Design of taller timber buildings against deformations and vibrations: a state-of-the-art review

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Holistic design of taller timber buildings - HELEN

Working Group (WG) 2

Deformations and Vibrations

State-of-the-art (STAR) report

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Forward

This report is a publication of the European Network **COST Action CA20139** “Holistic design of taller timber buildings – **HELEN**”, established with the aim to “work towards optimized holistic approaches to improve the performance of taller timber buildings and to widen their competitiveness and use across the EU and rest of the world” (https://cahelen.eu/).

The activities conducted in the first year of the Action by the **Working Group (WG) 2** – Deformations and Vibrations - are summarized in this document in the form of a state-of-the-art report (**STAR**) regarding design, analysis and construction methods of taller timber buildings and their components against **deformations** and **vibrations**.

The report is the result of a deep review of scientific literature, international projects, national regulations, design guidelines, as well as case studies.

The information collected in this STAR document represent the starting point of discussion to identify solutions, research targets, methods and resources for the future of taller timber buildings and their design against deformations and vibrations, where a key role is given to experimental methods, performance indicators and research efforts.

Two different sub-groups (SGs) have been defined for WG2 STAR activities, namely **SG1 – Deformations** and **SG2 - Vibrations**. For each SG, different subtopics have been detected among WG2 members, to have extended discussion, and are summarized in present document.

As such, the present report is divided into two major sections and summarizes some major outcomes of STAR. More precisely:

- the first part includes the overview review conducted by SG1 on the “Deformations” issue;
- the review regarding the SG2 “Vibrations” issue is summarized in the second part;
- finally, it is important to note that for both SG1 and SG2 parts of this STAR report, relevant input and discussion on relevant topics and open gaps is provided by active WG2 contributors and affiliated research units

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WG2.SG1 – Deformations

Connection types for taller timber buildings

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1. Introduction

In tall buildings, connection deformation can potentially cause serviceability failures through deflection of the structure (Skidmore Owings & Merrill, 2014; Smith, 2011), and in slender structures could also lead to ultimate limit state failure through second-order P-delta effects (Teweldebrhan & Tesfamariam, 2022). Connection deformation also affects both serviceability and ultimate-limit state behaviour of mechanically-jointed composite beams and slabs, including timber-concrete composites (Yu et al., 2009) and dowel-laminated timber (El-Houjeyri et al. 2019). The stiffness of connections is also a key parameter in modelling for vibration and acoustic serviceability (Edskär & Lidelöw, 2019; Tulebekova et al., 2022), to ensure, for example, occupant comfort or usability of sensitive instruments. Seismic design also requires modelling of connection stiffness and ductility. An overview of most recent studies and issues is summarized in the following paragraphs.

Figure 1: Connections for the Mjøstårnet building, with large groups of steel dowels passing through multiple slotted-in steel plates. Reproduced from (Abrahamsen, 2018).

2. Connection types

2.1. Dowel-type connections

Dowel-type connections include nails, screws, bolts and dowels, and are the most common way to create connections between timber elements on a construction site. Many different types of connections rely on dowel action, where a (usually steel) connector acts across a shear plane to hold two parts together. Examples include slotted-in steel plates with bolts or dowels passing through the timber and the plate (Abrahamsen, 2018: Dorn et al., 2013; Reynolds et al. 2022), timber-to-timber connections where the connector passes through over- lapping timber elements and steel hold-downs or angle-brackets which are secured to the timber with nails or screws (Ringhofer et al. 2018). Dowel-type connectors are also used to connect pieces of solid wood to create larger building elements, such as in nail-laminated (Hasan et al., 2019) or dowel-laminated timber [8, 49]. Their force-displacement response of dowel-type connections is highly nonlinear, because of gap opening and construction tolerances (Reynolds et al., 2022), nonlinear, irreversible material behaviour, even at low loads (Bader et al., 2016; Dorn et al., 2013).

2.2. Connections resistant to withdrawal

Nails, screws and bolts can also be used in connections which apply force along their axis. In this mode of loading they transfer load into the timber by resisting withdrawal. Part of the behaviour of hold-downs or angle brackets relies on this mode of loading. Long screws used for reinforcement, particularly against perpendicular-to-grain splitting, are loaded in axially, relying on withdrawal resistance (Dietsch & Brandner, 2015; Jockwer et al., 2016; Trautz & Koj, 2009). Screws are generally stiffer when loaded axially than they are in shear (also known as dowel action).

2.3 Connections in timber-concrete composites for flexure

Timber-concrete composites require a shear connection between the concrete and timber to ensure composite action. Connection stiffness is crucial here, and thus while connectors such as nails and screws have been used, they are commonly inclined to take advantage of their increased stiffness in withdrawal (Yeoh et al., 2011). Various numerical investigations are available in literature for the accurate mechanical characterization, especially concerning the testing setup issues (Bedon & Fragiacomo, 2019; Bedon et al., 2021) The steel connectors can also be removed by casting the concrete into grooves to provide interlock between the layers, or by using an adhesive connection between layers (Frohnmüller et al., 2021), which can achieve an almost fully composite section. Combinations of screws and adhesive have also been used to increase the ductility after initial failure of the adhesive (Braun, 2020).

2.4 Acoustic barriers

Acoustics is often an important design driver for lightweight construction systems such as timber (Olsson & Bolmsvik, 2008). Transmission between a “source room” and a “receiving room” can be airborne or structure borne. Acoustic separation is often achieved using a connecting layer much softer than the timber of structural elements above and below the insert. To prevent acoustic bridges via connections, soundproofed steel angle brackets have recently been developed, in which the rigid parts are elastically separated from one another using interlayers. Elastomers are frequently used at junctions so as to reduce low frequency noise. Common types include closed cellular polyurethane and mixed cellular polyurethane. The influence of flexible sound insulation layers on the deformation of timber systems has been studied (Azinović et al., 2021; Kržan & Azinović, 2021), showing a small influence on strength, but a large influence on deformation, and suggesting methods to mitigate this effect (De Santis & Fragiacomo, 2021).

2.5 Adhesive connections

Adhesive connections are vital for creation of laminated timber elements, but are also used in structural joints between elements (Angelidi & Thomas Keller, 2018; Angelidi et al., 2018; Vallée et al., 2017). Adhesive connections are generally considered to be rigid for practical engineering design purposes, but flexible adhesive joints have been proposed for structural joints in seismic regions (Azinović et al., 2021; Śliwa-Wieczorek et al., 2020a; 2020b; 2021), and to increase the capacity of laminated timber (Szeptyński, 2020). Flexible connections between elements in bending affect the level of composite action which can be achieved, and a variety of methods are used in research to assess the bending strength and stiffness of the resulting system, including experimental, analytical (e.g. the gamma method) and numerical (finite element analysis), see (Jelušič & Kravanja, 2018). Experimental and CZM-based numerical analyses accounting for moisture and adhesive types are reported in (Barbalić et al., 2021; Bedon et al., 2022).

Design methods and experimental approaches for connections in taller timber buildings

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1. Design methods and limits

EN 1995-1-1 (Eurocode 5) uses empirical equations to assign an elastic stiffness to joints (referred to as the "slip modulus" K_{ser}). The derivation of these equations is described by Ehlbeck & Larsen (1993). Through the equations, a stiffness is assigned per shear plane per connector, based only on dowel diameter and density, and then multiplied by the number of shear planes and the number of connectors. Modifications are then applied for service class and duration of loading.

1.1. Theoretical descriptions and modelling

The force-deformation behaviour of connections is non-linear in various ways, as described in (Dorn et al., 2013) and shown in Fig. 1. Behaviour under initial loading follows a different path to unloading and reloading, which means that the deformation is dependent on loading history as well as the applied load at a particular time.

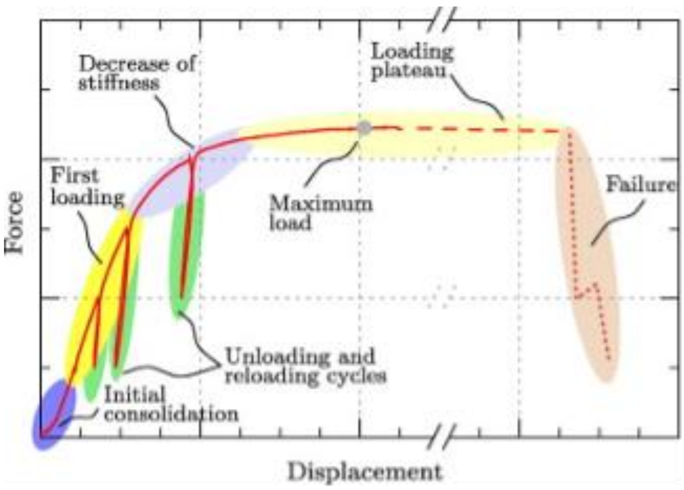

Figure 1: Generalised force-displacement response of a dowel-type connection with a slotted-in steel plate. Reproduced from (Dorn et al., 2013) with permission from Elsevier®, license agreement 5420820441315, November 2022.

Experiments on dowel-type connections (Sandhaas et al., 2017) show that dowel stiffness is not generally well predicted by the EN 1995-1-1 equation for K_{ser}, especially when the connection contains multiple dowels or dowels of unusual dimensions. In multi-storey timber buildings, other effects on deformation may assume in- creasing importance due to the scale of the structure. In timber both creep and moisture-induced strains are significant and their effect has been measured in a multi-storey timber building (Yu et al., 2009). It should be noted that the building considered in that study was designed to mitigate the creep and moisture-induced strains by avoiding loading timber perpendicular to grain in floors, thus the effect might be expected to be larger in buildings with platform construction. In platform-frame cross-laminated timber buildings, the friction between the panels creates relatively rigid connections in the serviceability limit state, and the dynamic stiffness has been shown to be well predicted based on panel deformation (Reynolds et al., 2015).

1.2. Diaphragm behaviour of floors

Whenever timber is used in the floors of multi-storey buildings, its capacity to act as a diaphragm, transferring load to the lateral load resisting system is important (D'Arenzo et al., 2019; Moroder et al., 2015; Moroder, 2016; Moroder et al., 2016). Since timber floor plates, even in CLT, are rarely made from one continuous element, deformation in connections is a key driver of the overall diaphragm action in the floor (D'Arenzo et al., 2019). Timber diaphragms tend to be more flexible than their concrete counterparts, with increasing floor spans further reducing stiffness.

2. Experimental methods

The EN 1995-1-1 (Eurocode 5) cites the experimental method in EN 26891 for experimental determination of the stiffness of joints. These standards describe the stiffness of joints as the "slip modulus", and it is assigned an elastic stiffness based on the secant stiffness of the joint under first loading between 10% and 40% of its estimated failure load.

2.1. Group effects in multi-dowel connections

The strength of a dowel-type connection does not increase linearly with the number of connectors. This has been well studied (e.g. (Blaß, 1990; Hossain et al., 2019; Nozynski, 1980)), however the same appears to be true of the stiffness of connections, and tests have been carried out with varying numbers of fasteners to quantify this effect (Jockwer & Jorissen, 2018a; Reynolds et al., 2022).

2.2. Long-term performance

Wood exhibits time-dependent deformation (de Borst et al., 2013; Holzer et al., 1989; Ozyhar et al., 2013; Ranta-Maunus, 1990). Given the interaction between timber and connector in a connection, that time-dependent deformation is also exhibited by connections (Reynolds et al., 2013).

2.3. Composite action in beams with connection deformation

The use of ductile adhesives may allow designing ductile joints, which can compensate for the material ductility that timber lacks. The effect of the different adhesives on the joint capacity and ductility has been studied and quantified. Strain field measurements using the Digital Image Correlation (DIC) technique and a quadratic strain interaction criterion provided a better understanding of the mechanical behaviour of the two different joint types (Angelidi & Keller, 2018; Angelidi et al., 2018).

2.4. Monitoring structural integrity

Monitoring the condition of timber structures naturally requires assessing the condition of connections, and stiffness and deformation behaviour is a good candidate for non-destructive assessment of connections (Serdjuks et al., 2022).

Beam-on-foundation (BoF) modelling for stiffness prediction of laterally loaded dowel-type connections in taller timber buildings

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1. Introduction and background

In taller timber buildings, serviceability limit state verifications, like the deformation verification are the predominant design cases. However, corresponding design concepts in the current design codes, like e.g. in Eurocode 5 (EN1995-1-1), are based on simplified empirical equations, developed for deformation insensitive timber structures, and thus, are not suitable for a reliable design of taller timber buildings. Due to the large number of connections, substantially contributing to the global structural stiffness of taller timber buildings, a suitable and reliable prediction of the connection stiffness is essential. The design model for the prediction of the stiffness of connections needs to include effects of multiple shear planes, a large number of fasteners in a row, as well as the effect of fabrication tolerances. Validation of the beam-on-foundation (BoF) approach (see e.g. Hirai, 1983; Bader et al., 2016), a computationally efficient numerical model for the behaviour of laterally loaded connections, has shown that the method is perfectly suited to study these large number of influence factors on the connection stiffness, without the need for cumbersome and expensive experimental testing programs. In this contribution, we like to present this engineering modelling approach based on the finite-element method, and its application to predict the stiffness of laterally loaded dowel-type fasteners in multiple-fastener connections. For this purpose, the BoF-model for the prediction of the non-linear load-displacement behaviour of the single fastener is combined with 2D plate elements, which allow to consider the wood member elasticity or steel plate elasticity in between the fasteners. This allows for example for evaluation of group effects on the joint stiffness, serving as basis for proposal of engineering design rules.

2. Beam-on-foundation model (BoF)

BoF-models are used for the prediction of properties of mechanical connections since the early thirties of the last century (Hager, 1930; Kuenzi, 1955; Norèn, 1968; Wilkinson, 1971; Hirai, 1983). However, these approaches have remained unused in practical design due to their complex implementation and their high running time, at the time of their invention, while today computational resources allow for fast and efficient numerical methods-based design. Models of different complexity were used from simplified (i) rigid-ideal plastic models, which allow only for strength prediction (cf. Johansen (1949)); to (ii) bi-linear elastic approaches, being able to predict stiffness and strength (Sawata & Yasumura, 2003; Cachim & Franssen, 2009), and (iii) nonlinear elastic models, which are optimized for numerical simulations (e.g. Lemaître et al., 2018). BOF-models might be even used for earthquake design by application of plastic, or even hysteresis models (Izzi et al., 2018; Girhammar et al., 2017). In recent years, the validity of the BoF approach for efficient prediction of the connection stiffness and even capacity was proven by several contributions, like (Bader et al., 2016; Schweigler et al., 2016; Lemaître et al., 2018a ; 2018b ; 2019 ; 2020 ; De Santis et al., 2021; Schweigler et al., 2021).

3. Embedment stiffness definition and prediction

To support the design with reliable input data related to the load-deformation behaviour of steel dowels embedded in wood or wood-based products, Schweigler et al. (2019) provided a large database of embedment parameters for different wood species and wood products. For a common basis, a procedure to measure and define embedment stiffness and strength parameters was proposed, and subsequently applied for compilation of an embedment database. It was even aimed to provide correlation equations of embedment parameters with characteristic wood properties, like e.g. the elastic embedment stiffness, $k_{f,el}$, with the wood density, ρ. The analysis of this database showed no distinct correlation between the dowel diameter and the elastic embedment stiffness. However, in previous scientific works, other type of prediction equations to predict embedment stiffness were proposed with other parameters such as the wood elasticity modulus, E_0, and the dowel diameter, d (see Table 1).

Table 1 – Design equations for embedment stiffness (in N/mm²/mm).

	Harada (1951)	Wilkinson (1971)	Nakatani and Sawada (1980)	Hirai and Sawada (1982)	Bléron (2000)	Schweigler et al. (2019)
$k_{f,el}^{first\ loading}$	$\frac{E_0}{140}$	–	$\frac{E_0}{17.8 \cdot d + 16.1}$	$\frac{E_0}{10.9 \cdot d + 31.6}$	$\frac{k_{f,el}^{reloading}}{A^*}$	$0.1374 \cdot \rho - 12.29$
$k_{f,el}^{reloading}$	–	$0.87 \cdot \rho$	$\frac{E_0}{5.67 \cdot d + 11.4}$	Unknown	$\frac{1.9 \cdot \rho_k}{d^{0.98} - \frac{1.9 \cdot \rho_k}{245}}$	–
ρ (kg/m³)	Unknown	$\{380 - 710\}$	$\{420 - 770\}$	440 (CoV 4.8 %)	$\{375 - 412\}$	$\{380 - 850\}$
d (mm)	$\{5 - 23\}$	$\{2 - 6\}$	$\{2 - 10\}$	$\{8; 10; 12\}$	$\begin{Bmatrix}12; 14; 16; \\ 18; 20\end{Bmatrix}$	$\{12; 16; 20; 24\}$
Nb. of tests	Unknown	≈ 15	≈ 40	≈ 50	100	1565
Testing Method	Unknown	Joint and compression	Half-hole	Joint	Full-hole	Full-hole

$A^* = 30.502 - 5.0545 \cdot d + 0.2866 \cdot d^2 - 0.0052 \cdot d^3$

4. Connection stiffness prediction

Mathematical functions, like e.g. the approach from Foschi (1974), allow to define load-displacement curves based on the embedment parameters from the embedment database, which then serve as input to the BOF-model for prediction of the connection stiffness and capacity. A summary of such methods is given in Schweigler et al. (2018). A review of prediction equations for connection stiffness can be found in Loferski (1980) and Jockwer & Jorissen (2018b). In Table 2, the main results are summarized.

Table 2 – Design equations for timber-to-timber connection stiffness (one fastener and one shear plane in N/mm).

Equation	Reference	Method	Fastener type
$0.043 \cdot \rho_m^{1.5} d$	EN 1995-1-1	Test	Bolts, dowels, screws, pre-drilled nails
$3.000 \cdot \rho_k^{0.5} d^{1.70}$	SIA 265	Unknown	Bolts, dowels, screws, pre-drilled nails
$1/(2(L_1 + L_2) - (J_1 - J_2)^2/(K_1 + K_2))^*$	Kuenzi (1955)	Theory	All types
$3.562 \cdot k_{f,el}^{0.75} d^{1.75}$	Wilkinson (1971)	Test + theory	All types
$3.562 \cdot k_{f,el}^{0.75} d^{1.75} \cdot \tanh(\mu \cdot t_1)^{**}$	Sawada (1976)	Test + theory	All types
$29.0 \cdot d^{2.24}$	Jockwer & Jorissen (2018)	Test	Bolts, dowels

* with L_1, L_2, J_1, J_2, K_1, and K_2 defined from hyperbolic functions, see (Kuenzi, 1955)

** with $\mu = \sqrt[4]{k_{f,el} \cdot d/(4E_s I_s)}$ and t_1 the thickness of outer timber members

Most prediction equations are limited to single-dowel connections. Nevertheless, some effort was done to predict design equations for the stiffness of a group of fasteners in timber-to-timber connections by applying nonlinear regression analysis based on numerical simulations (Lemaître et al., 2019), and based on experimental results (Jockwer & Jorissen, 2018). Modeling strategies for groups of fasteners are summarized in Bader et al. (2017). The BoF-model has proven to be more suitable than utilizing experimental results since more parameters can be integrated, such as the drilling tolerance, thickness of connection members, multi-materials, number of fasteners in a row, number of rows of fasteners, or multiple shear planes connections. Another application of the BoF-model could be the stiffness prediction for ultimate limit state design, since the BoF-model is able to predict the nonlinear load-slip curve of a laterally loaded connection. Today, this value is given as a rough estimate by 2/3 of the connection stiffness in the serviceability limit state (EN1995-1-1).

Impact of the non-linear load-deformation behaviour of joints on the performance of timber structures

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1. Background

The design of joint is critical for the design of timber structures. In fact, the load-carrying capacity and the mechanisms of collapse of structures strongly depend on the structural configuration and the load-deformation behaviour of joints. The precise understanding and exact characterization of the mechanical behaviour of joints is therefore of great importance in order to be able to build high performance timber structures. Currently, in design standard EN 1995-1-1 (Eurocode 5), rigid-ideally plastic limit design approach for the calculation of connection strength and empirical formula of elastic stiffness that depends on few parameters of influence are used (EN 26891). Moreover, uncertainties related to stiffness and ductility are not considered. In research, large numbers of experiments on the connections have been performed by researchers, in the attempt to determine the capacity of connections and impact of the various geometrical and material parameters. However, many questions remain open, in particular about the stiffness and ductility of connection, since studies often focus on the load-carrying capacity. Stiffness and ductility are fundamental characteristic to be defined, since affect the distribution of forces in the elastic phase and failure mode of structure.

2. Impact of connection non-linearity on reliability

A parametric and sensitivity study on a simple statically indeterminate structure has been performed in (Caprio et al., 2022). The mechanical behaviour of joints has been simplified as elastic-perfectly plastic behaviour. The uncertainties related to bending capacity, stiffness and ductility of joints have been considered. Based on this study, the conclusions are the following:

- Stiffness and ductility have a strong impact on reliability against collapse of the structure
- The simple deterministic considerations on stiffness and ductility might not always be adequate for the evaluation of the reliability of the entire structural system
- For complex or statically indeterminate timber structures, the classical element-by-element verification might not be appropriate and reliability-based analysis should be preferred.

Therefore, the realistic description of mechanical behaviour of joints and the understanding of related uncertainties cannot be ignored.

3. Characterisation of connection non-linearity

The nonlinear load-deformation behaviour of the connection is a consequence of the nonlinear single fastener slip behaviour (Schweigler et al., 2018). Analytical parametric equations can be used to represents the nonlinearities.

Analytical equations for the description of slip behaviour of joints have been proposed by previous researchers. The equations are based on exponential, power functions, a combination of the two or polynomials. Detailed summary of different models for the analytical description of the load-deformation behaviour of joints is given in (Schweigler et al., 2018) and (Flatscher, 2017). The joint load does not only depend on slip, but also on other parameters, such as fasteners-to-grain angle, dowel diameter, wood species, density etc. For example, the behaviour of single self-tapping screw is a lot sensitive to screw to grain angle, as illustrated in Fig. 1.

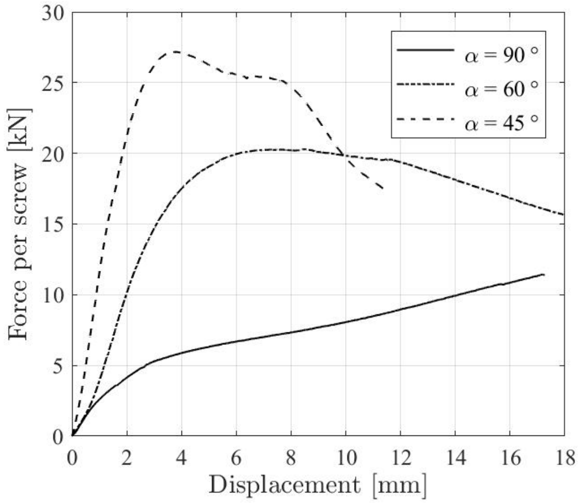

Figure 1: Examples of the different load-deformation behaviour of screw connections with different angles α between screw axis and load application described in (Jockwer et al., 2014).

Following the same multi-step approach illustrated in (Schweigler et al., 2018), first analytical equations (polynomials or exponential or other) are fitted to experimental determined slip curve for different value of the selected parameter of influence (for example screw to grain angle), then in a second step regression analysis is applied to each coefficient of the analytical equation to connect it to the parameter of influence. These two regression steps can be combined in a third step. This step can be repeated for other parameters (Schweigler et al., 2018). The starting point is data-set of experiments on timber joints that can be used for this multi-step approach.

4. Conclusions and ongoing work

The main conclusions are:

- Realistic representation of nonlinear behaviour of joints and related uncertainties are important for the analysis of reliability of structures
- Realistic representation of joints and related uncertainties might serve as input for numerical models that uses spring elements to model the behaviour of joints.

Currently, a review about the most important mechanical, geometrical and load related parameters that affect the behaviour of dowel-type joints, joints with glued-in rods and joints with self-tapping screw is being carried out. The ability of different analytical models to approximate the non-linear slip behaviour of common timber joints is being discussed. Coefficients of analytical model can be determined using non-linear least square regression or they can be determined manually from the experimental curve. The two approaches will be compared. In the next step experimental data will be used to link the selected mathematical model to the most influential parameters (density, fastener to load angle, diameter etc).

Stiffness of dowel-type connections

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1. Stiffness of connections in context of Eurocode 5

In Eurocode 5 stiffness of timber dowel-type connections is defined via a slip modulus (N/mm) for a single dowel and per shear plane. The stiffness of a connection is thereby found by multiplying by the number of fasteners, and the number of shear planes. This leads to a single, linear value for the connection stiffness. Two factors are taken into account by the formulas set forth in EN 1995-1-1 (Eurocode 5): dowel diameter and mean density of timber. Depending on the type of fastener, the diameter and density are raised to a certain power. For predrilled bolts, nails, screws:

$$K_{ser} = {\rho_m}^{1,5} \frac{d}{23} \tag{1}$$

The connection stiffness is an important value in timber engineering. As the translational and rotational stiffness of the connection is determined by the stiffness of the single dowel, the force distribution in a construction can be heavily influenced by the single dowel stiffness. In shear walls, the interaction between panel and timber, has an important influence on the load/deformation behaviour of the wall. When designing higher timber buildings, the influence of connection stiffness plays an important part in the behaviour of the whole structure. When designing for robustness, ductility of connections is a very important design parameter.

2. Problem with the current description of connection stiffness

It is clear that the dowel-type connection deformation behaviour is not linear. K_{ser}, and K_u, do not allow for any design taking into account the real non-linear behaviour of connections. A first issue therefore is the implication that designing for robustness through ductility is hindered by the limitations of the current slip modulus. Secondly, the load distribution between fasteners within a connection, specifically in the case where rotational and translational forces are combined, is heavily influenced by the non-linear behaviour of the single dowel. It is furthermore not possible to take realistically into account the influence of connection stiffness on the force distribution within a structure. Lastly, the current formulas do not allow for evaluation of modern building techniques using interlayers (e.g., acoustic separating layers).

3. Current state of the art

The field of connection stiffness is still a developing one. For optimal use in construction design, not only more information on the non-linear behaviour is needed. As the influence of connection stiffness can be both positive and negative, it is appropriate to possess information on both upper and lower limits for the stiffness, in addition to mean values.

3.1. Parameters

Different parameters can be identified to play a role:

- As already defined in Eurocode 5:
    - Dowel diameter
    - Timber density
- Other parameters not taken into account:
    - Thickness of timber members (linked to failure mode)
    - Direction of loading versus the grain of the timber
    - Axial effects: rope effect
    - Steel quality
    - …

3.2. Measurement examples

Following examples are a result of the research project WOODLINK: on stiffness of connections, executed by WOOD.BE, and supported by the Belgian government. These results are not yet published. The first graph is an illustration of the real load-deformation behaviour of a single nail connection between two LVL blocks. It is clear that K_{ser} as defined by Eurocode 5 does not describe this behaviour adequately.

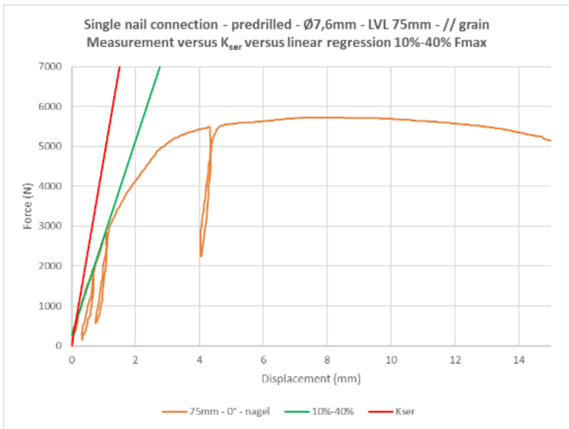


Figure 1. Test result single nail loaded in shear.

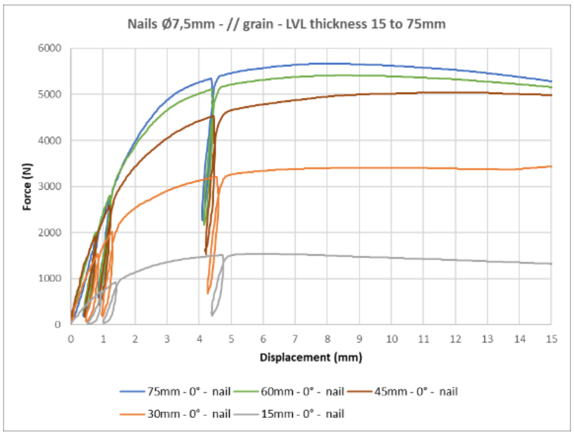


Figure 2. Timber thickness versus load-deformation behaviour.

The next graph illustrates the influence of the thickness of the timber members. The LVL members were varied between 15 and 75mm, in steps of 15mm. As the failure mode passes from timber failure (mode c) to dowel failure (mode f), a limit is reached in terms of strength, as well as stiffness. The final picture gives an overview of the test results versus K_{ser} as defined by. The shown values for the stiffness are defined as a linear regression of the load-deformation curve, between 10% and 40% of the maximum force up to 15mm displacement.

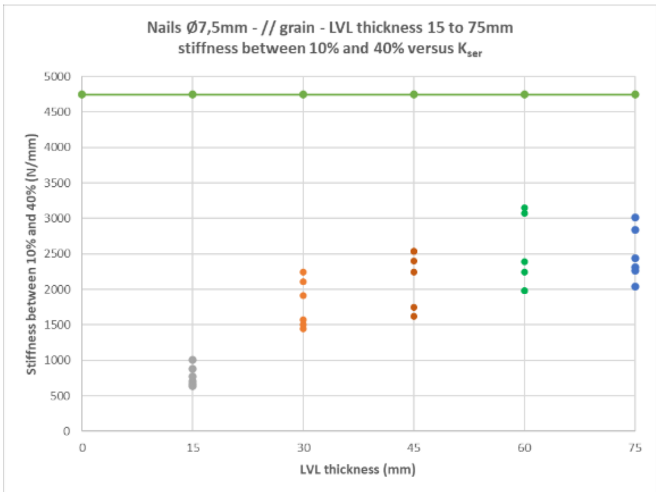


Figure 3. Measured stiffness versus K_{ser} for varying timber thickness.

3.3. Models

A promising model that can be used to evaluate the stiffness of dowel-type connections is the so-called beam-on-foundation model. In this approach, the single dowel is modelled as a discrete number of elements, by use of finite element modelling. The reaction of the wood is modelled by use of non-linear springs, which can be obtained by way of embedment testing following EN 383. The discrete elements of the dowel are connected by means of rotational springs who simulate the plastic hinges in the dowel. In this simple model, no axial effects are taken into account, but test do show axial effects may be considerate, especially in the plastic domain. This type of model allows for more complicated connection layouts, and for example the integration of interlayers.

4. Conclusions

The influence of connection stiffness on structural design can be of great importance. Today a conservative approach towards this influence is necessary. Refinement of the current stiffness models could be a means to a more robust and effective design.

Effect of soundproofing interlayers on the strength and stiffness of CLT wall buildings

Yuri De Santis, University of L'Aquila, Italy

1. Introduction

Acoustics is often one of the main problems for timber buildings. Typical irritating sounds are people talking, television and footsteps. Transmission between two rooms can be airborne or structure borne. Sound can reach the "room of the listener" through various transmission paths: the separating wall itself could radiates sound energy directly into the room of the listener, the separating wall could transmit vibration to the adjacent walls, which radiate energy into the listener room, the side walls of the "source room" could transmit vibrations to the separating wall or to side walls of the listener room (Hagberg & Ingemanssin, 2009; Rothoblaas - Flanksound project; ISO 12354-1). All sounds that propagate through propagation paths other than direct transmission through the separating wall or floor are called flanking sounds. It is essential to solve the problems of flanking transmission in order to deal with the sound insulation. Flanking sound can be reduced limiting the vibrations transmitted to the contiguous walls and floors in the source room, reducing the radiation of sound from the walls and floors of the receiving room and reducing the vibrations transmission from the elements of the source room to the elements of the receiving room. The latter strategy requires a complete separation of the structural and non-structural part of the adjoining apartments from each other.

2. Separation with soft layers

Separation is often achieved using layer significantly softer than the timber of structural elements above and below the insert. In the vertical direction, the separation is achieved using an elastic layer between overlapping walls and between floors and walls (Ljunggren & Ågren, 2013; Karacabeyli & Lum, 2014). However, the layer is subjected to the static load of the section of the building above the layer. This means that stiff layers must be used in the lower part of high buildings, increasing coupling and thus degrading the sound insulation. Acoustic bridges via connections can be prevented by soundproofed steel angle brackets.

In the soundproofed connections the rigid parts are elastically separated from one another using interlayers (Fig. 1). Elastomers are frequently used at junctions so as to reduce low frequency sounds. Common types include closed cellular polyurethane ("CCP") and mixed cellular polyurethane ("MCP"). Since the choice of the most adequate properties for the material is essential, elastomers should be characterized defining Young's and shear moduli for varying load-frequencies. Admissible vertical loads that guarantee the maintenance of the insulating properties and admissible shear strain must also be defined (Negreira et al., 2014; Reichelt et al., 2016). The coefficient of elastomers on timber can be estimated as $\mu \geq 0.5$ and therefore it is useful to take the load transmission capability of the elastic layers into account and design. Although separation is an efficacious solution of the sound insulation problem, it is often not the most straightforward since there might be a conflict against the building's overall deformability and stability requirements. Therefore, elastic connection must be carefully designed in order to allow the structure to appropriately manage the horizontal wind and seismic loads.

3. Mechanical behaviour of soundproofed connections

The influence of flexible sound insulation layers on the seismic performance of cross laminated timber walls has been studied in (Azinović et al., 2021). According to the authors the bedding insulation layer under the wall led to only minor changes in the load-bearing capacity of the walls under lower vertical loads but the stiffness of the wall decreased to less than 40% that of the uninsulated wall, due to additional lateral deformations enabled by the insulation. Experiments confirmed that a higher vertical load substantially increases the load bearing capacity, as well as the stiffness of the shear wall, due to the associated increase in friction.

Figure 1: Soundproofed steel-to-timber connection.

The cyclic response of insulated steel angle brackets with inclined and perpendicular screws used for cross-laminated timber connections has been assessed in (Kržan & Azinović, 2021). The monotonic and cyclic tests on the CLT wall-to-floor connections highlighted that insulation under the angle bracket has a marginal influence on the load-bearing capacity; however, it significantly influences the stiffness characteristics resulting in a 22% and 45% reduction of the effective stiffness in pure shear and tensile loading respectively. The relative energy dissipation and equivalent viscous damping coefficient were lower for the insulated specimens than for the uninsulated specimens, but the difference decreases with increasing displacements and repeated cycles. Friction energy dissipation was found.

Recently, De Santis & Fragiacomo (2021) proposed an analytical model for the stiffness prediction of screw connection with deformable interlayers. The authors found that for connections with screws inclined with respect to the sliding plane, the slip modulus decreases much slower than for connections with perpendicular screws as the thickness of the intermediate layer increases.

Moment resisting timber frames using connections based on threaded rods

Osama Abdelfattah Hegeir, NTNU, (Norway); **Haris Stamatopoulos**, NTNU (Norway)

1. Introduction

Timber buildings are prone to wind-induced vibrations due to their light weight and moderate stiffness. Excessive wind-induced accelerations can cause discomfort to the building's occupants, and lateral displacements can damage or affect the functionality of the building. Therefore, in multi-storey timber buildings, wind-induced accelerations and displacements are typically among the main design criteria. There are several structural systems that can be used as lateral load resisting systems, such as CLT shear walls, diagonals, and moment resisting frames (MRFs). MRFs are advantageous considering the architectural flexibility since they impose fewer architectural restrictions and provide more open space.

2. Moment Resisting Timber Frames (MRTFs)

A MRTF structural system was proposed at NTNU (Vilguts et al., 2021), see Fig. 1 (a). The system consists of continuous glulam columns connected to glulam beams using semi-rigid moment connections with rotational stiffness K_θ. A Parametric study using 2D plane frame model (Fig. 1 (b)) (Vilguts et al., 2021) has shown these MRTFs can be used up to 8-10 storeys considering lateral displacements and wind-induced accelerations (serviceability requirements). In the study (Vilguts et al., 2021), the spacing between adjacent frames was limited to 2.40 m. A minimum of 10000-12500 kNm/rad beam-column connection stiffness was proved necessary to meet the serviceability requirements (Vilguts et al., 2021). An example of the serviceability performance of such MRTFs by use of a linear-elastic model is shown in Fig. 2. The calculation of wind-induced accelerations was based on modal analysis of the frame and the approach described in EN1991-1-4 (Eurocode 1). Fig. 2 shows that a significant improvement can be achieved with respect to both accelerations and lateral displacements when semi-rigid beam-to-column connections are used. Therefore, the investment in such connections is of great importance.

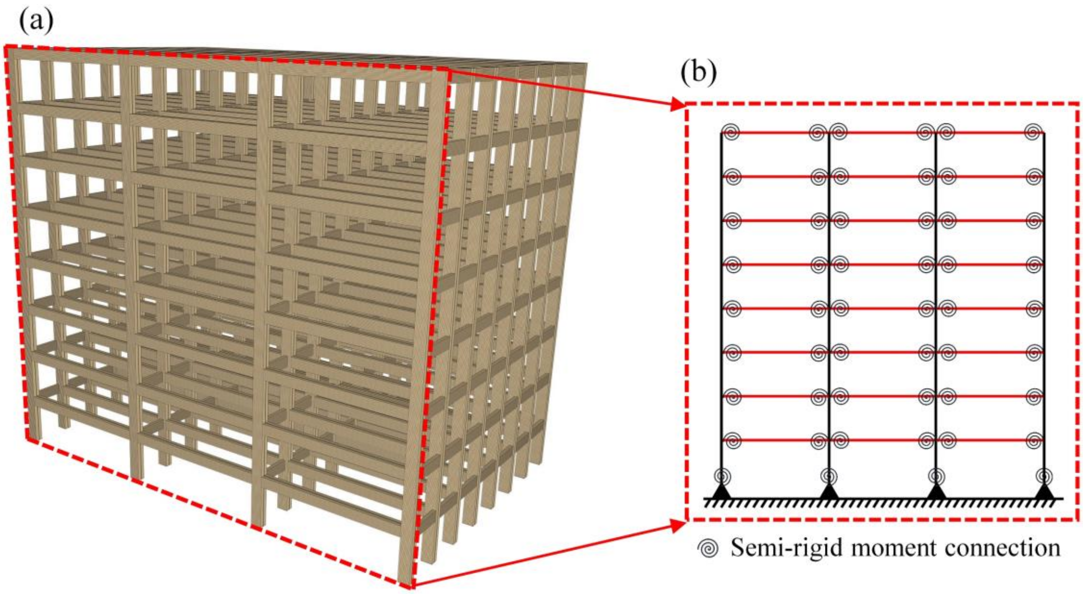


Figure 1: Structural system (a) 3D physical model (Vilguts et al., 2021), (b) 2D analytical model.

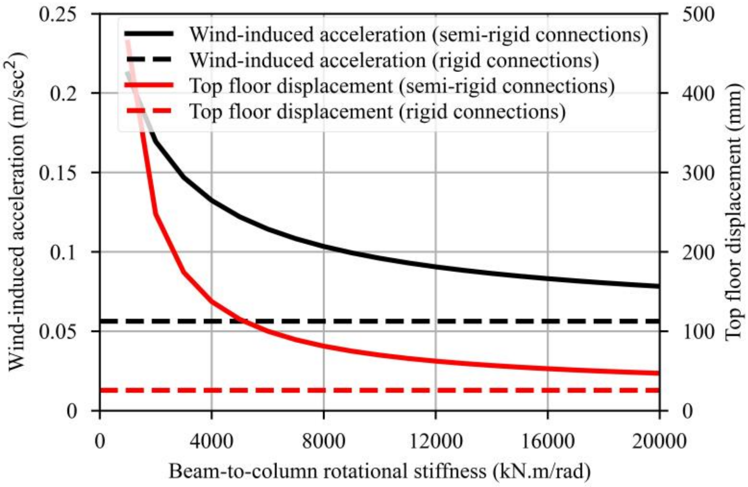


Figure 2: An example of improved performance of a 3-bays 10-storeys MRTF (wind velocity = 26 m/sec-linear elastic analysis).

In addition to the improved lateral performance of the structure, vertical deflections and vibration performance of floors are improved if semi-rigid moment connections are used. A parametric study using a simple beam model (Malo & Stamatopoulos, 2016) has shown that the use of semi-rigid connections can significantly improve the human-induced vibration performance relative to pinned connections, allowing for longer spans. In the study (Malo & Stamatopoulos, 2016), Hu and Chui vibration criterion (Hu & Chui, 2004) was used as an indicator to evaluate the performance of the beam. Fig. 3 shows the relative performance of the human-induced vibration of a simple beam. The relative performance is the ratio between the performance of a beam with semi-rigid connections to the performance of the same beam with pinned connections (minimum value is unity). A possible range of K (normalized connection stiffness: $K_\Theta l/EI$ where K_Θ is the rotational stiffness of the beam) assuming a reasonable connection stiffness for timber beams is 0-5, confer Fig. 3 (a).

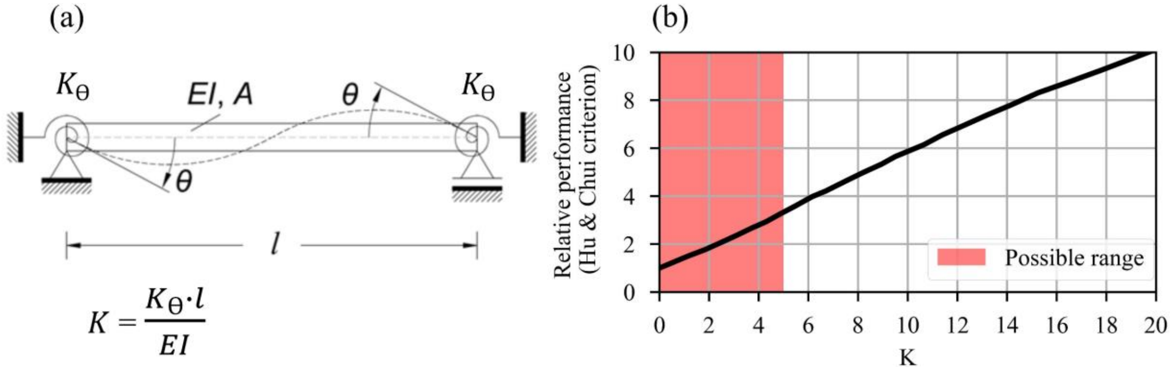


Figure 3: (a) Analytical model of beam and (b) vibration relative performance (Malo & Stamatopoulos, 2016).

3. Semi-rigid moment connection using threaded rods-experimental work

Achieving moment connections with good stiffness is challenging in timber structures. Threaded rods have shown good strength and stiffness properties when loaded axially, see e.g.(Stamatopoulos & Malo, 2020) for a summary. Several variations of moment connections based on threaded rods have been investigated experimentally, e.g. (Malo & Stamatopoulos, 2016; Vilguts et al., 2022; Vilguts et al., 2021). These connections have shown satisfactory stiffness; however, research is still ongoing to achieve further improved properties with respect to stiffness, capacity, ease of assembly etc. Fig. 4 shows some examples of moment connections based on threaded rods developed and tested at NTNU.

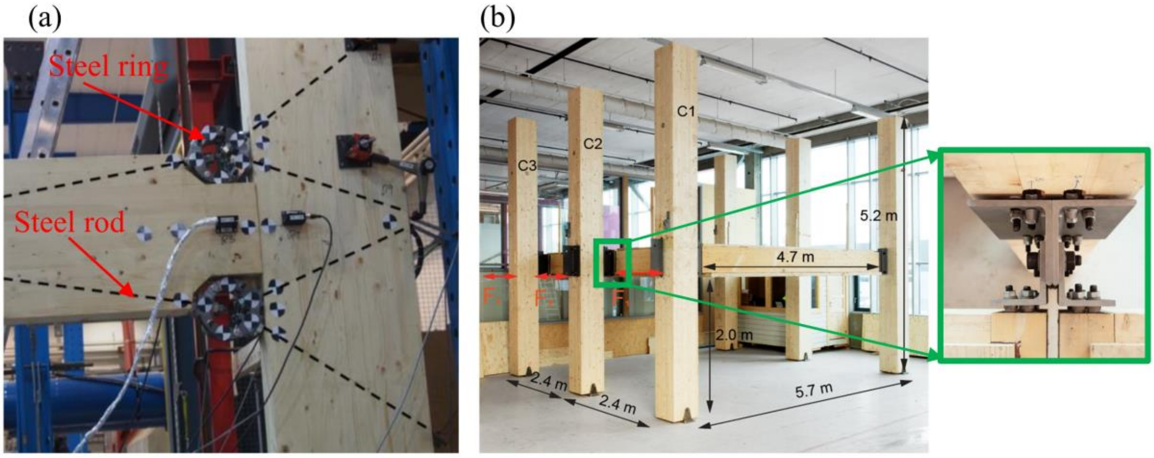


Figure 4: Examples of Moment connections (a) full scale connection (Stamatopoulos et al., 2022) , (b) full scale mock-up (Vilguts et al., 2022).

4. Semi-rigid moment connection using threaded rods-analytical work

Additional to the performed experimental work, structural simulation using finite element method (FEM) was also used to investigate the behaviour of moment resisting connections based on threaded rods (Vilguts, 2021), see e.g. Fig. 5. Analytical models have also been developed and verified using experimental work (Stamatopoulos et al., 2022).

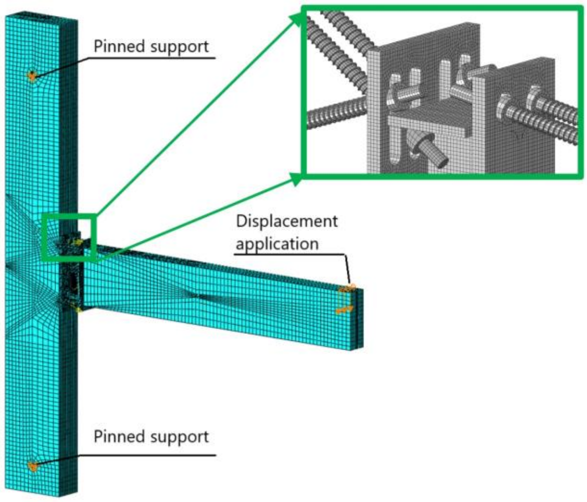


Figure 5: Examples of FEM simulation of moment connections (Vilguts, 2021).

5. Conclusions and future work

This contribution provides a brief summary of an ongoing research at NTNU on MRTFs, and semi-rigid moment connections based on threaded rods. MRTFs have shown applicability to build up to 8-10 storeys with out-of-plane spacing between adjacent frames of 2.40 m considering serviceability requirements. Further research is needed to extend the applicability of such system to taller buildings and larger out-of-plane spacing. The capacity and ductility of connections are of great importance and should also be investigated to pave the way for using such connections in practice.

Experimental Investigation of CLT Connection Deformation

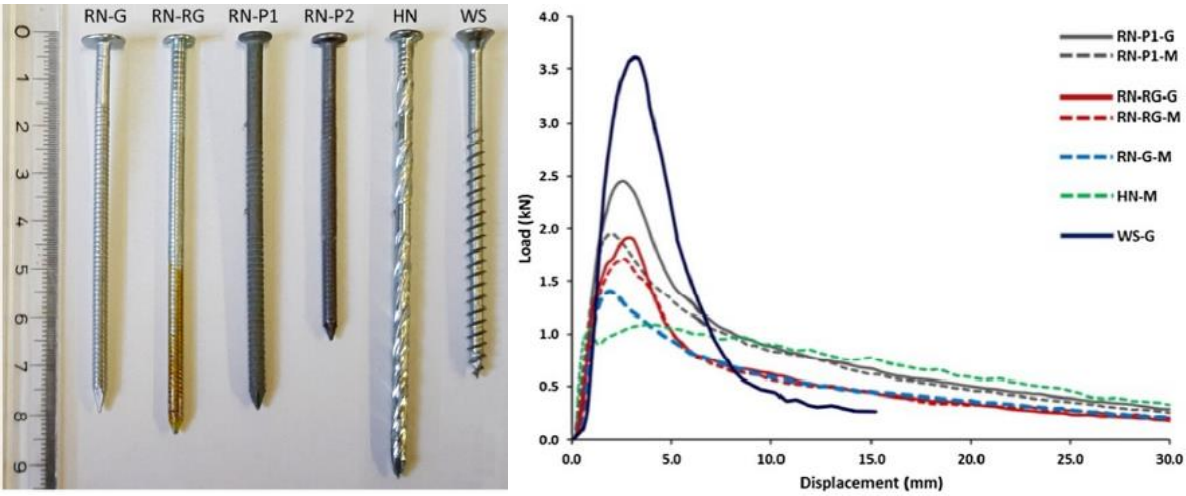
Aygül Ceylan, Yildiz Technical University (Turkiye); **Zehra Canan Girgin**, Yildiz Technical University (Turkiye)

1. Introduction

Cross laminated timber (CLT) is an innovative engineered wood product, especially as a shear wall in order to meet the rigidity and strength requirements in multi-storey timber buildings. Many experimental studies have been devoted to comprehending and developing the seismic performance concerning the connections of CLT panels under seismic loads so far. CLT panels have major rigidity regarding the linked connections and in experimental tests is commonly observed an elastic behaviour in the panels and an inelastic behaviour in the connections (Popovski et al., 2014; Sullivan et al., 2018). CLT panels are linked with metal connectors (angle bracket, hold-down, metal plate, etc.) via nail, screw, dowel, etc. fasteners that coated different chemicals to resist corrosion in damp conditions. Metal connections are related to the withdrawal strength of fastener, or holding capacity, as well as shear strength. To focus the withdrawal resistance of a single fastener instead of a group under interaction will be an economical and realistic method to predict the pullout performance per fastener as well as to prevent failure modes. Therefore, the withdrawal resistance of a single fastener from a CLT specimen, which has not been adequately investigated so far, is systematically addressed by shank threated nails and wood screw in (Ceylan & Girgin, 2020) study. As a result of the evaluation obtained from the withdrawal resistance tests, the highest withdrawal strengths were attained in domestic phosphate-coated annular ring nails, and these nails were used in CLT wall-to-floor connections tests in the next. The detailed results of experimental studies are also included in the PhD thesis (Ceylan, 2021).

2. Withdrawal resistance of resin and phosphate coated annular ring nails in CLT specimens

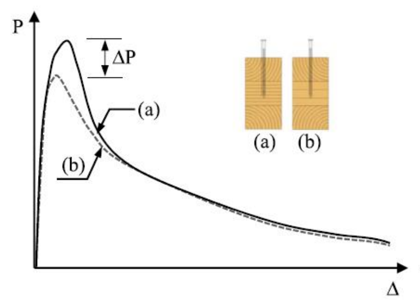
The galvanized fasteners (ring nail, helical nail, screw, etc.) are common in timber engineering that connected the angle brackets, hold-downs, plates, etc. Although chemical coating (esp. galvanized) is generally used for treatment, no article has been found for resin or phosphate coated annular nails, except for Ceylan & Girgin (2020). In this study, the withdrawal strength tests of the four types of nails with annular/helical shanks and wood screw (self tapping screw) were executed on 200 CLT specimens of 50mmx50mmx100mm. Each single fastener was driven perpendicularly into the surface (side face) of CLT specimen via manual/gun drive as in the wall-floor angle bracket connections. Not only the numerical values of holding capacity but also the load-displacement curves are focused in the experimental tests. As a result, the phosphate coated annular nails among all the nail types have the highest efficiency due to the improved mechanic friction of rough crystalline coating as well as the resistance to outdoor damp conditions (Fig. 1). Furthermore, the withdrawal energy during the pull-out of single fastener, which is not investigated so far but may have highly significant implications for metal connections of CLT panels, was evaluated graphically. So higher withdrawal resistance and withdrawal energy of phosphate annular nails may lead to more economical and high-performance solutions for CLT connections in future applications.

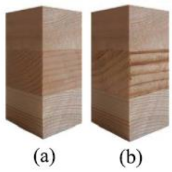


a b

Figure 1: (a) Nail types and wood screw for withdrawal tests, (b) combined load–displacement curves for averaged of all fasteners (Ceylan & Girgin, 2020).

This study also draws attention to the difference caused by driving style (gun or manual) as well. The peak load in gun drive, comparing with manual one, indicates 25% increment for phosphate coated and 13% for galvanized+partially resin coated nails. In phosphate coated annular nails, for manual drive case, 40% improvement in holding capacity compared with common galvanized ones was realized from the experiments. For CLT specimens, the effect of pattern of growth rings with manual/gun drive option (Fig. 2a) not available in the literature are also partially discussed. In the experiments, particularly, inclined close-close-close grained layers were focused to minimize the uncertainties. It may be expected lower values in the range of 7.5–13.5% compared with close grained middle layer ones. Finally, it should be mentioned that some unexpected premature failure cases were observed. Head deformation in some galvanized annular nails and broken head in some resin coated annular nails (Fig. 2b) were observed.





	ΔP		
Drive	RN-P1	RN-RG	WS
G	10.6%	7.5%	10.4%
M	13.5%	8.1%	-

a b

Figure 2: (a) typical withdrawal load–displacement with respect to grain density and averaged differences, (b) unexpected failure modes in withdrawal tests (Ceylan & Girgin, 2020).

3. Experimental Investigation of CLT Wall-to-Floor Connection Deformation

In order to develop energy-absorbing CLT panel connections many experimental studies have been conducted on the effectiveness of the connections, especially for the earthquake prone regions. One of these researches, see (Ceylan & Girgin, 2019) was experimentally investigated the performance of a full-scale CLT wall-to-floor specimen assembled with metal connection under axial tensile force due to bending moments of seismic loads, after withdrawal tests of fasteners. Domestic angle bracket, plates, and phosphate coated annular ring nails were used in metal connection of the CLT panels.

All the displacements and strains were measured and collected during the test of the specimen, behaviour of connection and the failure modes (Figs. 3-4) was observed. As a result, the back side deformation of CLT wall member was prevented with the plates for a longer period compared with no-plate case and the withdrawal resistance of from CLT floor increased through phosphate coated annular ring nails and extra three nails in the corner of angle bracket on the front side. As a result of experimental tests it was concluded CLT panel connections can successfully dissipate energy with domestic angle brackets, plates and the type of phosphate coated annular nails fasteners. The results are promising, and the further experimental researches will continue for the most effective connection type.

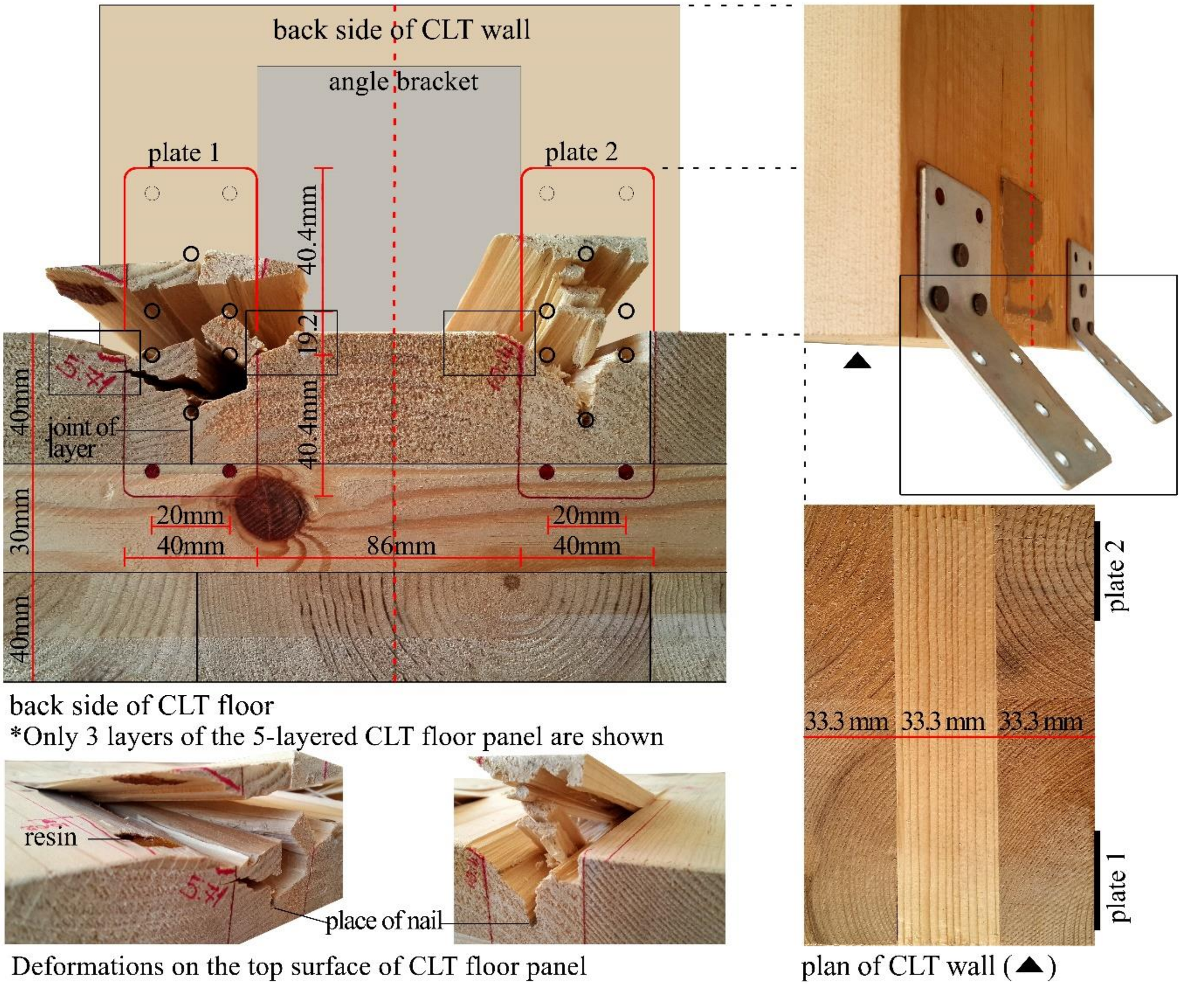


Figure 3: The back side deformation of CLT wall-to-floor connection (Ceylan & Girgin, 2019).

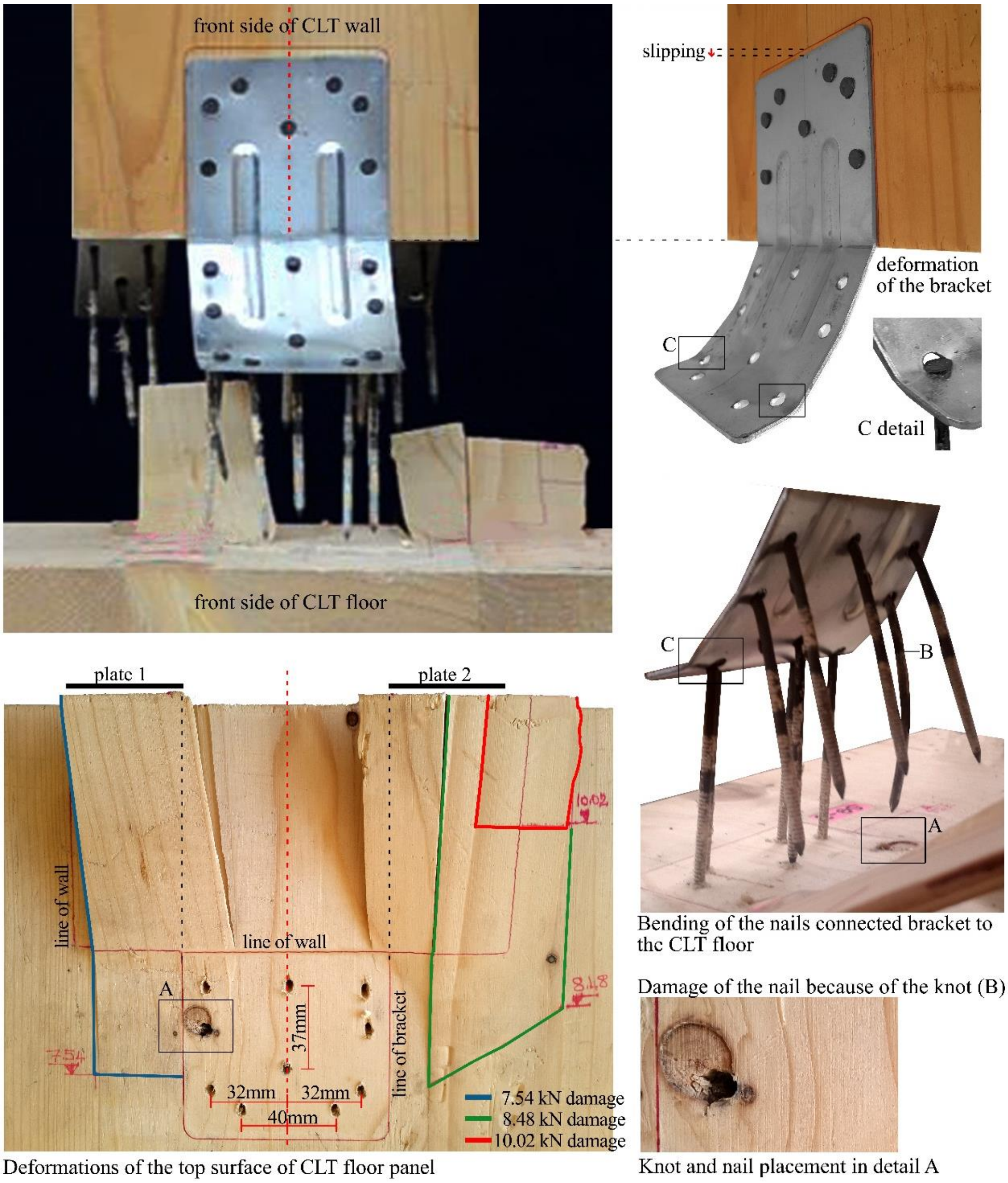


Figure 4: The front side deformation of CLT wall-to-floor connection (Ceylan & Girgin, 2019).

4. Conclusions and Future Work

This contribution provides a brief summary of the withdrawal resistance of various annular ring nails in CLT and ongoing research on the behaviour of CLT wall-to-floor connections under building loads. It is very important to carry out comprehensive research and experimental investigation on CLT connections to determine the behaviour and deformations. From this point of view, it is possible to develop building codes related to multi-story timber buildings by evaluating experimental results. Moreover to provide domestic timber with sustainable forest management for CLT panel production leads to improve forest asset as well as a positive contribution to the economy.

Creep behaviour of structural timber elements and considerations for mass timber construction

Conan O'Ceallaigh, University of Galway (Ireland), **Patrick McGetrick**, University of Galway (Ireland)

1. Introduction

Timber as a structural material demonstrates many benefits over more commonly used structural materials. It is a naturally grown, aesthetically pleasing material with a high strength-to-weight ratio and has the added benefit of trees sequestrating carbon from the environment which is stored in the timber during its in-service life. Furthermore, in recent years, there has been a significant advance in engineered wood product technology and connection systems that have allowed timber to rival more commonly used structural materials and reach new heights, paving the way for environmentally friendly structures. When using timber as a structural material, particularly in bending, the behaviour is often not governed by its structural strength or ultimate limit state, but by the serviceability limit state, namely deformations and vibrations. As a result, careful consideration must be given to long-term performance which is often termed creep deformation. When subjected to loaded situations for long periods, timber is susceptible to creep strains or deformations, and for timber structures, the creep deflection can be large relative to the instantaneous deflection (see Figure 4). Three primary components contribute to the total creep deflection of a structural timber element. These three components are (i) time-dependent or viscoelastic creep, (ii) mechano-sorptive creep due to moisture changes and (iii) pseudo-creep that is attributed to swelling and shrinkage of the timber.

Figure 4: Creep deflection of timber beams subjected to a sheltered external climate (credit: Martin Ansell, University of Bath).

Viscoelastic creep in wood is described as additional strain with time at constant moisture content and constant environmental conditions under sustained loading. This additional strain manifests as an increase in deflection when subjected to bending. Timber and creep in timber are also heavily influenced by the surrounding environment. Under changing relative humidity, hygro-expansion or swelling/shrinkage deformations of wood must be considered but also, under load, the creep behaviour of wood is accelerated with changing relative humidity. This behaviour is known as mechano-sorptive creep behaviour and is a strain/deformation due to an interaction between stress and moisture content change in wood. Typically, there is an increase in the deflection during each drying phase and a decrease during the wetting phase of a relative humidity cycle. In a variable climate, the total strain/deformation comprises the elastic, viscoelastic, mechano-sorptive and swelling/shrinkage components. The typical behaviour can be observed in Fig. 2, whereby the mean creep deflection of a series of glued laminated beams over a 75-week period can be observed (O'Ceallaigh, 2016). Group UC is subjected to four-point bending in a constant climate with a relative humidity of 65% ± 5% and a temperature of 20°C ± 2°C and experiences an initial elastic deflection when loaded followed by viscoelastic creep with time. Group UV is also subjected to four-point bending but in a variable climate cycling between a relative humidity of 65% and 90% ± 5% with a cycle length of 8 weeks. It can be seen that the creep deflection is significantly greater when subjected to a variable climate as the deflection behaviour comprises the elastic, viscoelastic, mechano-sorptive and swelling/shrinkage components.

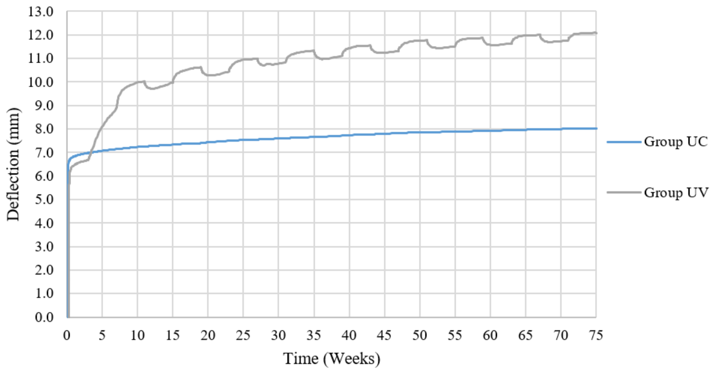


Figure 5: Mean creep behaviour of beams (Group UC) in a constant climate with a relative humidity of 65% ± 5% and a temperature of 20°C ± 2°C compared to beams (Group UV) in a variable climate cycling between a relative humidity of 65% and 90% ± 5% with a cycle length of 8 weeks (O'Ceallaigh, 2016).

2. Creep behaviour of Engineered Wood Products

2.1. Background

It is difficult to separate and characterise the individual creep components as they often occur simultaneously within a loaded structural element in practice. In the design of such structural elements, factors are available that account for additional deflections with time. Eurocode 5 provides deformation modification factors or k_{def} factors which account for creep effects with time. The k_{def} factor is used to increase the initial elastic deflection of the designed element. These factors are dependent on the type of timber product (solid timber, glued laminated etc.) and the different service class conditions in which the product will be used. The recent developments in mass-timber products such as cross-laminated timber (CLT) and the associated connection systems have resulted in a rise in the use of timber in medium to high-rise structures. While the technology is well established, there has yet to be a building that has withstood the test of time to correctly examine if current design guidelines for the calculation of creep are appropriate for CLT under the increasing structural demands of modern construction. While creep modification factors are well established for products such as solid timber and glued laminated timber, there are currently no specified k_{def} factors for CLT in Eurocode 5. Instead, the specification of modification factors or k_{def} factors for CLT is specified by the product manufacturers within their respective European Technical Approvals (ETAs). The following section examines some of the most significant studies that have attempted to accurately characterise the k_{def} factors for CLT.

2.2. Experimental and Numerical Modelling Activities

The following studies have performed state-of-the-art research activities to determine and aid the development of design guidelines for the safe prediction of long-term or creep effects in engineered wood products. It is important to note that there have been a significant amount of studies that have examined the creep behaviour of timber under several different climates and service class conditions and these form the basis for our current design standards in Eurocode 5. There is, however, limited experimental information on the creep behaviour of modern engineered wood products such as CLT (Binder et al. 2022). Some of the most significant studies to date have been performed by Jöbstl & Schickhofer, (2007) and Unterwieser & Schickhofer, (2013) where CLT was subjected to experimental creep testing. Jöbstl & Schickhofer, (2007) examined both CLT and glulam elements under constant climate conditions and common load levels and demonstrated that greater creep deflection was observed for CLT but the influence of creep in transverse layers subjected to rolling shear can contribute significantly to this increased creep behaviour. Colling, (2014) indicated that creep in transverse layers could be significantly higher than that parallel to the grain, potentially by a factor of 10. Jöbstl & Schickhofer, (2007) also observed a dependence on the number of layers and proposed k_{def} factors depending on the number of layers with panels of seven layers or less being subjected to a factor of 1.1 or an increase of 10%. Building upon the work, Unterwieser & Schickhofer, (2013) highlights that CLT should potentially be assigned with similar creep modification factors to that of plywood (CEN, 2005) with no allowable creep modification factor for Service Class 3 conditions. It is also worth noting that creep behaviour in timber is significantly influenced by stress and the comparisons between glulam and CLT at common load levels may result in significant differences in stress levels and make comparisons difficult. However, it is apparent that the influence of rolling shear in transverse layers cannot be ignored.

The current consensus by a series of product manufacturers is that k_{def} factors of CLT should be comparable to that of solid timber, glued laminated timber and laminated veneer lumber and this is specified in many ETAs. Some European National Annexes are also in agreement with this but these values are not in agreement with the research reported above. At the time of writing, the k_{def} factors for CLT of 0.8 for Service Class 1 and 1.0 for Service Class 2 have been proposed in the most recent draft rules submitted to CEN TC 250/SC 5 for the next generation of Eurocode 5. This is a conservative approach based on the current experimental data and evidence available. It is expected that CLT will not be specified for Service Class 3 conditions and is solely limited to Service Class 1 and Service Class 2 conditions as is currently the norm.

The availability of long-term experimental data is a concern for the industry but there has been a significant effort to utilise finite element modelling to predict this behaviour over longer periods of time. Timber is a challenging material to model numerically due to its natural variability in properties and anisotropic behaviour; however, in recent years, timber has been modelled successfully under long-term loading situations thereby increasing the reliability and safety of structural timber design. The recent advances in the modelling of the creep behaviour of timber by O'Ceallaigh et al. (2020), Hanhijärvi & Mackenzie-Helnwein (2003) and Fortino et al. (2009) have resulted in validated fully coupled three-dimensional moisture-displacement models that can be used to predict the long-term behaviour of timber elements under varying climates and relative humidity conditions. Experimental monitoring of the long-term behaviour of engineered wood products is a costly and time-consuming process and the benefits of a validated model will provide a powerful tool to aid the further development of such engineered wood products in the future. This is coupled with a significant effort around the world to instrument and monitor some of the many demonstrator structures using CLT and novel mass timber solutions (Riggio & Dilmaghani, 2019; Schmidt & Riggio, 2019). Other studies monitoring elements such as CLT shear walls and Timber Concrete Composite (TCC) beams are also being successfully utilised in a number of structures as novel solutions to examine the deformation performance and the vibration criteria. Similar numerical studies of this technology were analysed by Fragiacomo & Ceccotti, (2006) and Binder et al., (2022) with modelling efforts proving successful. Fragiacomo & Ceccotti, (2006) developed a validated model based on two long-term experimental tests in outdoor conditions. Despite some uncertainties in environmental conditions and material properties, a good fit between experimental and numerical results was obtained. Binder et al., (2022) examined and compared TCC and CLT panels and demonstrated similar creep behaviour after a 50-year design life based on a numerical study.

It is clear that the use of CLT and mass timber solutions in construction will continue and there is still a significant opportunity to examine its long-term performance through experimental testing, instrumentation of in-situ elements and numerical activities in the future to further improve the safety and reliability of structural timber design.

WG2.SG1 References

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WG2.SG2 – Vibrations

Definitions for vibration issues in taller timber buildings

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There are several classification criteria for vibration problems in timber engineering based on the excitation sources, the structural components and the ranges of frequency excitation. Concerning the sources of excitation:

- Ambient vibration
- Forced vibrations

Within forced vibrations, there are several excitation sources:

- Human-induced
- Wind-induced
- Seismic-induced
- Machinery-induced
- Blast

For the structural elements:

- Sub-components (e.g., beams)
- Floors
- Buildings
- Frequency of excitation:
- White noise
- Low-frequency
- High-frequency

As such, a state of art analysis is summarized in the following chapters, to collect major research contributions and open gaps on some of the above listed aspect.

Sub-components and vibration issues

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The main problems related to the vibration of sub-components are associated to the mechanical characterization of mass timber elements or engineering wood products and the acoustic performance of non-structural components. Experimental analysis, in this regard, is of primary importance for mechanical characterization. Besides, literature data are still relatively limited in number and further research efforts are needed.

In the same way, the assessment of the stiffness of joints is essential for the joints' design, monitoring the condition of building structures and prognosis of the lifetime and safety of buildings or their elements (Serdjuks et al., 2022a). Typically, such assessment is done in a non-destructive way using either shock or vibration analysis with a network of accelerometers as sensors.

Serdjuks et al. (2022b), more precisely, developed a non-model vibration analysis method and measurement system. It is based on the correlation principle of normalized coaxial accelerations measured in 3D space. The method is based on the mathematical analysis of vibrations of structural joints in 3 spatial directions using 3D accelerometers located at different parts of a joint and orientated coaxially. The developed method for assessing the quality of structural joints includes the electronic system for testing and mathematical processing of the obtained data. The developed measuring device consisted of an electrodynamic actuator, two 3D accelerometers, a signals amplifier, an Arduino board for signals conversion and transfer, and a computer.

The correlation method was verified in a laboratory experiment using rigid, semi-rigid and pinned joints of timber beams. Stand with timber beams joined at right angles by steel plates and screws were fabricated and tested by static loading to confirm the present state of the joint. Timber beams with 150X50 mm solid sections made C18 strength class were used for the timber stand. The decrease of the joint's stiffness in the case of probable damages was modelled by the loosening of the steel screws. The stand was subjected to a vibration load provided by electrodynamics actuators fixed on one of the joint elements. This element was excited by a chirp signal in a frequency sweep range from 10 to 500 Hz, where the most prominent resonance of the stand was found. Acceleration responses were recorded by 3D accelerometers placed on the loaded and connected beams. Peak values of the cross-correlation function between the responses from the correspondingly orientated pairs of coaxial accelerometers were determined. It was shown that the difference between the peak values of the correlation functions obtained for the rigid, semi-rigid and hinge joints enabled specification of the joints' stiffness.

The use of new technologies, in view of meaningful non-destructive tests for mechanical characterization, is expected to offer a major contribution in the analysis, measure, diagnostic investigation of sub-components for taller timber buildings.

Floor vibrations in timber buildings

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1. Introduction

The scientific literature on this theme is quite extensive. It spans from modelling approaches to validation of technical recommendations. It mainly focuses on two sources of excitation: ambient vibrations (used for dynamic tests) and human-induced vibrations.

Overall, major questions are should answer the following questions:

- Which is the approximation in estimating the modal parameters using simplified methods, as recommended in the standards? Experimental tests and modelling attempts might have shed light on this issue.
- Which are the modelling approaches for human-induced loads. Are there any relevant findings from these studies that highlight an upgrade of the standards?
- Are there recent studies quantifying the level of discomfort of timber floors?
- Are there relevant researches on the floor's modelling?
- Any research on fatigue in timber floors (repetitive loads)?

The existing guidelines for timber floor vibrations typically assume that support conditions for floors can be considered as theoretical, pinned connection. In practice, however, the conditions can differ significantly from the assumption due to applied construction details (e.g., vibration isolation strips, flexible connectors, moment-resistant joints), imposed loads in the case of statically indeterminate systems (e.g. shrinkage-induced deformation in composite floors). This, in turn, can have significant effect on the vibration properties of the system, namely, natural frequencies, mode shapes and damping, compared to theoretical estimates. Consequently, this leads to uncertainties in the response evaluation of floors. Here, few publications related to the topic are summarised.

The study by (Jaaranen & Fink, 2022) deals with modal analysis and corresponding simulations of two-way timber-concrete composite floor. The results show that vertical flexibility of the supports as well as uplift in the corners can affect the mode shapes of the plate significantly. Furthermore, a model that could be used to further investigate the effects, is presented.

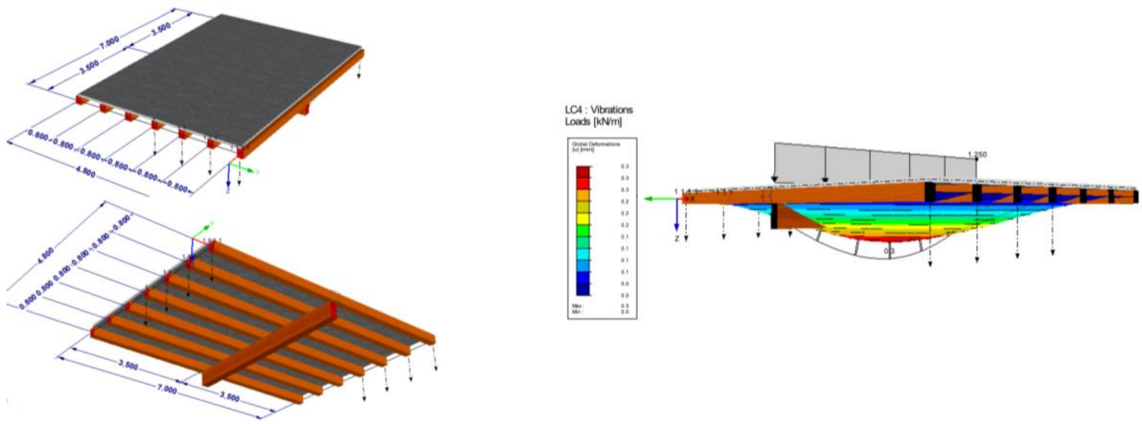
Jarnero et al. (2012) investigated the effects of different vibration damping interlayers on the modal properties of a prefabricated timber floor element, compared to typical simple supports. The results indicate that, as a common trend, the interlayers reduce natural frequencies but increase corresponding damping ratios. However, this trend is not fully consistent, and effects vary widely between different vibration modes; in some cases, even an opposite effect can be seen. The authors suggest that impulse velocity response of the floor is reduced by adding the interlayer.

Bolmsvik & Brandt (2013) compared the modal behaviour of two timber wall-floor assemblies: the floor is screwed or supported by elastomer interlayer. The trend was that use of the interlayer decreased natural frequency but increased damping. Furthermore, it was found that using the interlayer, the mean acceleration levels of the floor rose significantly for the frequencies below 40 Hz, which can have adverse effect on vibration comfort.

In his PhD thesis, Basaglia (2019) investigated experimentally the dynamic behaviour of a long-span ribbed-deck timber floor. The investigations showed a 15% decrease in the fundamental natural frequency by using a vibration isolation interlayer on supports. However, a striking increase of the damping ratio from 1% to 5-7% for two lowest modes was observed. It should be noted that this was one of many configurations with the isolation layer and not all of them displayed such a large increase. In the case with highest increase, the cause might be partially due to clamping effect induced by added weight on the supports.

Akter et al. (2021) studied the wall-to-floor-to-wall connections in platforms. Although a large portion of the paper concentrates in the moment-rotation behaviour of the connection, also effects of the connection to the floor deflections are discussed. In discussion, they suggest that moment-resistance of the joint can decrease static deflection of the floor up to 40%. The effect, however, depends widely on the thicknesses of used CLTs. Although their result considers only static behaviour, the use of these kinds connections is likely to have a pronounced effect on the floor vibration behaviour as well.

The TCC concept has been studied and developed over the past decades. The variety of solutions shows the meaningfulness and functionality of this system, as well as the continuous work of scientists over time (Skaare, 2013). To benefit from these advantages, the composite needs to provide sufficient stiffness to meet the serviceability criteria and load capacity to resist loading at every stage of the building life (Stepinac et al., 2020; Perkovic et al., 2021, see Fig. 1).



(a) (b)

Figure 1: Example of (a) structural system and (b) deflection-stiffness design. Reproduced from (Perkovic et al., 2022) under the terms and conditions of a Creative Commons CC-BY license agreement, November 2022.

An example of connector types and load slip curves according to EN 1995 is given. This paper discusses possible limitations related to residential areas, and additionally, the possible solutions that EN 1995 does not discuss in the case of resonant response (f1 < 8 Hz). The theoretical studies were accompanied by numerical analyses considering certain simplifications suitable for practical use (Santos et al., 2015). Numerical modelling is a powerful tool aimed at expanding knowledge and saving time and, ultimately, finance. Efficient data input and intuitive handling facilitate the modelling of simple and large structures. The numerical analyses aimed to extend the knowledge of the behaviour of the tested system. Furthermore, the numerical simulations served to confirm and complement the experimental results. In this paper, the RFEM pro-gram is used, a powerful 3D FEA program helping structural engineers meet requirements in modern civil engineering. One such case is certainly composite systems, specifically, timber–concrete systems. An additional aggravating circumstance is defining and calculating a semi-rigid connection between the different elements and materials. There are several options to calculate a semi-rigid composite beam or floor. The main difference is in the modelling method itself. Some methods ensure simple modelling (such as the gamma method). However, there are other more complex methods (shear analogy). Another option for modelling a composite system is shown in this paper. Since the definition and analysis of connecting elements are time-consuming, it is recommended to connect the surfaces of the elements to the other surfaces directly. Although there are several options in this software, the coupling member surface with the line release option will be shown below. This work was intended to research TCC systems and their applications while focusing on FEM analysis and vibration performance of standard TCC systems in residential and office buildings, and potential problems that may occur related to vibration design. In addition to the proposed models for the calculation of vibration, velocity, and acceleration, analytical models for calculating different types of slip modulus are given. This is an important detail because the degree of coupling conditions the stiffness of the system and, thus, the vibration conditions themselves. The composite timber–concrete system is an efficient system that is applicable during new construction or restoration, and consists of a monolithic concrete slab connected to timber beams. Comparing the load-bearing capacity of this composite system with the load-bearing capacity of the constituent elements, it can be concluded that the system has up to four times higher stiffness and up to twice the load-bearing capacity. For wide-span ceilings, the vibration design is often governing. The advantage of the lighter material of timber over concrete becomes a disadvantage, be-cause a high mass material is advantageous for a low natural frequency. Having long stiff support beams and shorter floor spans can ensure improved vibration performance when compared to systems with longer floor spans and shorter beam spans. An assessment and calculation of the TCC system was made, which was satisfactory for the frequency, additional acceleration, and stiffness limit criterion. Finally, FE analysis showed that stresses occur locally within the connector area in the concrete slab on both sides of the joint. The advantages of TCC (vs. sole timber) that can be emphasized are increased stiffness through composite action, increased floor mass at decking level, improved sound insulation (airborne sound), and reduced sensitivity concerning vibrations. If, on the other hand, the TCC is compared with pure concrete, it can be concluded that the weight is reduced, the CO2 emissions are reduced, the building process is faster, and reduced effort is needed for the props and formwork.

2. Comfort analysis

As part of the research work carried out by the Working Group 3 of COST Action FP0702, the need for vibrational comfort design for buildings and current regulations for comfort assessment of structural vibrations of timber floors in Europe have been summarised. Also, the design practices of timber floors with respect to vibrational serviceability criteria, including those for fundamental frequency, unit point load deflection and unit impulse velocity, in up to thirteen European countries have been gathered and their differences been further assessed by analysing flooring systems constructed with three types of joists, i.e., solid timber joists, engineered I-joists and metal web joists. The unit point load deflection criterion is the most crucial one for structural design of timber floors with various types of joists and usually dominates the whole design (Zhang et al., 2013).

Kowalska-Koczwara et al. (2018) presented selected aspects of the influence of urban transport vibrations on humans in buildings. The first analysed issue was the influence of the type of source of transport vibrations on the results. The analysis shows that the excitation caused by the passage of light-wheeled vehicles has a more negligible impact on the perception of human vibrations than the vibrations caused by heavy rail vehicles. Next, the authors determine the relationship between the human perception vibration ratio (HPVR) and the vibration dose value (VDV) for individual dynamical events. Finally, a significant and practical result of the work was to determine the zone of the possible location of the measurement sensor used to evaluate the influence of vibrations on people in buildings. Kreis (2021) investigated the vibration of two-Way Spanning Timber-Concrete Composite Slabs made of Beech Laminated Veneer Lumber with Steel Tube Connection.

Timber buildings and vibrations – Operational Modal Analysis aspects

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Timber buildings are prone to high-level vibrations, which is related to possible discomfort to the occupants (ambient vibrations). Additionally, the dynamic properties are important to predict their response under seismic and wind-induced vibrations.

The dynamic response depends on the amplitude of the excitation. The low-amplitude excitation has been investigated from experimental tests and model updating. The high-amplitude excitation is significant to understand possible nonlinearities of the response in terms of modal parameters. The damping, in particular, is extremely relevant for earthquake engineering. Are there researches which estimate the damping from high-amplitude tests (shake-table tests)? The participants should collect and organize the main findings on this topic, from ambient tests, continuous dynamic monitoring, shake table tests? Do the environmental parameters (i.e., temperature, relative humidity) significantly affect the dynamic response? (continuous dynamic monitoring). Is timber vibration a limitation for tall buildings?

Even though the popularity of timber structures has grown a lot during recent years, the engineering knowledge concerning the dynamic behaviour of tall timber buildings is still limited (Abrahamsen et al., 2020; Fig. 1). In taller, more slender and flexible timber buildings, serviceability considerations associated with lateral movement assume increased importance compared to low-rise buildings, where strength is usually the governing design criterion. For instance, the wind-imposed forces on a tall and slender building, while they may not damage any structural element, may cause deformation or vibration in the building which could cause discomfort to occupants, damage non-structural elements, or otherwise prevent the normal operation of the building. Both recent technological developments and increased use of engineered wood products reflect in deficiency of current timber codes and lack of knowledge by professional engineers. As engineers strive to take multi-storey timber buildings to new heights, it is necessary to understand how existing buildings, and current construction systems, are behaving in-service, and how their performance relates to what predicted at the design stage. A better understanding of the dynamic behaviour of mid-rise and high-rise timber buildings is of paramount importance in order to design future buildings more efficiently.

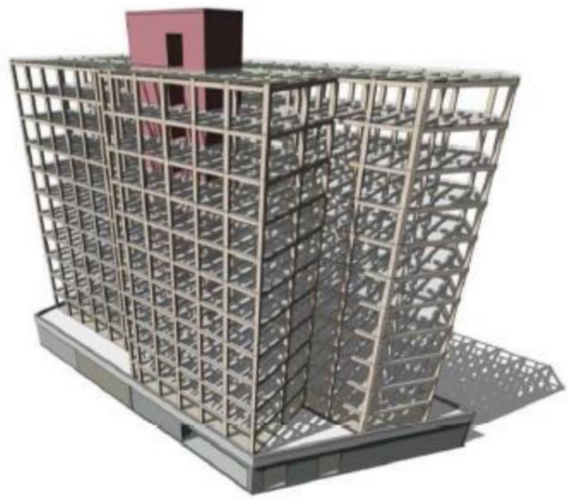

Figure 1: Structure of the Treed-It building (concrete core, glulam structure). Figure by ©Abrahamsen et al. (2020).

Probably the first ambient vibration tests (AVT) on a timber-frame building were performed by Ellis & Bougard (2001). The tests were conducted on a full-size, six-storey timber framed structure constructed inside BRE's Cardington laboratory. They performed both Forced Vibration Tests and Ambient Vibration Tests at different stages of construction, which allowed to evaluate the contribution to the global stiffness of the timber frame alone, the contribution of the staircase, and that of the finishing and cladding (bricks). The results of their research indicate that the building's non-structural components play a large role in the contribution to the lateral stiffness of the building at service levels. More recently, some other researchers have attempted to extract the modal properties of mid-rise timber buildings (Reynolds et al., 2011; Feldmann et al., 2016) using OMA methods. The research conducted by Reynolds and colleagues constitutes probably the largest database of AVT performed on timber structures in Europe to date. They tested different types of timber structural archetype: post and beam, timber-framed, pure CLT and hybrid timber-concrete structures. It is also worth to mention the tests performed in Germany and Austria on eight timber observation towers (with a height up to 45m), a 100m tall wind turbine and on three multi-storey residential timber buildings (with a height up to 26m). The findings of all these testing campaigns have allowed to assess the simplified relationship between height and natural frequency for multi-storey buildings given in Eurocode 1.

In North America, where there is a great tradition in wooden frame housing, efforts have been made to understand the dynamic behaviour of smaller low-rise residential buildings. Filiatrault et al. (2002) performed FVT using shake-table testing and highlighted the highly non-linear response of timber framed shear-walls to the amplitude of the excitation and motion induced by FVT. More recently, in Canada, researchers from FPI innovation, and in the U.S. researchers from Oregon University, have tested multistorey residential and commercial timber structures, up to six storeys, using OMA methods. The results of these campaigns have shed some light on the dynamic behaviour of tall timber buildings providing viable information concerning stiffness and damping of the tested structures to designers and stakeholders (Tulebekova et al., 2022). It is the opinion of the author that monitoring mid-rise and high-rise timber structures represents a big opportunity for the whole branch. This will aid in learning important lessons and enhance the confidence of the engineering community towards the use of this material.

Buildings and wind induced vibrations

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As the tall timber buildings are relatively new type of building, their horizontal vibration behaviour is not as well-known as it is for tall steel and concrete buildings. As mentioned, their lower mass and stiffness makes them more prone to wind-induced vibration problems. Few additional differences are that timber connection are often relatively flexible and soundproofing often requires use of flexible vibration isolation layers between storeys. Furthermore, due to lower stiffness of timber, non-structural components can have significantly higher overall stiffening effect in timber buildings compared to steel or concrete buildings. If these additional flexibilities and stiffnesses are not accounted for, it can lead to significant inaccuracies in modelling.

Furthermore, damping is likely affected by these details, and further understanding of their effects would be beneficial for designing more efficient tall timber buildings. Here, few publications related to the topic, although not covering everything, are summarised.

Talja & Fülöp (2016) summarize Eurocode design for wind-induced vibration and presenting some considerations for CLT buildings. In (Tulebekova et al., 2022), the authors investigate the effects of connection flexibility and non-structural components to the wind-induced vibration behaviour of an existing, tall GLT-framed timber building. For the purpose, a detailed finite element model, including non-structural elements, was established (Fig. 1).

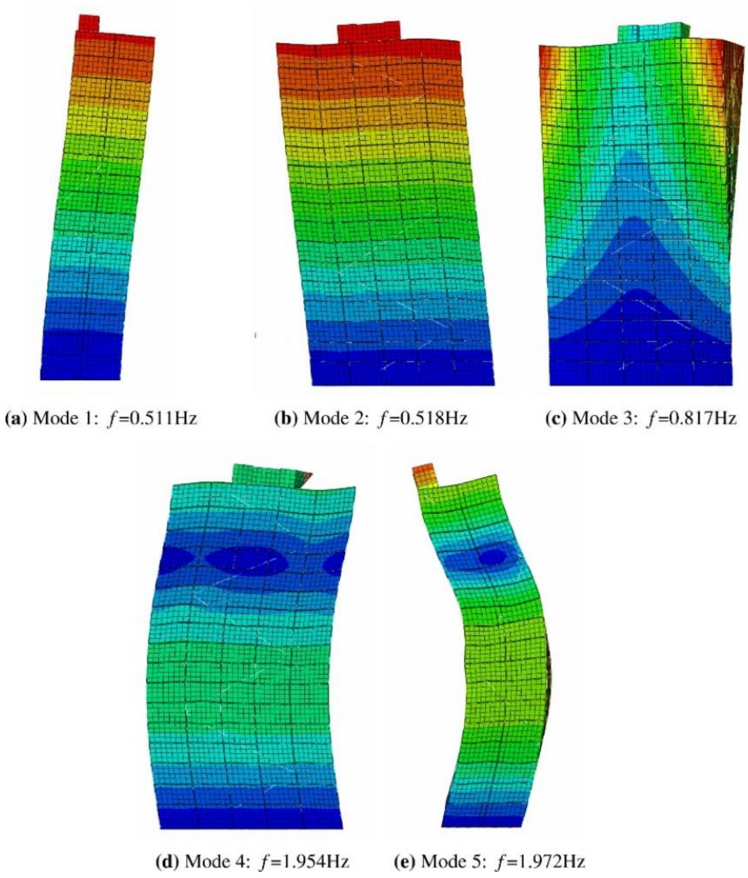

Figure 1: Numerical mode shapes after model updating for the tall timber building. Reproduced from (Tulebekova et al., 2022) with permission from Elsevier®, under the terms and conditions of a Creative Commons CC-BY license agreement, November 2022.

Flexibility of the connections was accounted for by introducing “connection-zones”, of whose stiffness could be adjusted by reducing their cross-sectional dimensions. The connection stiffness parameters were set by calibrating the model against experimental modal parameters from in-situ ambient vibration measurements. The main findings were that natural frequencies were sensitive to connection stiffnesses, especially the axial ones, and the mode shapes were significantly affected by the non-structural partitions, making these two factors important for accurate modelling of the building vibrations.

Reynolds et al. (2016) carried out ambient vibration measurement of 11 timber buildings of 10-49 meters high. Based on their investigations, the natural frequencies display a clear trend with respect to the building height. For damping, although some potential trends can be found, the scatter is very large. Furthermore, damping does not seem to clearly depend on the building type (timber-concrete, timber-steel or all timber).

Feldmann et al. (2016) presented a summary of ambient vibration measurements of 12 tall timber structures, including variety of towers and three residential buildings, with different structural systems. The reported results consist mainly of fundamental natural frequencies and damping ratios for these structures. The authors suggest the observed damping ratios are correlated to mass-ratios of different construction materials, used structural solutions and vibration amplitudes to some degree.

The role of connections on vibration issues

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The exploration of high-amplitude dynamic response of Cross Laminated Timber (CLT) buildings has been the objective of several studies in recent years (Aloisio et al., 2020a; Aloisio et al., 2021; Mugabo et al., 2019; Reynolds et al., 2015). Experimental tests and numerical modelling conducted at the wall and building level proved that the major deformation contribution during the dynamic response of CLT structures depends on the joints and mechanical connections (Ussher et al., 2017; Weckendorf et al., 2016), see Fig. 1. Therefore, the dynamic response of CLT buildings can be distinguished in two phases (Ussher et al., 2022).

In the first level, under low-level excitation, the connections do not activate and the building behaves as an elastic continuum. In the second phase, under higher-level excitation, the connections activate, the global structural stiffness reduces and consequently a reduction in the natural frequencies of the building can be observed.

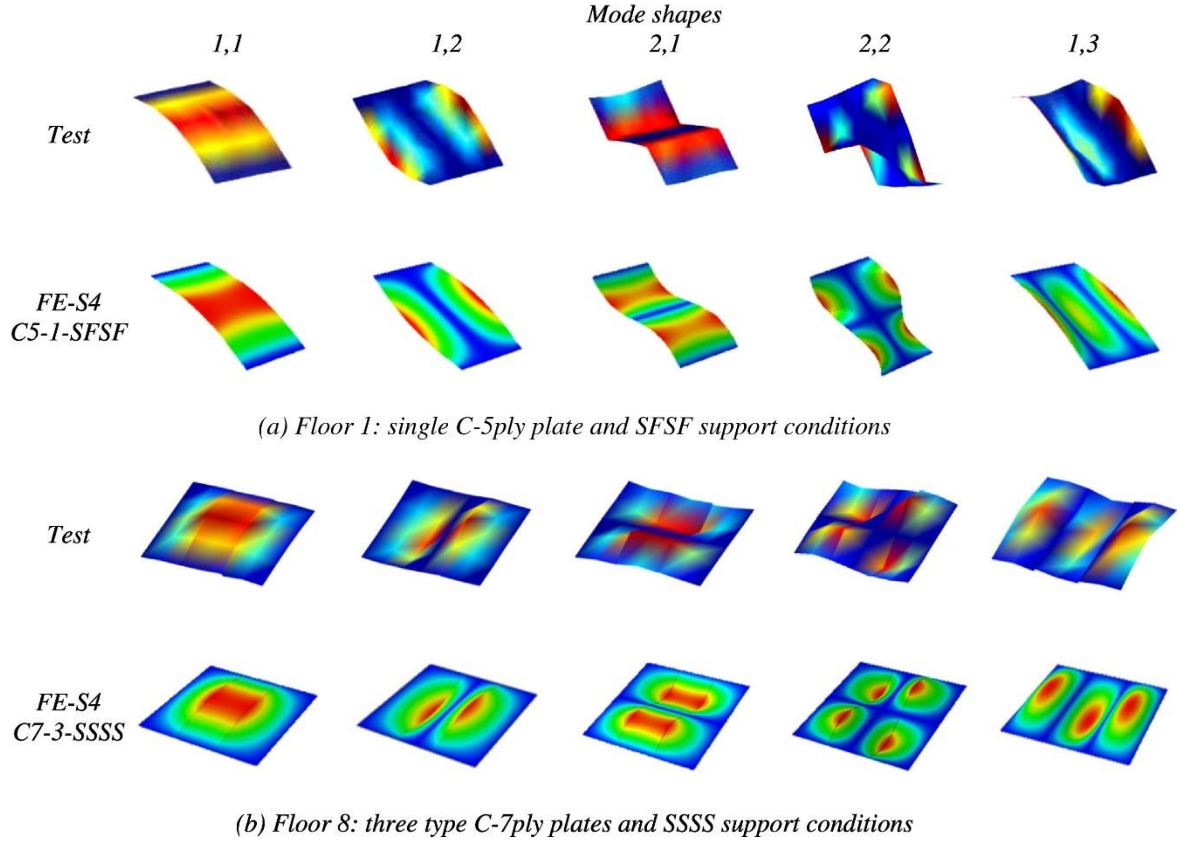

Figure 1: Comparison of test and FE model mode shapes for selected slab systems. Reproduced from (Ussher et al., 2017) with permission from Elsevier®, license agreement 5420840313461, November 2022.

This phenomenon is crucial in seismic engineering to carry out linear dynamic analyses. The practitioner must assume an estimate of the first natural period of the CLT building. However, its variability due to nonlinear phenomena challenges the scholar in choosing empirical expressions for predicting the natural period of CLT buildings.

Casagrande et al. (2021) observed three regions in the dynamic response of CLT: "no rocking," "partial rocking," and "full rocking regions." They measured a 3.7%, 11.2%, and 18.7% decrement of the natural period for one, three, and five-story shear walls, respectively. Parallelly, ambient vibration tests on CLT buildings showed that in operational conditions, the connections do not activate. Accordingly, CLT buildings are very stiff under low-excitation level.

Kurent noticed that CLT floors in CLT buildings behave like rigid diaphragms, in line with research by (Aloisio et al., 2020b) where they concluded that the CLT floors behave like rigid diaphragms for the fundamental modes. Additionally, Aloisio et al. observed that the estimated empirical formulation for predicting the first natural period of CLT buildings in operational condition is similar to the one used for masonry structures according to Italian technical codes. Interestingly, Kurent et al. (2021) showed that the wall-floor joints influence the vertical in-plane stiffness of the shear walls, which is reflected mainly for the lowest modes.

Vibrations and acoustic aspects

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The EU Environmental Noise Directive of 2002 specifically addresses the prevention of environmental noise pollution. The Directive applies to noise to which humans are exposed, particularly in built-up areas. In 2008, the directive was extended to apply to vibration treated as pollution (BS 6472). In the Directive, direct or the indirect influence of vibration, heat or noise in air, water, or the soil are considered pollution. Despite the Directive, both stimuli noise and vibration are not combined together in the context of sustainable indoor comfort. International and national standards mostly treat these factors separately. In the literature and relevant standards, the perception of vibration in buildings has been analysed and studied in depth over the past decades (BS 6841; ISO 2631-1). On the other hand, as suggested by many other authors, the main “discomfort” experienced in buildings seems to be related to a combined effect of noise and vibration. As a matter of fact, noise and vibration occur simultaneously in buildings and, even if the acoustical or vibrational thresholds meet legal or standard limits, their inhabitants nevertheless report annoyance (Nering et al., 2020), see also the experimental setup recalled in Fig. 1.

The evaluation of exposure to two simultaneous stimuli single event (e.g., train pass by) was proposed in work of Nering & Kowalska-Koczwara (2022), based on previous work of Howarth & Griffin (1991), where annoyance level was introduced. Acoustic issues are often representative one of the main problems for lightweight constructions (Fossén et al., 2008).

(a) (b)

Figure 1: Example of (a) microphone measurement position in the tested room, (b) 3-axis accelerometer test position.. Reproduced from (Nering et al., 2020) under the terms and conditions of a Creative Commons CC-BY license agreement, November 2022.

Typical annoying sounds are people talking, television and footsteps. Transmission between a “source room” and a “receiving room” can be airborne or structure borne. Sound energy can reach the “receiving room” through various transmission paths: the separating wall itself could radiates sound energy directly into the receiving room, the separating wall could transmit vibration to the adjacent walls, which in turn radiate energy into the receiving room, the side walls of the “source room could transmit vibrations to the separating wall or to side walls of the receiving room (ISO 12354-1). All sounds that propagate through propagation paths other than direct transmission through the separating wall or floor are called flanking sounds. It is essential to solve the problems of flanking transmission in order to handle the sound insulation. Flanking transmission can be reduced limiting the vibrations transmitted to the walls and floors in the source room, reducing the radiation of sound from the walls and floors of the receiving room and reducing the vibrations transmission from the elements of the source room to the elements of the receiving room (Ljunggren & Ågren, 2013).

The latter strategy requires a complete separation of the construction frameworks of the adjoining apartments from each other. Separation is often achieved using layer much softer than the timber of structural elements above and below the insert. In the vertical direction, the separation is accomplished using an elastic layer between overlapping walls and between floors and walls. However, the layer is subjected to the static load of the volumes above the layer. This means that stiff layers must be used in the lower part of high buildings, increasing coupling and thus worsening the sound insulation (Negreira et al., 2014; Reichelt et al., 2016). Additionally, to prevent acoustic bridges via connections, special soundproofed steel angle brackets have recently been developed, in which the rigid parts are elastically separated from one another using interlayers. Elastomers are frequently used at junctions so as to reduce low frequency noise. Common types include closed cellular polyurethane ("CCP") and mixed cellular polyurethane ("MCP"), see (Azinović et al., 2021). Since the choice of the most adequate properties for the material is of crucial importance, elastomers should be characterized defining Young's and shear moduli for varying load-frequencies. Admissible vertical loads that guarantee the maintenance of the insulating properties and permissible shear strain must also be defined. The coefficient of elastomers on timber can be estimated as $\mu \geq 0.5$ and therefore it is useful to take the load transmission capability of the elastic layers into account and design. Although separation, is an effective solution of the sound insulation problem, it is often not the easiest since there might be a conflict against the building's overall deformability and stability requirements. Therefore, elastic connection must be carefully designed in order to allow the structure to appropriately manage the horizontal wind and seismic loads.

The influence of flexible sound insulation layers on the seismic performance of cross laminated timber walls has been studied by (Azinović et al., 2021). According to the authors the bedding insulation layer under the wall led to only minor changes in the load-bearing capacity of the walls under lower vertical loads but the stiffness of the wall decreased to less than 40% that of the uninsulated wall, due to additional lateral deformations enabled by the insulation. Experiments confirmed that a higher vertical load substantially increases the load bearing capacity, as well as the stiffness of the shear wall, due to the associated increase in friction. The cyclic response of insulated steel angle brackets with inclined and perpendicular screws used for cross-laminated timber connections has been assessed by (Kržan & Azinović, 2021). The monotonic and cyclic tests on the CLT wall-to-floor connections highlighted that insulation under the angle bracket has a marginal influence on the load-bearing capacity; however, it significantly influences the stiffness characteristics resulting in a 22% and 45% reduction of the effective stiffness in pure shear and tensile loading respectively. The relative energy dissipation and equivalent viscous damping coefficient were lower for the insulated specimens than for the uninsulated specimens, but the difference decreases with increasing displacements and repeated cycles. Friction energy dissipation was found. Recently, De Santis & Fragiacomo (2021) proposed an analytical model for the stiffness prediction of screw connection with deformable interlayers. The authors found that for connections with screws inclined with respect to the sliding plane, the slip modulus decreases much slower than for connections with perpendicular screws as the thickness of the intermediate layer increases.

State of the Art on Vibration-based Structural Health Monitoring of tall timber buildings

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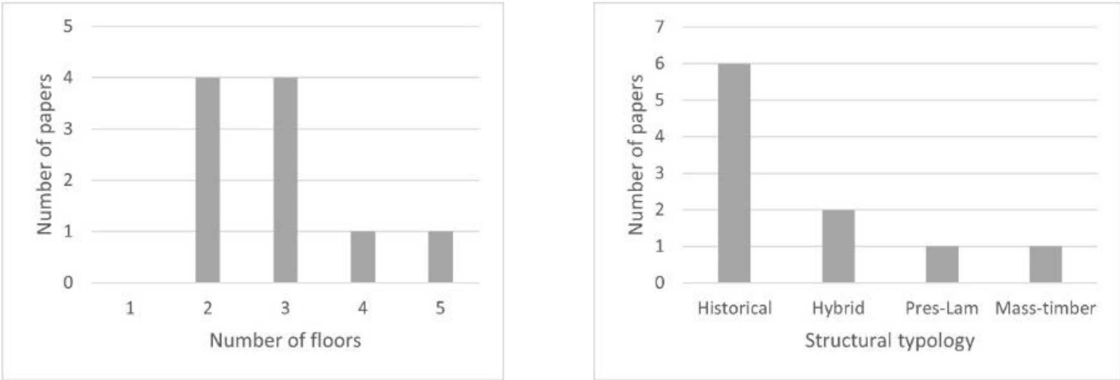
1. Introduction

Vibration-based Structural Health Monitoring (VSHM) aims at tracking in time the dynamic properties of structures, such as modal frequencies, modal shapes, and damping factors, to identify changes in structural behaviour (Farrar & Worden, 2007). The rationale behind VSHM is that the dynamics of a structure depend on its stiffness, mass, and damping properties. Therefore, information about these variables, and their variation in time with respect to a reference condition, can be obtained by studying the evolution of the dynamic response of structures. Traditional VSHM systems are generally composed of hardware components, such as sensors (in general accelerometers), data acquisition systems, cables, transmission systems, and software aimed at processing data, extracting modal parameters and Damage-Sensitive Features (DSFs), and ultimately obtaining damage indices which alert about variations of DSFs between a reference (possibly undamaged) and current state of the structure. In the last decades, VSHM has been employed on different types of civil structures, such as bridges, buildings, damns, and stadia. Several examples can be found in the literature about long-term VSHM monitoring of concrete, metal, and masonry structures. Recently, few papers have been published on earth structures. Nevertheless, the literature on VSHM of tall timber buildings is still in its infancy. This short State of Art aims at providing a general overview of current literature on this topic, highlighting the different uses of VSHM information and specificities of timber in this field, as well as identifying future research needs and directions.

2. State of Art survey

The Scopus database is used to create a list of papers focusing on the topic of VSHM of timber structures (research carried out in October 2022). The list of papers is obtained considering the following keywords: “Timber” AND “building” AND “monitoring” AND ("vibration" OR "dynamic"). This research leads to 66 documents published between 2007 and 2022. For the sake of comparison, considering the keywords “concrete”, “steel”, and “masonry” instead of “timber” leads to 742 (published between 1979-2023), 498 (published between 1985-2023), and 311 (published between 1987-2023) documents, respectively. As for timber, considering only journal papers, the cluster reduces to 23 documents. Following, these documents are analysed one by one: 13 over 23 papers are excluded from the list since they are not available or are considered out of topic. Thus, only 10 papers are further analysed. Most of the case studies presented in these 10 papers relate to short timber buildings, e.g., with 2 or 3 floors, see Fig. 1(a). There are no papers dealing with tall buildings. As for the structural typology, a wide palette of different buildings and timber products is found. Most of the papers investigate the dynamic behaviour of historical buildings while only 4 papers deal with modern constructions, see Fig. 1(b). In turn, different types of modern timber buildings are studied, i.e., hybrid structures (e.g., timber + concrete), Pres-Lam buildings (unbonded post-tensioning tendons in beam-column connections), and mass-timber buildings. Regarding the use of vibration-based data, only three papers focus on the long-term monitoring of structures, while the remaining papers deal with the calibration of numerical models.



(a) (b)

Figure 1: Outcome of the Scopus research.

3. Uses of VSHM information

The evaluation of the dynamic properties of timber buildings can be used for several purposes, such as damage identification, model calibration, and supporting the development of design codes and guidelines.

Damage identification. Damage, such as cracks and reduction of cross sections in structural members, can modify the stiffness of a structure and in turn its dynamic properties (Peeters & De Roeck, 2000). According to the number and location of sensors, the adopted SHM technique, and the types of models employed to describe the structure, different levels of damage identification can be attained. The traditional classification (Rytter, 1993) includes the following levels: (i) damage detection (alert about the existence of damage); (ii) damage localization (find the position of damage); (iii) damage quantification (assess the gravity of damage); (iv) damage prognosis (forecast the evolution of damage).

Model calibration. Modelling the stiffness of timber connection or the story stiffness can be challenging if not impossible in case experimental data are not available. This is especially true for historical constructions, which are generally affected by even higher uncertainty with respect to new structures. For instance, in (Lyu et al., 2017), experimental modal parameters are employed to calibrate a numerical model of a heritage Tibetan timber building. Ultimately, calibrated models can be used for structural assessment purposes.

Development of design codes and guidelines. Since tall timber buildings are relatively new on the construction landscape, the understanding of their behaviour is still limited in comparison with other types of structures. Expanding the knowledge on this type of structure will improve the confidence of designers and ultimately foster the diffusion of tall timber buildings (Ellis & Bougard, 2001). For instance, an important issue is understanding the dynamic behaviour of tall timber buildings under wind excitation to improve serviceability performances (Feldmann et al., 2016; Reynolds et al., 2011). Recently, in the realm of the DynaTTB research program (Abrahamsen et al., 2020), several dynamic tests are being carried out on tall timber buildings to improve the understating of damping properties of these structures and support the development of reliable Finite Element (FE) models.

4. Specificities of timber buildings

The dynamic properties of a structure do not vary only due to the occurrence of damage. Environmental and operational factors (EOFs) can modify the properties of healthy structures. This is a major concern in damage identification because of two reasons. First, EOFs might hamper the identification of structural anomalies. Second, variations in the dynamic behaviour due to EOFs might be erroneously attributed to damage. Therefore, the influence of EOFs on different materials and structural typologies must be carefully investigated. Extensive research on the effect of environmental factors, such as temperature and humidity, has been carried out on concrete, steel, and masonry structures, see e.g. (Magalhães et al., 2012). Operational factors extensively studied include, for instance, human actions and vehicular traffic, see e.g., (Hu et al., 2017). In the case of timber, EOFs are expected to strongly affect its dynamic behaviour. Nevertheless, the research on this topic is quite limited. In addition to temperature and humidity, which have been investigated extensively for other construction materials, one of the main concerns in the case of timber is its Moisture Content (MC). It influences several properties of timber, such as strength, density, and elastic modulus. In (Larsson et al., 2022), the relationship between environmental factors and the dynamic response of a hybrid timber-concrete building is investigated. To this purpose, modal parameters, i.e., modal frequencies, modal shapes, and damping ratios, are tracked continuously for three years together with hygrothermal parameters, i.e., temperature, relative humidity, absolute humidity, and moisture content. The results of the long-term monitoring show that modal frequencies change with the temperature, showing maximum and minimum values in early autumn and early spring, respectively. Instead, damping ratios do not present seasonal variations. As for the MC, it is observed that in addition to seasonal variations, the modal frequencies decrease in the first year after construction due to the drying out of timber elements. In (Granello & Palermo, 2020), the results of a 3-years monitoring campaign on a Pres-Lam building are presented. In this case, the results show that temperature and relative humidity as well as post-tensioning losses do not affect the dynamic behaviour of the structure.

5. Gaps to fill with research

Further research should be conducted in the field of VBMS of tall timber structures due to the lack of experimental data on real structures and knowledge about the structural performance of existing tall timber buildings. The general lack of data can be attributed to the low number of existing tall timber buildings and the - even lower - number of instrumented timber buildings or of experimental tests on full-scale buildings. The influence of EOFs should be better investigated, considering the great variability of timber materials and building typologies, especially hybrid structures. In addition, several timber products, such as cross-laminated timber, are relatively new materials, and their long-term behaviour is yet not known.

6. Conclusions

Despite the great interest in VSHM for civil structures, very limited applications exist in the field of tall timber structures. Despite the Scopus survey does not claim to be exhaustive, it shows that research on this topic is relatively recent and not very widespread, especially in comparison with other construction materials such as concrete and masonry. This is probably due to the limited application of this construction material, especially for tall buildings. Regarding the influence of environmental factors on the dynamic behaviour of timber structures, in the literature conflicting results can be found, probably depending on the large variation in the different timber construction typologies. Therefore, further research on VBMS of timber structures, and especially tall buildings, is recommended in terms of instrumenting more timber buildings and performing long-term monitoring campaigns on different typologies of timber buildings.

Current study on the influence of inter-panel connections on pedestrian-induced vibration of CLT floors

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With developments of new construction techniques and light yet high-strength building materials, vibration serviceability of floors due to pedestrian-induced loading has become a matter of growing concern in the civil engineering (Galbraith & Barton, 1970; Griffin, 1990; Racic et al., 2009; Sedlacek et al., 2006; Živanović et al., 2005). Moreover, the results of conducted experimental campaign (Hamm et al., 2010) showed that a large percent of timber floors that satisfy ultimate limit state design criteria fail to satisfy vibration serviceability assessment (VSA) norms. The influence of the inter-panel connections on both free and forced vibrations of CLT floors is often neglected in numerical modelling, treating a multi-panel floor as a monolith slab or with no inter-panel connections at all (Willford & Young, 2007; Erol & Sylvain, 2019; Eurocode 5). The research conducted within a current phase of Substrate4CLT project (Towards Sustainable Buildings) involves a number of numerical studies designed to examine the influence of the most common connection types on both vibration modes and responses of a range of different CLT floors due to pedestrian-induced loading. Although the connections are relatively complex, the current research involves a simple yet robust model suitable for both 2D and 3D finite element modelling of CLT floors, regardless the plate kinematic model, floor layout and considered walking paths. The model is based on findings of Paolini et al. (2017) and Macpherson et al. (2018). The Canadian CLT Handbook (Erol & Sylvain, 2019) warns that bare CLT floor systems differ from traditional lightweight wood joisted floors, thus the traditional methods and criteria for VSA of lightweight timber floors may not be applicable to CLT floors. Arup's design guideline for footfall-induced vibrations (Willford & Young, 2007), derived from a comprehensive database of recorded walking footfalls, offers a universal VSA framework that applies to any type of floor structure regardless of the material. Their so-called "vibration performance" approach to serviceability assessment advocates the evaluation of a vibration response level. This is radically different from the traditional approach of limiting the static deflection (*w*), the fundamental natural frequency (*f*) and comparing the *w/f* ratio to some prescribed values (Erol & Sylvain, 2019; Eurocode 5). The ongoing research project aims to study vibration levels of various CLT floors using Arup's model of walking loading, where the cut-off frequency between the low- and high-frequency floors is 10.5 Hz. Numerical simulations of various CLT floors carried out so-far showed that different modelling strategies for inter-panel connections provide considerably different modal properties and vibration responses. In case of no inter-panel connection, each panel behaves dynamically as an individual floor. Ideally, the connections would provide a rigid link between the panels, making no difference between a multi-panel floor and the monolith counterpart. In reality, the connections are far from rigid, so some differences in modal properties are expected. The differences in natural frequencies are the biggest for modes in which the modal coordinates are the largest along the connection line, i.e. when the connection line moves dominantly with respect to the rest of the floor. Moreover, the study suggests that the modal properties are more sensitive to the rotational stiffness of the connection than to the bending stiffness. The biggest differences between vibration simulations of the monolith floor and the floors with the panel connections were observed in cases when a pedestrian was walking along the connection line. This means that the connection lines should be kept away from critical walking paths or should be diverted by a clever arrangement of structural and non-structural elements, such as furniture and partition walls. Finally, the connections made a higher impact on the vibration performance of high-frequency floors than low-frequency floors. This is most likely due to fundamentally different nature of the two walking force models pertinent to the two floor types. Question arises which model should be used if a floor happens to have the fundamental frequency equal and even close to the cut-off 10.5Hz. A universal force model that would eliminate the need for the artificial division between low- and high-frequency floors is urgently needed for design of any type of floor regardless the material.

Future research should:

- estimate experimentally rotational, bending and shear stiffnesses of connections from dynamic tests on real CLT floors, to examine if their values are dependent on the vibration amplitude;
- include experimental vibration measurements of real floors which would evaluate more reliably the extent to which CLT floors with connections have different dynamic properties in comparison with how the VSA is carried out in current design practice.

Reduction of the floor deformation and vibration by rational use of timber-concrete composite instead CLT

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1. Introduction

The trend toward using modular buildings in constructing multi-storey timber buildings leads to the need for large spans, which create more challenges in terms of long-term deformations and vibrations. Due to their low bending stiffness, conventional timber floor structures make it difficult to meet these requirements. In contrast, long-span floor structures are a potential field of application for timber-concrete composite (TCC). One of the most widely used structural solutions for timber-concrete composite slabs is the concrete layer with cross-laminated timber (CLT) slab (hereinafter CLT-concrete slab). So, the work aims to check the rationality of the proposed CLT-concrete slab as a floor structure for residential and office buildings compared with pure CLT slabs.

2. Materials and methods

For a more sustainable timber-concrete composite structure solution, the use of synthetic fibres instead steel reinforcement in the concrete layer is proposed (Aydin, 2013). A rigid connection between the fibre-reinforced concrete layer and the wood-base panel realised by the stone chips method (Buka-Vaivade & Serdjuks, 2022) is ensured. The comparison of the CLT-concrete slab and CLT slab is made for the most rational slab cross-sections, which require both ultimate and serviceability limit states. Due to different materials with different properties, especially in weight and price, material consumption cannot objectively characterise the rationality of timber-concrete composite structures. For the mutual comparison of structural solutions, a criterion of rationality has been introduced - the cost factor *c*, which links different types of materials in different variable proportions. The design of timber-concrete composite slabs is carried out by adapting the recommendations from the upcoming rules for timber-concrete composite structures and vibration. Both regulations – "Eurocode 5: Design of Timber Structures — Structural design of timber-concrete composite structures — Common rules and rules for buildings" and "Vibrations" are currently under development within the framework of CEN TC250/N2330 and CEN TC250/SC5 WG3 Subgroup 4. More about the used methodology and developed software for determining the most cost-effective cross-sections of the CLT and CLT-concrete slabs is described in (Buka-Vaivade et al., 2022). The most cost-effective cross-section parameters have been determined using developed software for spans from 3 to 8 meters with a step of 0.5 m at different categories of use and vibration quality classes. For the B category of use, the slabs are designed for 3 kN/m^2 distributed imposed load, for A – for 2 kN/m^2. For results cross-comparison, the total floor width used in the vibration checks is assumed to be 5 meters.

3. Results and discussions

The decisive check is on vibrations for CLT slabs, while for CLT-concrete slabs – ultimate deflections. Therefore, rational parameter values have been determined for CLT slabs at three possible vibration quality classes, but for CLT-concrete slabs only at a higher quality class. In Fig. 1, you can see the symbols used in the graphs in Fig. 2.

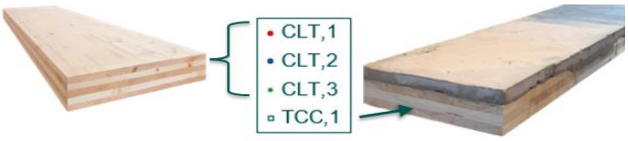
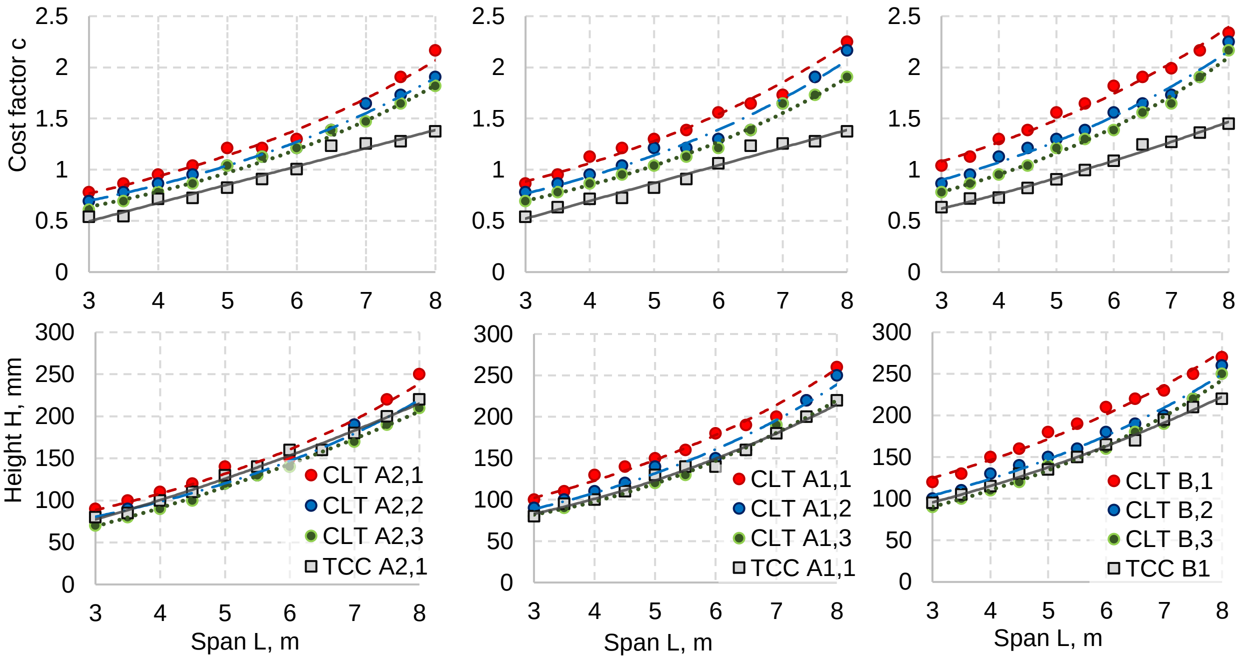


Figure 1: Used symbols for CLT and CLT-concrete (TCC) slabs. 1, 2 and 3 – vibration quality classes, respectively high, base and economic.



(a) (b) (c)

Figure 2: CLT and CLT-concrete (TCC) slab cost factor – slab span and slab height – span curves for the building category of use: a) A2; b) A1; c) B. 1, 2 and 3 – vibration quality classes, respectively high, base and economic, A2, A1 and B – single house, multi-storey residential, office areas.

The determined cost factor is based on the cost of the relevant cross-section material in the Latvian market in 2021/2022, at the turn of the year, for one square meter slab materials. But the developed software provides an opportunity to define the prices of the used materials according to the current situation in the building materials market. For CLT-concrete slabs, the thickness of the concrete layer varies from 20 mm to 85 mm. Such a concrete layer significantly improves the dynamic response of the structure. Summarising the results obtained in the calculations, the use of CLT-concrete slabs, compared to simple CLT slabs, is absolutely justified for the floors of multi-story residential buildings and office buildings at any selected vibration quality class. Such a solution can reduce the proposed rationality criterion - the cost factor in categories A1 and B by 22 % and 23 % on average. And it also almost does not increase the total height of the slab compared to simple CLT slabs that correspond to the economic (third) vibration quality class. In the case of single houses, CLT-concrete slabs can reduce the value of the cost factor by an average of 19 % compared to the most economical CLT slab solution. Still, simultaneously with the cost factor reduction, the slab's total height increases slightly by an average of 6 %. The percentage changes of CLT and CLT-concrete slabs cost factor *c* and total height *H* values compared to CLT slab parameters corresponding to 3, or economic vibration quality class, are summarised in Fig. 3. The benefit of using CLT-concrete in floor solutions increases with higher requirements for vibration quality class, larger spans and more busy areas. At the highest vibration quality class in office-type buildings, the structural solution of CLT-concrete can reduce the cost factor by up to 44 % and the slab height by up to 25 %.

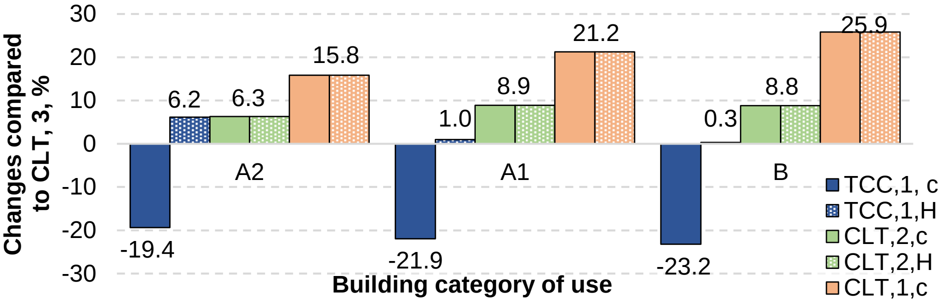


Figure 3: Changes in cost factor c and total height H values of CLT and CLT-concrete (TCC) slabs compared with CLT,3 slab characteristics. 1, 2 and 3 – vibration quality classes, respectively high, base and economic, A2, A1 and B – single house, multi-storey residential, office areas.

4. Conclusions

A comparison of CLT-concrete and CLT slab rationality for use as a floor structure for both residential and office buildings was made. The obtained results show the benefits of using TCC. A concrete layer with a rigid connection to the CLT slab significantly improves the structure's dynamic response. Using TCC reduces floor deflection while simultaneously reducing the overall thickness and cost of the structure.

Acknowledgement

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Quality assessment of timber frameworks joints by the non-model vibration analysis method

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1. Introduction

One of the essential parts of structural analysis and design is the calculation of joints. Joints play an essential role in the behaviour of the building structures. The joints can be classified as the rigid, semi-rigid and pinned dependently on its stiffness. The stiffness of the joints particularly influences the total structural firmness of buildings. The stiffness control of the joints during the building lifetime is essential to ensure that the current situation corresponds to the designed one and that the building is safe. The joint stiffness affects the distribution of internal forces in a structure both in members and joints (ultimate limit state) and deformations (serviceability limit state). The structural health of joints is directly related to their stiffness. Structural health monitoring (SHM) methods enable investigation and testing of structural joints behaviour during the whole service life of buildings. Choice of SHM method depends on the material of the joined structural members, its loading case, joints' structure and stiffness. Since the beginning of the 21st century, many SHM methods have been developed to investigate structural behaviour based on shock and vibration analysis. Vibration analysis methods allow determining possible damages of structural joints based on frequency response, modal shape and damping. Methods of vibration analysis are classified into two categories - methods using ready-made mathematical models and methods that do not employ such the models for vibration analysis (Boscato et al., 2019; Kamgar et al., 2012; Rahgozar, 2020; Fang et al., 2020; Masciotta et al., 2017). The present study aimed to propose a vibration analysis method for the quality assessment of structural joints based on the correlation of coaxial accelerations from sensors orientated coaxially in space. The method does not employ ready-made mathematical models for vibration analysis. A stand composed of timber beams with a moment joint of variable stiffness was developed and tested using the proposed method to verify the feasibility of the latter.

2. Materials and methods

A non-model vibration analysis method for correlating coaxial accelerations was developed. For the initial implementation of the hardware/software system, a method and measurement system implementing the principle of correlation of normalised coaxial accelerations measured in 3-D spwaswere proposed and experimentally tested. The developed measuring device consisted of an electrodynamic actuator, two 3-D accelerometers, a signals amplifier, an Arduino board for signals conversion and transfer, and a computer. The developed measuring setup and its major components are shown in Figure1 (Serdjuks et al., 2021). A non-model vibration analysis method was proposed and experimentally checked. The developed method is based on the mathematical analysis of structural joints' vibrations in 3 spatial directions using 3-D accelerometers located at different joint parts and orientated coaxially. A stand of timber beams was arranged as shown in Fig. 2 (Serdjuks et al., 2021) as a simple model in static loading and vibration test to verify the static diagram of the structure and evaluate the proposed method of coaxial correlations correspondingly. The stand consisted of a girder and an orthogonal beam forming T-connection and made of solid timber of C18 strength class with 150x50 mm cross-sections. The beam was freely supported, one with spans of 2.06 m and two spans of 1.5 m each. The girder and the beam were joined rigidly by steel corners and bolts.

(a) (b) (c)

Figure 1: (a) Developed measuring device; (b) electrodynamic actuator; (c) Arduino board.

(a) (b)

Figure 2: (a) scheme of the timber beams static loading; (b) accelerometers placement near considered joint with an indication of directions for vibration records fixations.

The vibration test examined the ability of the proposed method of coaxial accelerations correlation to determine the stiffness of the joint in the timber beam stand. The decrease of the rigid joint stiffness was modelled by the gradual removal of screws and bolts in the connecting steel corners (Serdjuks et al., 2021).

3. Results and discussions

Seven grades of stiffness were considered. Grade 1 (initial): rigid joint, all screws and bolts tightened. Grades 2-5: rigid joint with the decreased stiffness with gradually loosened screws and bolts. Grade 6 (Fig. 3(a)): pinned joint, with only one bolt. Grade 7 (Fig. 3(b)): absence of the joint between the girder and the beam.

(a) (b)

Figure 3: (a) Grade 6: pinned joint, with only one bolt; (b) grade 7: absence of the joint between the girder and the beam.

The beam was subjected to a vibration load provided by electrodynamics actuators, fixed on the edge of the beam, as shown in Fig. 2(a). Vibration response signals in both parts of the joint, the girder and the beam, were recorded in 3 spatial directions by two 3D accelerometers fixed respectfully on the girder and the beam (Fig. 2) and transferred to the computer. A vibration test was done at all seven grades of the joint. Differences in the vibration signals were noted in three directions: 0-1, 2-3 and 4-5. The highest values of peak values of correlation functions were obtained in the direction 4-5. The vibration experiment confirmed that the differences in vibration signals occur due to loss of the joint stiffness and the decrease of NPVCF values calculated from coaxial correlations reflect the grade of stiffness loss in the joint of the timber beams stand. It was shown that shear stiffness for 1-7 grades of the joint stiffness decreased consequently with the grade. The study showed that the differences between NPVSF parameters calculated based on 3D coaxial accelerometers correlation for the rigid, semi-rigid and pinned conditions of the joints enabled quantification and specification of the joint's shear and rotation stiffness. Analysis of vibration in 3D space enables assessment of the stiffness of joints of planar structures in general cases. For quality assessment of structural joints of spatial structures, the analysis of vibration in 6D space is preferable. It enables the evaluation of shear and rotation stiffness in 6 degrees of freedom (Serdjuks et al., 2021).

4. Conclusions

A vibration analysis method of 3D coaxial accelerometers correlation for quality assessment of structural joints in three spatial directions was proposed. The method is based on the mathematical analysis of natural vibrations of structural joints in 3D spatial directions using 3D accelerometers located at different parts of a joint and oriented coaxially. The method enables the evaluation of the changes of the structural joint's shear and rotation stiffness caused by the damaging or degradation of the joint during exploitation. The proposed method was experimentally tested on the timber T-joint in the rigid, semi-rigid and pinned conditions. It was shown that the difference between the peak values of the normalized correlation functions obtained for the rigid, semi-rigid and pinned joints enabled specification of the joints' shear and rotation stiffness.

Acknowledgement

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Flexible joints for timber structures under wind loading

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1. Introduction

Under the wind action, tall buildings are 3D bluff bodies that cause the flow to separate from the surface of the structure rather than follow the body contour. The asymmetric pressure distribution, created by flow recirculation around the cross section, results in an alternating transverse force as these vortices are shed. If the structure is flexible most wind-induced vibration is exhibited as lateral translation and rotation about the building vertical axis. Linear accelerations are primarily perceived by the vestibular system of the human body whilst angular accelerations are more detectable with visual cues (Rizzo et al., 2021). Two buildings with the same acceleration magnitudes and frequency content can lead to dissimilar performance if the duration of accelerations differs. Finally, the return period also determines the acceptable level of accelerations: a longer return period will naturally allow for higher accelerations to be tolerated.

Several studies have been executed to assess occupants' comfort (Rist & Svensson, 2016) but few studies systematically investigated the effects associated with wind-induced vibrations on non-structural elements, with a focus on specialized elements and smart building systems. The Eurocode has little information regarding comfort requirements for wind-induced accelerations (Eurocode 5). Other standards include some recommendations (Kwok et al., 2015).

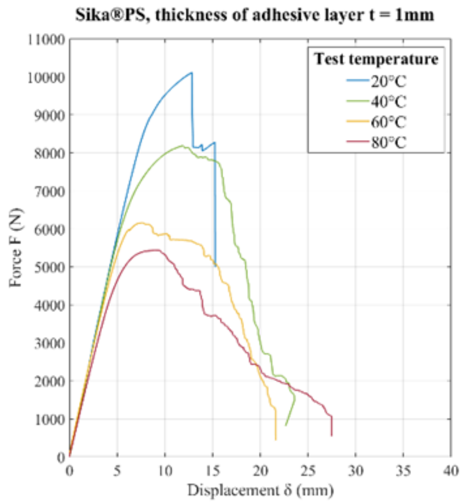
The current trend of increasing the height limits of timber buildings makes wind-induced vibrations a non-negligible issue. Lazzarini et al. (2021) discusses the dynamics of high-rise timber structures focusing on accelerations and comfort assessment of the currently tallest timber building in the world, namely, the 18-storey timber building in Norway. Flexible joints for structure and non-structural elements can mitigate the vibration effects on human safe and costs of repeating or maintaining.

A specific investigation focused on flexible joints for timber structures has been given by (Śliwa-Wieczorek et al., 2020a; 2020b; Śliwa-Wieczorek & Zając, 2021; Kwiecień et al., 2019; Pečnik et al., 2021) with the aim to estimate the force-displacements diagram depending on the temperature and the adhesive layer thickness as it is described in Section 2.

2. Mechanical experiments

The aim of the experimental program was to evaluate the influence of elevated temperature on both the load-bearing capacity of the laminated beams and the deflection. Additionally, the impact of adhesive layer thickness on the structural response of the joint was investigated for four temperature levels: 20°C, 40°C, 60°C and 80°C. In this experimental program, 6 timber beams were tested for each temperature and for each thickness (t = 1, 2 and 4 mm) with a three-point bending test (72 beams in total were tested).

Finite element model of the laminated beams was built and used to compare the measurements from the 3-point bending test. Fig. 1 illustrates the experimental setup and a typical force-displacements diagram for different temperatures.



(a) (b)

Figure 1: Experimental test on wood-adhesive-wood specimens: (a) setup and (b) results

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Human-Induced floor vibrations

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1. Summary

Due to slender but also larger spans in timber constructions, the serviceability of slabs is becoming more and more important. Many contemporary developments have led to the need to pay more attention to areas such as vibration, despite adequate load-bearing capacity. This report aims to provide a summary of the state of the art with regard to person-induced floor vibration. In recent years, more research has been added to the range of walking person measurements. An important issue is the possible modelling. Different types of computational models in the literature are described and also compared in the following. Finally, active and passive options are presented, which are currently used to reduce annoying floor vibrations.

2. Introduction

Products such as cross laminated timber have contributed to the fact that large spans can currently be bridged and the load-bearing capacity no longer plays a role. The decisive factor for constructions in multi-storey residential buildings is often serviceability. Merely increasing the slab thickness to provide sufficient stiffness is no longer a viable option in the context of resource-conserving use of building materials. In relation to structures such as pedestrian bridges or in bridge construction in general, as in (Hamm, 2003) or (Zivanovic et al., 2005), person-induced vibrations have long played an important role. Also in structural engineering, more and more research work is invested in the measurements of human-induced excitation. Laboratory tests combined with field tests and computational models serve as the basis for predicting human-structure interaction (Chiniforush et al., 2019; Hassanieh et al., 2019). In order to properly assess the vibration behaviour of floor elements, models for calculation are necessary in addition to extensive measurements. Realistic models for dynamic effects caused by moving people are currently still a major challenge in the construction industry. Many models refer to the basic research of Bachmann & Baumann (1988). In the draft of the future Eurocode, the dynamic loads of persons are also increasingly addressed.

3. Human-Induced vibrations

The effects of person-induced vibrations have been studied in different materials. In the past, many experiments have been conducted with reinforced concrete elements or other materials, such as in (Hudson, 2013) or (Hudson & Reynolds, 2017). According to the most recent regulations, timber floors must be verified for serviceability limit state, which in case of induced vibration is related to the perception of annoying oscillations caused by walking. The live feel of timber floors is familiar to many, especially in single-family housing with a timber framework. However, this problem is not limited to timber-framed residential buildings: the trends of seeking large open-spaced architectural layouts and adopting new construction practices certainly affect timber floors' serviceability significantly. The ability to predict timber flooring systems' behaviour remains a difficult task and a topical subject. The assessment of timber buildings' vibration performances under walk-induced vibrations and the comfort requirements for users have been investigated by many researchers for many years (Smith et al., 2007; Ohlsson, 1982; Smith & Chui, 1988; Hu et al., 2001; Hamm et al., 2010). This effort has been translated in more recent in standard rules proposal for the new generation of Eurocodes (Hamm et al., 2020). However, the expansion of timber construction also in application where steel or concrete was dominant, could also bring to the need to apply also to timber floors more advance verification approaches that have been proposed for traditional material. The effect of support conditions or vertical partitions should be also taken into account. The vibration behaviour is of course also significantly influenced by the support conditions. For example, in (Huang et al., 2020), the effects of person-induced vibrations on different types of support of CLT elements are investigated. Simulations with the software OPENSEES were compared with laboratory tests.

4. Load consideration for slab structures

An important issue in calculating the effects of person-induced loads is certainly the load models used in the calculation. An overview regarding some models used until 2018 is provided by Muhammad et al. (2019). It is also noted in this research important key parameters of the models for walking individuals. An essential point here is also models for multiple pedestrians. However, a lot of work has also been done in this regard in the last much years. In (Muhammad & Reynolds, 2020), for example, the consideration of different test subjects and thus different types of loading is addressed. Compared to the deterministic approaches based on Fourier series, the probabilistic model of this work is intended to account more realistically for real walking in terms of temporal and spatial characteristics. An important point is certainly the overlapping of the individual steps. In the research work of Cai et al. (2019), these overlaps between successive steps are analysed in a series of finite element simulations and their effects on three different floor plates are determined. That the evaluation of the serviceability of floors currently occurs from a single person's model is addressed in (Mohammed & Pavic, 2019). The authors also address the difficulty of realistically modelling the movement behaviour of multiple people. In this paper, they therefore refer to the social forces model in their simulations to simulate the motion behaviour of multiple people.

5. Passive and active damped slab structures

The use of passive and active systems to reduce problematic vibrations are not inventions of the present. These systems have been used in bridge structures, for example, for decades. This sector is also becoming increasingly important for building construction. Systems such as tuned mass dampers are being investigated, for example, in the research work of Chen et al. (2019). However, the active systems also need to be mentioned in the countermeasures regarding undesirable person-induced swinging. Passive vibration dampers in bridge structures are not uncommon. In building construction, more research is also being done in this area. For example, in (Huang et al., 2021), a rotating inertia damper with double tuning is proposed, which introduces an inert-based cubic control system to better match human-induced floor vibrations. However, adaptive passive systems are also used in some cases. For example, an adaptive passive multiple TMD system with variable mass is investigated in (Wang et al., 2020). The results of this research show that the system can return itself independently, providing the best vibration control. Active solutions have been less investigated for timber floor structures at present. In general, the existing literature is mainly based on other materials. This means that timber construction certainly has potential upside in this area. As in works by Díaz & Reynolds (2010) or Wang et al. (2018), special control laws of active countermeasures of person-induced vibrations in floors and bridge structures are addressed.

Effects of the support conditions on timber floor vibrations

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1. Introduction

Serviceability issues of timber floors are commonly related to vibrations, especially for longer span floors. Conventional approaches for ensuring adequate vibration serviceability involve limiting responses of the floors, such as static load deflections, natural frequencies and impulse response magnitudes, or combinations of those (Toratti et al., 2018). It is widely accepted that the supports play an important role in the vibrational response of the floors, but there exists no clear guidance for design. Typically, the supports on the edges of timber floors are assumed as either ideally pinned or free. For example, Eurocode 5 does not give guidance for any other scenario. However, many existing studies indicate that the assumption of a pinned connection is not always valid, and the supports can exhibit significant vertical flexibility and/or rotational stiffness. Both affect the static and dynamic responses of the floor, leading to different results when compared to the theoretical predictions. These two non-ideal conditions are shortly reviewed and discussed.

2. Vertical flexibility of the supports

Vertical support flexibility decreases the overall stiffness of the floor, leading to lower natural frequencies and higher static deflections. There are many causes for vertical flexibility, such as (i) vibration isolation layers, (ii) floor supported by mechanical connectors, (iii) flexibility of supporting structural members (e.g., beams, walls, or columns) and (iv) incomplete contact interfaces. Use of vibration isolation layers, placed between the floor and the supports, is a common method to mitigate sound transmission problems in timber buildings (see Figure 4 (a)). The behaviour of timber floors supported with and without vibration isolation interlayers were compared in Jarnerö et al. (2012), Bolmsvik & Brandt (2013) and Basaglia (2019). The main trend is that vibrational isolation interlayers tend to decrease the natural frequencies and increase damping ratios of the floors. However, the effects can be even opposite for some vibration modes and test setups had large variety, so no complete conclusions can be drawn from these studies. Bolmsvik & Brandt (2013) mention that the mean acceleration levels of the floor increased significantly below 40 Hz frequencies, when interlayers were used. Besides that, also the use of mechanical connectors to support the floor (Figure 4(b)) can affect the vibrational behaviour (e.g., Chui et al., 2004).

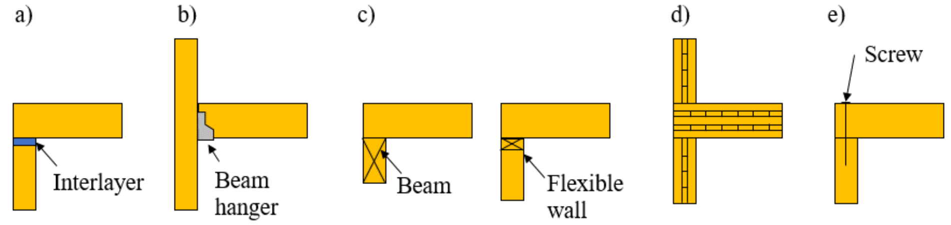

Figure 6: Examples of timber floor edge details inducing vertical flexibility (a, b, c) and rotational restraints (d, e).

Vertical flexibility can also result from the flexibility of the supporting member (Fig. 1 (c)) or incomplete contact interfaces. The effect of supporting beams has been already well recognized and is included in the current draft of Eurocode 5 revision. The effects of other types of components, however, are typically neglected. The authors' own investigations on two-way timber-concrete composite plates (Jaaranen & Fink, 2022) indicated pronounced effects from the support flexibility when the plate was supported on a light timber wall. A conclusion from simulation studies was that for accurate results, the support flexibility needs to be accounted for. Furthermore, in two-way timber floor systems, uplift in the corners can lead to imperfect contact conditions, unless the floor edges are tightly fixed to the supports. The response with imperfectly supported edges is different compared to predictions assuming ideal pinned supports on edges.

3. Rotational restraints

Rotational restraint effect increases the overall stiffness of the floor, leading to higher natural frequencies and lower static deflections. These restraints can be due to (i) floor being installed between walls or (ii) floor edges being screwed tightly to the supports. In CLT construction, a common solution is to place the floor panels between the adjacent walls as shown in Fig. 1(d). This introduces rotational stiffness to the joint due to clamping effect. Literature review by Zhang et al. (2019) indicate large differences in the CLT floor stiffness due to rotational restraints caused by different support conditions. According to simulation studies in (Akter et al., 2021), the main factors influencing the stiffness are thickness of the walls and the vertical load in the wall, although other factors, such as floor plate thickness, also have effects. The clamping effect can be also introduced by screwing down the floor plate to the supports (Fig. 1(e)). A variety of test results for CLT plates, clamped to the supports by screws or external force, can be found in Hernández Maldonado (2021). The general trend is that clamping increases stiffness, therefore increasing fundamental natural frequencies, and decreasing static deflection, while damping ratios were independent of the rotational stiffness. The effects and analysis of rotational restraints has been discussed more in general by e.g., Malo & Köhler (2013) and Zhang et al. (2019), with related case studies.

4. Conclusions

Support conditions have a clear impact in the vibration behaviour of timber floors, and assuming conventional pinned supports may lead to significant inaccuracies in the predictions. Vertical flexibility decreases stiffness of the floors and designs may be unconservative. For vibration isolation layers, it is not always clear whether the overall effects are adverse or beneficial for vibration performance, and more investigations may be needed. For other causes of vertical flexibility, the research could be directed for improving and validating analysis methods as well as identifying conditions, in which these effects need to be accounted for. Rotational restraints lead to improved performance compared to pinned assumption. Therefore, there may be a large potential for material savings, if the effect can be accounted for. To avoid under-performance, the rotational restraint effects could be validated under in-situ conditions.

Modelling timber building elements by Finite Element Analysis

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1. Introduction

Timber buildings are prone to annoying vibrations and low-frequency impact sound. Moreover, the design in terms of serviceability is generally largely influenced by its vibration performance (Dolan et al., 1999). Hence, improvement of floor performance and, consequently, reliable prediction tools are necessary. Often, timber floor vibration characteristics are evaluated by empirical criteria or simple formulas using only the fundamental frequency or other measures in combination with it. Nevertheless, it has been shown that higher order modes should be included (Alvis et al., 2001). Therefore, numerical methods, e.g., the finite element (FE) method, offer a good alternative but require to be tuned to fit the experimental data. The following report gives a short overview of recent advances in FE modelling of timber floors and buildings and its difficulties.

2. Model Updating

Experiments validate the applicability of a chosen model; however, usually, models do not represent the experimental results accurately at the first guess. Therefore, model updating is performed to match measurements and simulations well. In the process of model updating, parameters of significant variability are tuned by an iterative procedure to optimize an error function that represents the problem at hand best (Mottershead et al., 2020). Generally, for vibration analysis, accurate stiffness- and mass-related parameters are required, which are tuned by means of eigenfrequencies and mode shapes. Basaglia et al. (2020) used the natural frequency error for the eigenfrequencies and the modal assurance criterion (MAC) to compare the mode shapes, which are common measures. By means of this, a sufficient match of numerical and experimental data is often possible for the first couple of modes, e.g., less than 6 % for the natural frequency error and a MAC-value above 0.73 in (Basaglia et al., 2020). However, if damping comes into play, the model updating becomes more complex since frequency response functions (FRFs) are utilized. FRFs are computationally more expensive to calculate, and many different damping models exist, making it harder to identify an appropriate setting. When using FRFs, criteria such as the Cross Signature Assurance Criterion (CSAC) or the Cross Signature Scale Factor (CSF) are used as a measure for comparison (Marinone et al., 2014). Nevertheless, an accurate match is often difficult to achieve in terms of FRFs (see, e.g., (Qian et al, 2019)). For an accurate prediction tool of vibration levels and sound insulation properties, not only eigenfrequencies and mode shapes are necessary, but also vibration amplitudes, which depend on damping. Mostly, measured damping values or parameters given in standards are taken as an easy alternative to damping-related model updating (see, e.g., (Basaglia et al., 2020)). However, further improvement of the prediction tools can be achieved by fine-tuning damping properties in the used FE models.

3. Stochastic Investigations

Furthermore, variations of input parameters for the models give deeper insight and provide a safety margin for the numerical results. To this aim, often Monte-Carlo simulations are performed (see, e.g., (Persson et al., 2019)). Furthermore, generalized polynomial chaos expansion can be used to calculate the stochastic vibration response (Sepahvand et al., 2012) or, additionally, identify uncertain material properties (Sepahvand et al., 2014). Probability distributions are then considered for the inputs, and samples are drawn to compute the response in terms of statistical properties such as confidence intervals. Moreover, to analyse which parameter's uncertainty might lead to strong variations in the response, sensitivity analyses are conducted. In (Basaglia et al., 2020), high sensitivity coefficients have been identified for some of the material properties as well as the support conditions. Furthermore, joints have a great influence on vibroacoustic behaviour (see, e.g., (Chocholaty et al., 2022)).

3.1. Material Properties

Material properties have a large influence on the resulting vibrations. The in-plane moduli of elasticity, density, and Poisson ratios reveal large sensitivity coefficients with respect to the eigenfrequency of the structures. On the other hand, the modulus of elasticity through the thickness of a, e.g., plate, as well as shear moduli G_{xz} and G_{yz}, are assumed to have negligible influence (Basaglia et al., 2020). Furthermore, the material parameters of wood show substantial variation due to its natural characteristic leading to, e.g., growth irregularities or knots (Persson et al., 2019). Consequently, it is essential to consider the variability in wooden material properties in FE analyses.

3.2. Supports

As boundary conditions strongly influence the modal behaviour and the modal behaviour has significant effects on the low-frequency response of structures, the supports of a building element also are an important part of a model. Basaglia et al. (2020) support this by computing high sensitivity coefficients of the observed modes w.r.t. support stiffness, especially in the vertical direction. Additionally, (Pasca et al., 2021) show that although free boundaries are the easiest to simulate, they might be hard to achieve in experimental settings. They further conclude that components at test are susceptible to their supports making it more difficult to find an accurate model.

3.3. Joints

Joints also significantly influence the vibrations and acoustics of a structure. As Persson et al. (2019) point out, variability due to different types of fasteners, as well as variability between nominally identical joints, occur. Moreover, modelling techniques vary strongly and also influence the numerical results. Furthermore, the effects, e.g., friction, within a joint might differ depending on the loading, which indicates nonlinearity. A comprehensive study on the influence of joints of a timber-steel structure, the inherent nonlinearities, and the variation among different fasteners has been studied by Chocholaty et al. (2022). Hence, uncertainties due to the model itself as well as the input parameters, i.e., material properties, supports, and joints, are an essential factor in capturing the behaviour observed by measurements. Persson et al. (2019) found a 4 dB difference for a 90 % confidence interval for the vibration dose value; hence, the inclusion of uncertainties in a prediction tool could make a difference in a design engineer's decision.

4. Application to taller timber buildings

Generally, the dynamic properties of a tall timber building are not known beforehand, which is why the fundamental frequency is often vastly underestimated. Currently, modal properties of buildings are identified on-site by means of ambient vibration testing or, as recently done, by input-output modal testing (Kurent et al., 2021). However, testing tall buildings is costly and complex. Therefore, modelling approaches could offer a good supplement during construction or even a handy tool in the design process. Consequently, further research in modelling taller timber buildings and on single timber building elements could benefit the overall design process.

5. Conclusions

As explained before, the design process of taller timber buildings can take advantage of elaborate modelling approaches. Those models can be built upon accurate models of single timber components. In this context, the uncertainty of materials, supports and joints are essential parameters that might improve the design and performance of timber buildings in acoustic as well as vibrational sense. Since experimental studies validate the models, model updating processes also amount to an important part. Hence, future studies can deal with the inclusion of models in the design process of taller timber buildings considering all available data.

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