moisture content and temperature, cause time-dependent dimensional changes in timber. Most significant serviceability-related effect for timber floors from these dimensional changes are the bending deformations. Whether the variations cause significant deflection or not depends on the type of the structural system and the gradient of the variations over the cross-section. If the variations are close to uniform, they alone do not cause significant deflection of the floors. In the case of significant asymmetric moisture gradient and/or differences in hygrothermal properties of individual layers in timber-based composite systems, however, differential strains can induce significant bending deformations.

In timber structures, creep causes additional, time-dependent deflection for floors. It is a phenomenon, where deformation increases after instantaneous (elastic) deformation under sustained loads. The rate of creep is highest close to initial elastic deformation and decreases with time. Timber creep can be divided into two parts, viscoelastic and mechano-sorptive creep. In the viscoelastic part the rate depends on time and in the mechano-sorptive part on the variation of moisture content in wood. Therefore, under

conditions where the moisture content of timber varies significantly, the creep rate can be significantly larger compared to constant moisture conditions. For a comprehensive review on timber creep, see [30].

3.2 Additional Effects on Hybrid Floor Systems

In hybrid systems, components with different creep and hygrothermal characteristics are joined together. As a result, these systems develop time-dependent deformations that are usually negligible in timber-only floors. In the case of TCC floors, timber and concrete are both subject to dimensional changes due to variations of temperature and moisture content. However, they respond to changes with different rates due to their different transport and expansion properties. Additionally, concrete shrinks significantly during and after curing. Due to these effects, differential inelastic strain develops between the components (even in a constant indoor environment due to the concrete shrinkage), which causes additional stresses and deformations in the structure [31]. Especially, the concrete shrinkage is relevant to all TCC floors as it causes permanent downward deflection. The inelastic strains from other sources change according to the varying environmental conditions and can cause upward or downward deflection depending on the situation. A proposal to account for the effects of the environmental variations and creep in TCCs in the context of Eurocodes are presented in CEN/TS 19103:2022 [10].

4 Analysis Approaches for Deflections and Vibrations

Analytical methods can be used to estimate load-induced deformations and vibrations in timber floors. In practice, their use is limited to rectangular floor layouts with uniform structure over the floor area. For one-way floors subjected to uniform loads, deflections can be obtained using Euler-Bernoulli beam theory with effective width and bending stiffness. In CLT floors, low rolling shear stiffness of the transverse layers causes significant shear deformation in bending. Their effects can be accounted for in analytical calculation by utilizing γ -method, shear analogy method or Timoshenko beam theory [4].

However, as mentioned, even floors designed as one-way system, have lateral stiffness to some extent. To avoid significant over-design, responses to point loads or dynamic responses are usually estimated based on plate theory using equivalent bending and twisting stiffnesses. Especially the dynamic response can be sensitive to the support conditions, their arrangements and stiffnesses, and should be accounted for. Simplified methods to account for the support flexibility are proposed, for example, in the revised version of EN 1995-1-1 [32] that will be published in the near future. The intrinsic limitations of simplified methods for the vibration serviceability assessment have been discussed in many research contributions. In [33], for example, the effects of rough modelling assumptions both in terms of floor components and connections, and in terms of human-induced loads have been properly emphasized, pointing out the importance of a robust methodology of general applicability to timber floors.

The long-term deformations due to creep are normally calculated by utilizing the effective modulus method, where the modulus of elasticity (and possible other stiffness

properties) is decreased based on the relevant creep factors, such as in standard EN 1995-1-1 [23]. In composite systems, the differential inelastic strains between the components can cause significant deflection. Their effects, with addition of creep, can be accounted for in the analytical calculations for TCCs according to methods presented in CEN/TS 19103:2022 [10].

Specialized experimental, numerical (static deflections and dynamic vibration analyses) and analytical methods are adopted to carry out deflection and vibration analysis of long-span timber floors for taller buildings. The main aim is to check their compliance with the performance requirements [34] in terms of: (i) ultimate limit state or strength capacity, undergoing the gravity and lateral loads, and (ii) serviceability limit state, controlling the deflection and vibration. Numerical simulations on floors are carried out by using both design-oriented software and general-purpose programs.

Design-oriented software packages are commonly used by practitioners for conventional structural analysis of timber floors due to (i) their compliance with design standards such as EN 1995-1-1 [23] and other regional codes, (ii) the ability to define the floor system accurately, either as a beam-slab configuration (e.g., joisted floors) or as a panel system (e.g., cross-laminated timber), and (iii) the capability to perform both static and dynamic analyses, also considering nonlinear and fire-related effects. For more advanced applications, such as seismic, blast, or fire scenarios, general-purpose finite element programs are typically preferred, as they provide a wide range of material models, element types, and solver options (e.g., implicit or explicit solvers). To promote consistency in modelling strategies, several initiatives have been launched, including the Modelling Guide for Timber Structures [35] and a working group WG11 under CEN/TC 250/SC 5, which is currently preparing dedicated finite element modelling guidelines as part of the next generation of Eurocode 5.

Great attention is paid to hybrid systems which are widely used and investigated. For numerical investigations, finite element models are generally calibrated against experimental results and are utilized for parametric studies for flooring systems. One of the key points is represented by the connections' stiffness since it strongly influences the coupling degree among slab and beams and so the overall stiffness of the composite system [36]. propose a calculation procedure to achieve the accurate values of maximum force and stiffness of a given timber-to-timber slab joined with Self-Tapping Screws (STSS) and loading condition. The procedure accounts for the effective shear force and stiffness of screws in a given position on the slab and provides it in a simplified way for STSS stiffness and force formulations (correlation coefficients).

5 Design Criteria for Controlling Deflection and Vibrations According to Different Design Standards

The design of floors in TTBs must account for various serviceability criteria, with particular focus on controlling deflections and vibrations. While international standards vary in detail, the fundamental principles are largely consistent. Most standards prescribe deflection limits as a function of the span length and loading conditions and include criteria for vibration performance, often based on natural frequency, point load deflection, and dynamic response (e.g. acceleration or velocity). The commonly applied standards are briefly presented below, and for further insights, please see [37], among others.

The European standard EN 1995-1-1 [23] defines deformation limits for timber floors based on the type of floor and boundary conditions. These limits address both live loads and combined dead plus live loads, ensuring that vertical deflections remain within acceptable ranges to maintain structural performance and user comfort. The new draft version of EN 1995-1-1 [32] introduces three specific criteria for vibration control: (i) minimum fundamental natural frequency, (ii) maximum deflection under a point load, and (iii) acceleration and velocity limits. These align with the existing approach by [38] but expand upon it through the introduction of floor performance levels. These levels explicitly define vibration limit values, allowing floor systems to be designed more precisely to meet user requirements. For further details on the proposed performance levels and vibration criteria, see [39].

Swiss standards for timber structures, as outlined in SIA 265:2012 [40], reference serviceability limits defined in SIA 260:2013 [41], addressing static deflection under concentrated loads as well as velocity response and acceleration criteria. In the United States, the ANSI/AWC NDS [42] and International Building Code (IBC) [43] specify deflection limits for floor systems based on live and combined loads, but do not explicitly regulate vibration performance, leaving this aspect to other guidelines or project-specific considerations. Similarly, the Canadian standard CSA O86:19 [44] includes deflection criteria for live and total loads while also incorporating vibration assessments based on natural frequency and static deflection under point loads, with further guidance provided in the Canadian CLT Handbook [45] for optimising CLT floor performance. Australian standards, such as AS 1720.1-2010 [46] and AS 1170.1-2002 [47], define deflection limits depending on floor usage but do not explicitly address vibration control in timber floors. In contrast, the Chinese standard GB 50005:2017 [48] specifies deflection limits for various floor types and loading conditions, while the “Technical Standards for Vibration Comfort of Building Floors” JGJ/T 441-2019 [49] provide additional criteria for vibration performance, including minimum frequency requirements.

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