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Vibration issues in timber structures: A state-of-the-art review

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ABSTRACT

The increasing use of timber structures worldwide has brought attention to the challenges posed by their lightweight nature, making them more prone to vibrations than more massive structures. Consequently, significant research efforts have been dedicated to understanding and mitigating vibrations in timber structures, while scientific committees strive to establish suitable design regulations. This study aims to classify and identify the main research themes related to timber structure vibrations and highlight future research needs and directions. A bibliometric-based selection process briefly introduces each research topic, presenting the latest findings and proposals for vibration design in timber structures. The paper emphasizes the key outcomes and significant contributions to understanding and addressing vibration issues in timber structures. These findings serve as valuable guidance for researchers, designers, and regulatory bodies involved in designing and assessing timber structures subjected to vibrations.

1. Introduction

Timber, widely appreciated for its sustainability, low cost, and satisfactory structural performance, is becoming an increasingly attractive material in the field of civil engineering [1]. Its minimal carbon footprint, coupled with the speed and efficiency of timber construction, presents a compelling response to environmental and economic pressures. However, the growth in the use of timber structures has led to a greater awareness of the unique challenges associated with this material, notably vibration issues due to its intrinsic lightweight nature. For instance, the rapid development of high-rise timber buildings introduces new complexities, as engineers and designers are tasked with managing the effects of wind and corresponding vibration issues on a scale previously unseen [2].

The principal objective of this manuscript is to conduct an in-depth exploration of these vibration issues in timber structures, with an emphasis on identifying novel insights and articulating the significant research gaps that remain. Leveraging a bibliometric analysis, the paper organizes an extensive array of studies, thereby offering a comprehensive perspective on this multifaceted topic. The discussion revolves around two central domains: flooring systems and whole buildings, each with distinct challenges and

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List of symbols and notations

ANN	Artificial Neural Network
AVT	Ambient Vibration Test
a_i	ith member centre of mass distance from the composite section centre of mass
a_{peak}	Peak acceleration response
a_{rms}	Root mean square acceleration
a_{rmq}	Root mean quad acceleration
b	Floor width
b_b	Width of the building
b_{ef}	Effective floor width
c	Damping coefficient
c_{fw}	Force coefficient
CFD	Computational Fluid Dynamics
c_f	Fourier coefficient of the dynamic load factor, which can be assumed equal to $c_f = 0.0714$
CCP	Closed Cellular Polyurethane
CLT	Cross-Laminated Timber
EU	European Union
$(EI)_L$	Longitudinal bending stiffness of the floor per unit of length
$(EI)_T$	Transverse bending stiffness of the floor per unit of length
EC5	Eurocode five
EOF	Environmental and Operational Factor
EMA	Experimental Modal Analysis
FVT	Forced Vibration Test
FE	Finite Element
F	Force applied in the point with the greatest deflection
F_p	Force corresponding to a person walking on the floor $F_p = 700$ N
F_{dyn}	Vertical dynamic force caused by a walking person, equal to $F_{dyn} = 50$ N
f_1	Fundamental floor frequency in Hz
$f_{1,lim}$	fundamental frequency limit
f_{lim}	Limit frequency between the resonant or a transient response in Hz
f_w	Walking frequency in Hz
$\Phi_{1,x}(z)$	First mode shape of the building as a function of the height z
GLT	Glued Laminated Timber
h	Cross-section height
h_b	Height of the building
$I_{mod,mean}$	Mean modal impulse, in N s
K_p	Peak factor
$k_{e,1}$	Frequency factor in case of a double span floor on rigid supports. In case of a single span $k_{e,1} = 1.0$
$k_{e,2}$	Frequency factor to consider the effect of the transverse floor stiffness. In case of a one-way spanning floor $k_{e,2} = 1.0$
k_{red}	Reduction factor
k_{res}	Factor to account for higher modes of vibrations
l_2	Shorter span of a double-span floor
LVL	Laminated Veneer Lumber
LCA	Life Cycle Assessment
l	Floor span (the longest span in case of double span floor)
μ	Resonant buildup factor, which may be taken as $\mu = 0.4$
m	Floor mass per unit of length
MCP	Mixed Cellular Polyurethane
MCDA	Multi-Criteria Decision Analysis

opportunities that influence the overall performance and applicability of timber structures. Through a meticulous examination of the existing literature and by identifying current research gaps, this paper seeks to serve as a comprehensive reference for researchers, designers, and regulatory bodies.

M^*	Floor modal mass
M_1	Modal mass of the first mode
OMA	Operational Modal Analysis
$q_{z,ref}$	Reference wind load
RMS	Root Mean Square
R	Resonance response factor
S	Percentage of decrease in structural rigidity
SHM	Structural Health Monitoring
SEL	Sound Exposure Level
SMA	Shape Memory Alloy
TMD	Tuned Mass Damper
t	Elapsed time in years from timber bridge construction
VDV	Vibration Dose Value
$v_{1,peak}$	Peak velocity response for the fundamental mode
w	Load deflection
$w_{1\ \text{kN}}$	Maximum deflection due to a vertical static point load of 1 kN
w_{lim}	Limit of maximum deflection due to a vertical static point load of 1 kN
ζ	Modal damping ratio

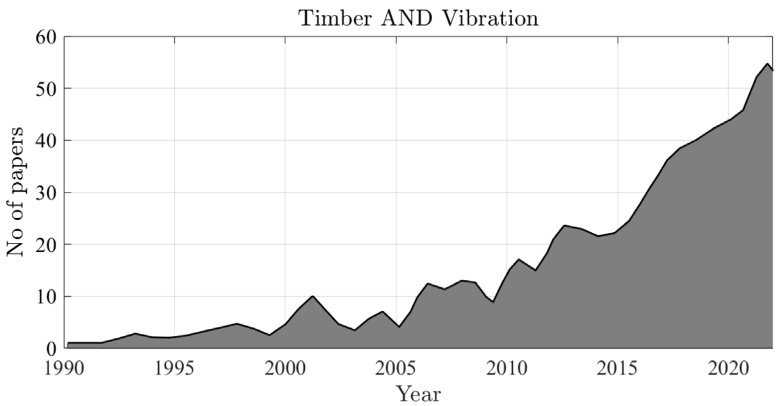

Fig. 1. Total number of publications obtained by reviewing 572 papers.

The remainder of this paper embarks on an exploration of these two domains. Section 2 presents the bibliometric analysis that forms the backbone of the review's structure. Section 3 is dedicated to flooring systems, with an overview of general vibration issues and their serviceability implications. The paper proceeds to investigate various modelling approaches, along with innovative design and vibration mitigation techniques. This leads to examining specific flooring systems, such as Cross Laminated Timber (CLT) and composite floors, before concluding with an analysis of timber bridges, herein assimilated to long-span floors.

Section 4 broadens the scope to encompass whole timber buildings, emphasizing high-rise structures. The importance of construction solutions in managing the vibration performance of these buildings and the pivotal role of lateral resisting systems are dissected. The apparent lack of specific serviceability criteria for whole buildings signals a significant research need, especially in the context of wind-induced vibrations. This section culminates with a review of recent experimental investigations, highlighting both their contributions and limitations and pinpointing areas ripe for innovative approaches. Finally, Section 5 synthesizes the key findings from the previous sections and outlines future research directions.

2. Bibliometric analysis

A list of papers was created using the *Scopus* database, excluding the conference papers and book chapters to initiate the exploration of timber structures. The Scopus list was obtained by employing specific keywords, namely "Timber" and "Vibration", resulting in 571 items. The analysis was carried out in October 2022. The authors conducted a bibliometric analysis of the compiled list in the subsequent step. The analysis provided valuable insights into the trends and patterns within the field. Fig. 1 showcases the total number of publications per year. Notably, the scientific production in timber structures is increasing over time.

Fig. 2 shows the pie charts of the main research objectives and methods referred to the selected last five-year research papers. In detail, Fig. 2(a) shows that 42.5% contribution in the last five years focuses on floor vibration, while 36.9% and 20.6% on building

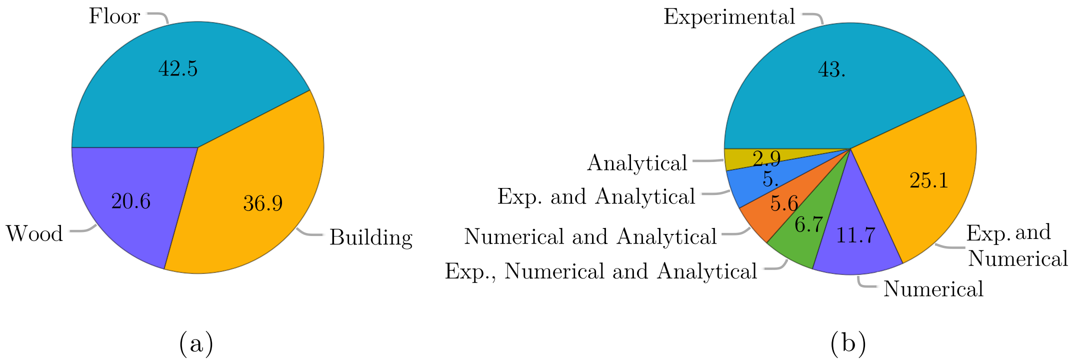

Fig. 2. Pie charts of the main research (a) objectives and (b) methods referred to the selected last five-year research papers.

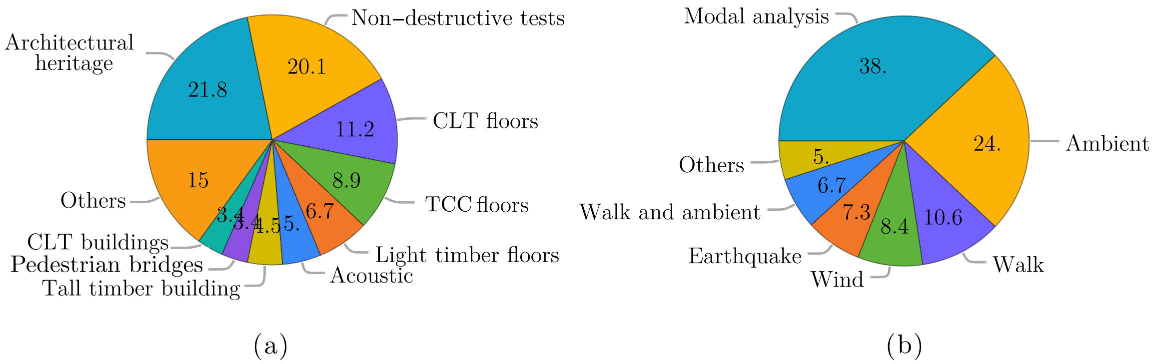

Fig. 3. Pie charts of the (a) main research topics and (b) vibration sources referred to the selected last five-year research papers.

and wood vibration issues, respectively. This finding is also in line with past research trends. The topic of floor vibration is the most studied and received more attention from the code-makers, as shown in Section 3. The papers referred to non-destructive tests do not explicitly address the vibration issues of timber but exploit vibration to estimate mechanical parameters. Fig. 2(b) confirms a peculiar aspect of timber engineering, showing the prevalent methods, namely experimental, analytical-numerical, or a combination. The difficulty in accurately grasping the response of timber structures, characterized by all sorts of uncertainties, generally persuades the researchers to prefer experimental rather than simulated investigations. Consequently, many selected papers present experimental studies without model validation/calibration (43%).

Fig. 3 shows the pie charts of the leading research topics and vibration sources considered in the selected last five-year research papers. Fig. 3(a) reveals the increasing research interests in CLT, both at the floor and building levels. Many papers are dedicated to vibration tests for timber grading, showing the importance of vibration-based methods for timber grading next to those based on visual inspections. Regarding excitation sources, 24% of the papers report results relevant to ambient vibration tests. Approximately 7% of the selected documents consider earthquake excitation.

Despite the great interest and the significant effort dedicated to studying the vibration of civil structures, the research on timber buildings, and even more on tall timber buildings, is still limited in comparison with other building materials. To analyse this gap, the Scopus database is used to create three lists of papers considering the following sets of keywords: (1) timber AND building AND vibration; (2) steel AND building AND vibration; (3) concrete AND building AND vibration. The first set of keywords leads to 481 documents published between 1970 and 2023, while the second the third sets lead, respectively, to 2140 documents published between 1925 and 2023, and 2909 documents published between 1957 and 2023. Fig. 4(a) shows the number of documents published yearly, while Fig. 4(b) displays the cumulative number of documents over time. Before 2010, documents focused on timber buildings were relatively rare. Also, the documents on timber buildings are generally lower than those on other structures.

3. Timber floor vibration

This section delves into the current research trends and perspectives that shape the understanding of timber floors, commencing with general concepts and gradually narrowing the focus to specific, innovative applications. It begins with a discussion on general vibration issues. The discourse then shifts to the serviceability criteria that dictate the practical use of timber floors. This leads to an exploration of diverse modelling approaches employed in the field. The discussion continues with design and vibration mitigation techniques, illustrating how theory moves into practical application. The focus then moves to specific floor typologies, including CLT

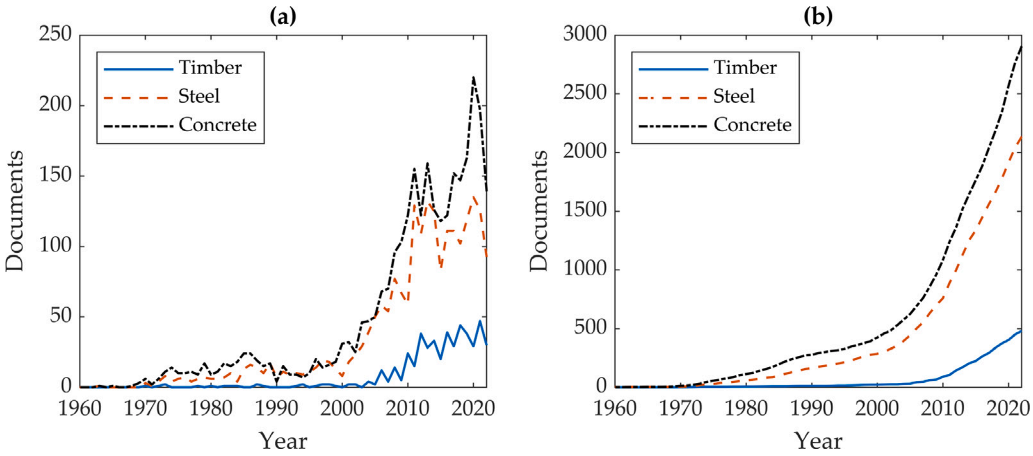

Fig. 4. Results of literature analysis: (a) number of documents published per year; (b) cumulative number of documents in time.

floors and composite floors. These flooring systems have experienced increased popularity over the past two decades, making them a pivotal part of this discussion. The section concludes with an examination of timber bridges. Despite timber's known durability limits as a construction material, there is significant interest in timber for pedestrian bridges, as highlighted by numerous recent applications.

3.1. General vibration issues

The vibration issues of timber floors can be categorized based on the frequency range under investigation. The low-frequency issues are related to the interaction with human activities (walking, running, e.g.), while the high-frequency ones mainly refer to the audio-frequency spectrum. Accordingly, this subsection is divided into two parts: human-induced vibration issues and floor acoustics.

3.1.1. Human-induced vibration issues

Timber floors are particularly susceptible to human-induced vibrations, which can give rise to various issues affecting their performance and occupant comfort. One significant issue is the potential discomfort experienced by occupants due to excessive vibrations. When timber floors resonate with the walking pace or other human activities, it can increase vibration amplitudes, causing discomfort and even affecting the usability of the space. Excessive vibrations can lead to discomfort while walking, using furniture, or performing tasks that require stability [3].

Dynamic amplification is another issue related to timber floor vibrations, particularly in long-span applications. Due to timber's lower density and stiffness than other construction materials, timber floors can exhibit greater flexibility, leading to potential dynamic amplification of vibrations. This dynamic amplification can result in increased vibration amplitudes, reduced occupant comfort, and even compromised functionality of sensitive equipment. It is crucial to address this issue to ensure the satisfactory serviceability of timber floors [4–10].

Human-induced vibrations in timber floors can also impact the functionality and performance of sensitive equipment and installations. In spaces where delicate instruments, equipment, or machinery are present, excessive vibrations can cause operational issues, measurement inaccuracies, or even damage to the equipment. This issue is particularly relevant in environments such as laboratories, healthcare facilities, and industrial settings where precise measurements and stable conditions are necessary [11].

Another concern is the potential fatigue and degradation of timber elements caused by prolonged exposure to excessive vibrations [12]. Over time, repeated dynamic loading can lead to fatigue failure, and reduced strength, and durability of the timber floor system [13–15]. This issue can compromise the long-term structural integrity of the floor and may require maintenance or strengthening interventions [16,17].

Additionally, the perception of vibrations in timber floors can vary among individuals, and some occupants may be more sensitive to vibrations than others. This issue highlights the importance of considering occupant comfort and well-being in the design and assessment of timber floors, as individual sensitivity can influence the acceptability of vibrations in different contexts [18].

Addressing these issues requires a comprehensive understanding of the dynamic behaviour of timber floors and the factors influencing human-induced vibrations. Experimental studies, such as impact tests and field measurements, play a crucial role in assessing the vibrational performance of timber floors and identifying potential mitigation strategies.

By considering these specific issues related to human-induced vibrations in timber floors, researchers and designers can develop effective design approaches, including appropriate damping measures, structural optimisation techniques, and user guidelines, to ensure the satisfactory serviceability, occupant comfort, and long-term performance of timber floor systems [19–23].

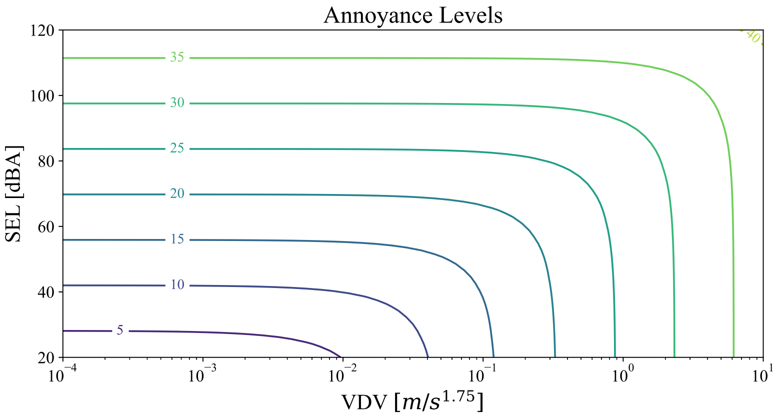

Fig. 5. Graphical representation of annoyance level (isolines) as a function of sound exposure level (SEL) and vibration dose value (VDV).

3.1.2. Floor acoustics

The EU Environmental Noise Directive of 2002 specifically addresses the prevention of environmental noise pollution. The Directive focuses on noise to which humans are exposed, particularly in built-up areas. In 2008, the Directive was extended to include vibration as a form of pollution [24]. The Directive considers the direct or indirect influence of vibration, heat, or noise as pollution. However, despite the Directive, noise and vibration are often treated separately in the context of sustainable indoor comfort. International and national standards typically address these factors individually. In the literature and relevant standards, the perception of vibration in buildings has been extensively analysed and studied over the past decades [25,26]. However, many authors suggest that the main discomfort experienced in buildings is related to a combined effect of noise and vibration. Noise and vibration co-occur in buildings, and even if the acoustic or vibration thresholds meet legal or standard limits, occupants can still report annoyance [27]. Nering et al. [28] proposed the evaluation of exposure to simultaneous events based on research by Howarth and Griffin [29]. They presented a graphical representation of the annoyance level as a function of Sound Exposure Level (SEL) and Vibration Dose Value (VDV) (Fig. 5). Acoustic problems are prevalent in lightweight constructions [30–32]. Typical annoying sounds in buildings include people talking, television noise, and footsteps. Transmission between rooms can occur through airborne or structure-borne paths. Sound can reach the listener's room through various transmission paths, such as direct radiation from the separating wall, transmission of vibrations to adjacent walls, or transmission of vibrations from side walls of the source room to the partition or side walls of the listener room [33]. Flanking sounds refer to all sounds propagating through partition walls or floors, and solving flanking transmission problems is crucial for effective sound insulation.

Olsson [34] recently investigated the impact sound transmission of lightweight timber floors. The study focused on transmission and insulation without reverberation using fluid elements connected to reflection-free boundaries. The results showed that a floor model with a hard screed surface exhibited higher impact force compared to a softer floor [35], although this effect was less pronounced at the lowest frequencies.

Other scholars also developed structural models for predicting low-frequency vibration in light timber floors [36,37]. Reducing flanking transmission involves limiting the vibrations transmitted to the walls and floors in the source room. The goal is to minimize sound radiation from the walls and floors of the receiving room and reduce vibrations transmitted from the source room to the receiving room [38]. Achieving this requires a complete separation of the structural and non-structural parts of the adjoining apartments.

Separation is typically achieved with soft layers, such as floor coverings [39]. An elastic layer is generally used between overlapping walls, floors, and bearing walls in the vertical direction. However, these layers are often subjected to static loads, so stiff layers are recommended for load-bearing structures. One drawback is that stiff layers can increase coupling and reduce the effectiveness of sound insulation [40,41]. Regarding the experimental investigations on floor coverings, Huang et al. [42] investigated the performance of three kinds of elastic cushion materials for timber floors: Portuguese cork, foam, and polypropylene plastic foam board. They found that foam boards exhibit the highest performance. More details about the studies on acoustic issues are detailed when addressing specific aspects of different floor typologies in the following paragraphs. Soundproof steel angle brackets can also prevent acoustic bridges, where interlayers separate rigid parts. Elastomers, such as Closed Cellular Polyurethane (CCP) and Mixed Cellular Polyurethane (MCP), are frequently used to reduce low-frequency noise [43].

While separation is an effective solution for sound insulation, it can increase the overall deformability of the building, potentially compromising its stability, as highlighted by Azinović et al. [43] and De Santis et al. [44]. Specifically, Azinović et al. [43] showed that the bedding insulation layer under the wall negligibly affected the load-bearing capacity under lower vertical loads. However, the stiffness of the wall decreased to less than 40% of the un-insulated wall due to additional lateral deformations caused by the insulation. Experiments also indicated that a higher vertical load substantially increased the load-bearing capacity and stiffness of the shear wall due to the associated increase in friction. The cyclic response of insulated steel angle brackets used for cross-laminated timber connections was assessed by Kržan et al. [45]. The tests revealed that insulation under the angle bracket had a marginal influence on the load-bearing capacity but significantly affected the stiffness characteristics, resulting in a reduction of effective stiffness by 22% and 45% in pure shear and tensile loading, respectively. Furthermore, the insulated specimens exhibited lower relative energy dissipation and equivalent viscous damping coefficient compared to the un-insulated samples, although this difference decreased with increasing displacements and repeated cycles.

The main research gaps are the combined effect of noise and vibration. Often treated independently in standards and regulations, understanding the interplay between these factors and their joint contribution to occupant annoyance is crucial for enhancing indoor comfort.

A related area requiring attention is flanking transmission, which describes sound propagation and vibration via indirect paths in buildings, such as walls, floors, or ceilings. Research into effective strategies to mitigate flanking transmission and bolster sound insulation in timber buildings is needed. Such studies should investigate the influence of varying structural configurations, materials, and connection details on flanking transmission pathways.

The role of floor coverings in impact sound insulation offers another important research area. Evaluating the performance of different floor coverings and their effect on the overall acoustic performance of timber floors is an essential step. As part of this, the effectiveness of various elastic cushion materials in reducing impact noise transmission should be assessed.

Accurate and reliable modelling approaches for predicting the acoustic performance of timber buildings represent another crucial research gap. Finally, experimental studies are vital for validating and refining acoustic design strategies for timber buildings. Thus, there is a call for comprehensive experimental investigations into the acoustic behaviour of timber floors, walls, and other structural elements, studying the impact of different construction details, materials, and connections on sound insulation and vibration transmission.

3.2. Serviceability criteria

Serviceability requirements for timber floors specifically focus on the performance of lightweight floor systems. Standards and guidelines in this regard consider parameters such as velocity and acceleration to assess floor response. The root mean square values (v_{rms} and a_{rms}) are commonly used as they provide an average measure of the response, accounting for the excitation duration. Another metric, known as root-mean-quad (a_{rmq}), is employed for cumulative measurements, particularly in the analysis of the VDV according to standards such as BS 6472 and ISO 2631 [46,47].

These serviceability requirements are defined by threshold values expressed using the response factor R. It serves as a multiplier applied to the base curve value, indicating the level of vibration perceptible to an average human. Different multiples of R, such as 4, 8, and 48, establish various performance levels for the floor system [48].

In the assessment of timber floors, the literature proposes different approaches, considering these parameters individually or in combination. Basaglia [49] distinguishes two main approaches for serviceability assessment based on the floor's intended use:

- Residential Timber Floors: These floors are typically characterized by smaller spans and lighter loads, resulting in higher frequencies. Basaglia suggests employing a pass-fail criterion that considers various parameters such as static deflection, peak velocity, root-mean-square acceleration, or a combination of these factors.
- Office Timber Floors: These floors generally have larger spans and heavier loads, leading to lower frequencies than residential floors. For low-frequency office floors, more detailed procedures have been proposed.

Chang et al. [50] introduced an approach that combines the Response Factor and VDV methods to assess the performance of these floors. Additionally, rules developed by Hamm et al. [51,52] and Abeysekera et al. [53], which are currently incorporated in the draft of Eurocode 5 (EC5), provide further guidance. The synoptic table in Table 1, Fig. 6, and Table 2 summarize these criteria.

The verification is based on two sequential criteria, stiffness and frequency-based. The first step, see Fig. 6(a), is a stiffness-based verification: the designer must verify the floor deflection under a concentrated 1 kN load (w_{1kN}) positioned in the most unfavourable position is below a given threshold. If this criterion is satisfied, the designer must also prove that the first natural frequency of the floor is above a certain threshold f_{lim}, representing the limit between the resonant and the transient response. The typical human walking pace has a dominant frequency (f_w) ranging between 1.5 to 2.5 Hz. Still, to account for the contribution of the higher harmonics, f_{lim} is typically set as four times the walking frequency [54].

Suppose the inequality in frequency is not satisfied. In that case, the designer must verify that the root mean square acceleration and velocity are below the thresholds defined in terms of the response factor R (see Table 2). The verification can limit to a velocity check if the inequality is satisfied. The first two verification steps, stiffness and frequency-based, are illustrated in the diagram in Fig. 6(b) where the y and x-axes show the floor deflection and the first natural frequency, isolating three regions. If the first natural frequency of the floor is below 4.5 Hz, the floor behaviour is not admissible (red). For low-frequency floors, with the first natural frequency between 4.5 Hz and f_{lim} (green region), the designer must satisfy both acceleration and velocity criteria. The sole velocity criterion must be verified in the case of high-frequency floors (light blue region). In the lack of more accurate predictions, EC5 provides simplified expressions of the main parameters (f_1, w_{1kN}, a_{rms} and $v_{1,peak}$) needed to verify the vibration performance of a timber floor.

The synoptic Table 1 resumes all the expressions provided by the current EC5 draft to verify the vibration performance of a timber floor. Eqs. (1) and (3) present the simplified formulations for estimating the first natural frequency and vertical deflection. Table 3 provides the values for the $k_{e,1}$ factor used to calculate the fundamental frequency in case of a double-span floor on rigid supports. The remaining equations estimate the simplified acceleration and velocity responses in the lack of more accurate predictions.

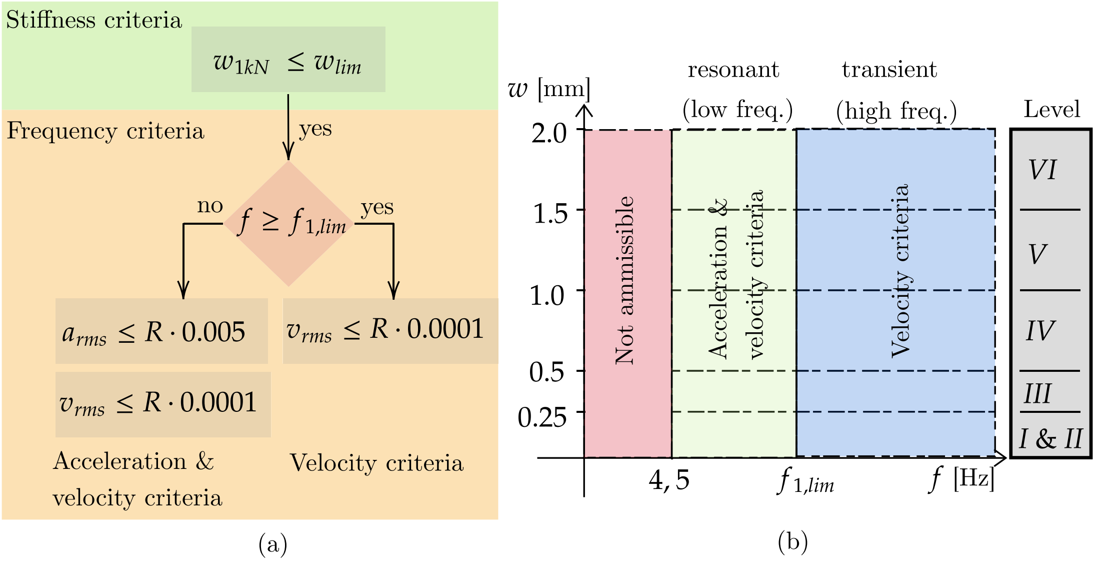

Fig. 6. (a) Pass failure design approach for limiting vibration in timber floor according to Eurocode 5 draft; (b) Floor classification based on the serviceability criteria. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Synoptic table of the mathematical formulation enclosed in the Eurocode 5 draft for assessing the serviceability of timber floors.

Serviceability criteria according to the new Eurocode 5 draft		
Frequency		
	$f_1 = k_{e,1} k_{e,2} \frac{\pi}{2l^2}\sqrt{\frac{(EI)_L}{m}}$	(1)
with		
	$k_{e,2} = \sqrt{\left(1 + \frac{\left(\frac{l}{b}\right)^4 (EI)_T}{(EI)_L}\right)}$	(2)
Deflection		
	$w_{1kN} = \frac{Fl^3}{48\,(EI)_L\, b_{ef}}$	(3)
with:		
	$b_{ef} = \min\left\{0.95\left(\frac{(EI)_T}{(EI)_L}\right)^{0.25}; b\right\}$	(4)
Acceleration		
	$a_{rms} = \frac{k_{res}\mu F_{dyn}}{\sqrt{2}\cdot 2\zeta M^*}$	(5)
with		
	$k_{res} = \max\left\{0.192\left(\frac{b}{l}\right)\left(\frac{(EI)_T}{(EI)_L}\right)^{0.25}; 1\right\}$	(6)
and		
	$F_{dyn} = c_f F_p$	(7)
Velocity		
	$v_{1,peak} = k_{black}\frac{I_{mod,mean}}{(M^* + 70\ \text{kg})}$	(8)
with		
	$I_{mod,mean} = \frac{42 f_w^{1.43}}{f_1^{1.3}}$	(9)
and		
	$M^* = \frac{m \cdot l \cdot b}{4}$	(10)

Table 2
Floor vibration criteria according to the floor performance level.

Criteria	Floor performance level					
	I	II	III	IV	V	VI
Response factor R	4	8	12	24	36	48
Upper deflection limit $w_{1kN} \leq w_{lim}$ [mm]	0.25		0.5	1	1.5	2
Frequency criteria for all floors	$f_1 \geq 4.5$ Hz					
Acceleration criteria for resonant vibration design situations ($f_1 < f_{1,lim}$)	$a_{rms} \leq 0.005$R m/s^2					
Velocity criteria (for all floors)	$v_{rms} \leq 0.0001$R m/s					

Table 3
Factor $k_{e,1}$ to calculate the fundamental frequency in case of a double span floor on rigid supports. l is the longer span, l_2 is the shorter span of a double span floor in m.

l_2/l	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
$k_{e,1}$	1	1.09	1.16	1.21	1.25	1.28	1.32	1.36	1.41

3.3. Modelling approaches

Predicting the dynamic effects caused by moving people is still a significant challenge. The human-floor dynamic interaction model requires the separate modelling of the floor and the individuals. Therefore, this subsection is divided into two parts, the first on the floor modelling and the second on the more complex interaction models. The highest source of uncertainty and greatest challenge stands in the human-floor interaction models.

3.3.1. Floor modelling

A timber floor can be, at first approximation, viewed as a single-degree-of-freedom system: a mass-less simple supported beam with a lumped mass at the mid-span. The main dynamic parameters are the natural frequency and damping. More complex multiple-degree-of-freedom models involve the determination of the contribution of each mode to the floor response. While simply-supported beams and plate models can provide a reliable and rapid estimation of dynamic parameters, more accurate modelling is often necessary for actual structures. In design practice, the finite element models should be used to obtain the modal properties of the floor rather than simplified mechanics-based models, thus avoiding over-design or excessive simplification of the phenomena. Several aspects of actual structures (e.g., support conditions, orthotropic behaviour, physical damping etc.) have been investigated by various authors through experimental and numerical modelling. Typical timber floors are mainly one-way systems. However, in some cases, the construction details can significantly influence the traversal bending stiffness, leading to a more effective two-way system. Jaaranen et al. [55] investigated the two-way LVL-concrete composite floors with various support conditions. The results show that the two-way action can be achieved in some cases, thanks to the performance of the transversal connection joining the adjacent LVL panels.

The assumptions of the simplified models described in the standards, like the pinned connection, are not valid for buildings where moment-resistant joints and the clamping effect of supporting walls in platform systems are present. For example, Akter et al. [56] studied the wall-to-floor connections in the platform CLT system. They assessed the clamping effect due to the vertical load, significantly reducing the floor vibration. Some studies highlighted that the flexural stiffness estimation for vibration assessments should be measured in a reduced portion of the conventional initial load phase that lasts until the reaching of 40% of the maximum force since the vibration occurred under a much smaller loading [57]. The damping also plays a crucial role in these structures. Therefore an accurate characterization is needed. According to Labonotte [58], there are two types of damping: material damping (e.g. internal friction inside the materials) and structural damping, arising from other sources such as friction between components and friction due to connectors. Multiple experimental tests based on the impact method were carried out in the past years to estimate structural damping in timber floors. For timber floors, the correct damping ratio values were indicated by various authors for standard implementation, for example, see [53,59,60]. There is no general research on floor modelling based on classical FE approaches. The dedicated paragraph will give a detailed note on the modelling of the composite floors.

3.3.2. Modelling approaches for individuals

A reliable prediction of floor vibration responses under human activities must rely on accurate walking load models. This approach has been assumed in different vibration design guides for floors [61–64]. In these documents, continuous walking was assumed as a perfectly periodic process described by a Fourier series for a given individual. For example, Basaglia [49] adopted three walking models in a project involving full-scale testing of long-span timber floors to predict the floor responses of a single long-span timber cassette floor.

Many models refer to the basic research of [65]. In recent years, various models for calculating human-induced loads have been created. Muhammad et al. [66] provide an overview of some models used until 2018. The authors mention the two basic load models for individual pedestrians in their paper: deterministic and probabilistic. They underline the importance of the three aspects for evaluating the serviceability of timber floors: the vibration source, vibration transmission path and vibration receiver. Emphasized is the randomness of walking parameters such as walking speed, frequency, weight, etc., and what advantages probabilistic walking

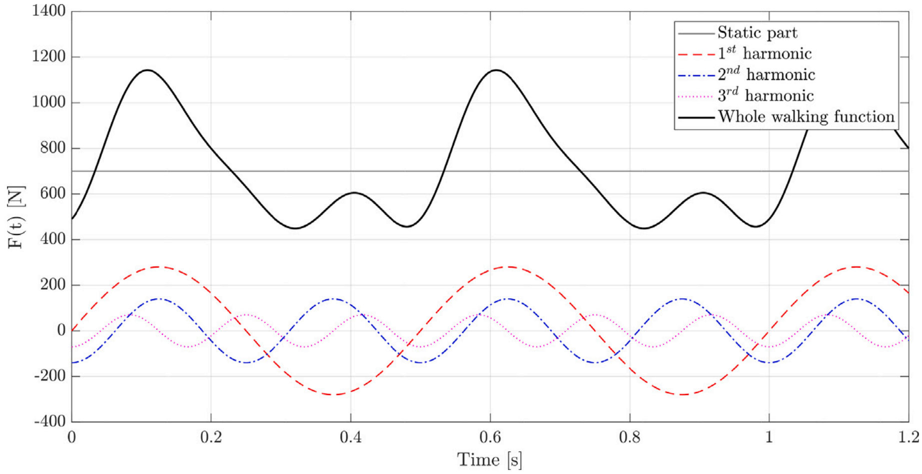

Fig. 7. Deterministic force function of a walking person with the Fourier approach.

models have when statistical approaches are used. The individual load models can be extended to groups of individuals. The models for individuals provide usable loading situations for the serviceability evaluation of the floors.

- Deterministic models: These models use Fourier spectra to describe the movement of people. The weighted superposition of several harmonic components enables the simulation of various walking frequencies. Fig. 7 shows the use of the deterministic approach to model a walking function as a composition of the static part and the first three harmonics. The model corresponds to a walking person weighing 71.3 kg. The static component of the function is denoted as 700 N (F_0). The figure illustrates a function with a walking frequency of 2 Hz. The first three harmonics ($f_1(t)$, $f_2(t)$, and $f_3(t)$) are defined as follows [65]:

$$f_n(t) = c_{f,n} F_0 \sin(n f_w 2\pi t - \phi_n) \tag{11}$$

$$f(t) = F_0 + \sum_{i=1}^{n} f_n(t) \tag{12}$$

  In this case, n represents the number of harmonics, $c_{f,n}$ denotes the Fourier coefficient, f_w represents the fundamental walking frequency, and ϕ_n the phase shift between the harmonics ($\phi_1 = 0$). By overlapping the static and the first three harmonic components, the resulting function is depicted in Fig. 7. Xie et al. [67] developed a deterministic approach to model the peak acceleration in wood–concrete composite slabs and compared it with the results of experimental studies. Casagrande et al. [68] also used a deterministic model for evaluating the floor response to walking. Different paths with the same step frequency, step length and weight of the person were modelled and compared with the experimental studies. Recently, Nguyen et al. [69] determined the loading factors of a Fourier series to simulate walking humans.
- Probabilistic models: A significant number of papers adopt probabilistic modelling. Probabilistic models are often used to describe the parameters of the Fourier series and model the walking of an individual unable to generate a perfectly periodic load. For example, Mohammed et al. [70] proposed a probabilistic approach to describe the individual walking load. This research presents an improved and probabilistic version of the Arup force model [71] for high-frequency floors. Fig. 8 shows a force function of sequential superposed footfalls. Recently, Garcia [72] developed a probabilistic model. The basic idea of this approach is generating stochastic force signals. All modelling parameters are functions of a variable running speed. The model applied in [73] enables the simulation of pedestrians with vertical walking forces. The walking force is described as a series of successive steps where the gait parameters (such as step frequency, step length, force amplitude, etc.) are randomly selected from experimental probability distributions. Muhammad et al. [74] proposed a probabilistic model for generating time histories of walking forces. This model refers to different walking speeds where the right and left leg effects are modelled separately. This approach can realistically reproduce the spatial and temporal characteristics of "real vertical walking".

3.3.3. Model approaches for groups of pedestrians

The challenge of modelling realistic load situations due to several people has been known for quite a while. The spatial and temporal uncertainties related to the influence parameters of a walking person are less than those of a group of pedestrians. Some scientific works have already addressed this challenge, and their models are briefly described below. For bridges, some approaches have already been published for simulating groups of people. Bassoli et al. [75] used the probabilistic approach for groups of people after [76], and [77]. Han et al. [78] simulated groups of pedestrians for bridge design. The individuals are modelled as lateral step forces which can enter the bridge from either end. The Millennium Pedestrian Bridge in London is used to assess the performance of this model. In [79], the effects of multiple people on the vibration performance of CLT floors are studied. Numerical modelling is also

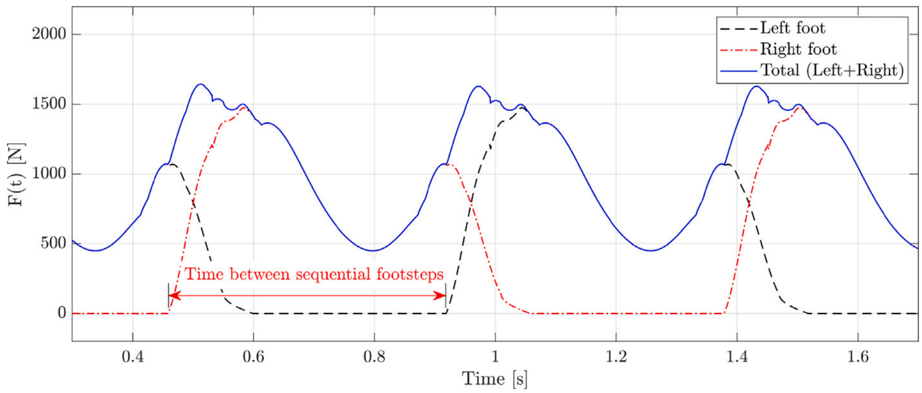

Fig. 8. Force function of sequential footfalls.

coupled with experimental tests and analytical studies. Using the VDV method, the authors estimated the serviceability of the tests. They used the maximum acceleration according to [50] by calculating the VDV and multiplying it with a factor for multi-person loading. The dependence on the type of movement is also included in the factor. In [80], a so-called social force simulates people or provides a realistic basis for motion models. The interaction between people originates from social interactions, resulting from individual needs. This approach allows us to determine where many people will stay and for how long. Using a heatmap, the authors present a floor plan with colour-coding of the areas.

3.4. Design approaches and vibration mitigation

Given the sensitivity of lightweight timber floors to vibration issues, the design must be carried out considering the criteria reported in Fig. 6. Several design optimisation approaches have been proposed in the literature, including the criteria in Fig. 6 in either the objective function or the constraints. Among all optimisation papers, those by Jelusic [81], Malaga-Chuquitaype [82], and Huang et al. [83] are perhaps the most innovative. Jelusic [81] optimises the design of timber floor joists, accounting for the self-manufacturing costs and the discrete sizes of the structure. The objective function includes the material and labour costs under design, strength, vibration, and deflection constraints. Malaga-Chuquitaype [82] presents a novel beam configuration that enhances the vibration comfort response of timber flooring systems while retaining the original environmental benefits of wood by integrating optimised resonators. The depth of the beam reduces towards the support freeing enough space for cantilever beams acting as vibration absorbers. The numerical study highlighted that the peak accelerations could be reduced with this innovative geometry. In a pilot study, Huang et al. [83] optimised a tunable mass damper to reduce the excessive vibration of a timber floor. Shape Memory Alloy (SMA) temperature is controlled to re-tune the main structure's natural frequency as the structure's mass or stiffness changes due to imposed loads or long-term effects, respectively. Through numerical simulations, it was proved that vibration amplitude could be reduced up to 26%. Additionally, Huang [22] developed a steel-based Multi-TMD (MTMD) system using shape memory alloy to reduce the human-induced vibration of CLT floors. The results show that these devices effectively reduce human-induced vibration. By contrast, the effectiveness of the steel-based MTMD systems was unsatisfactory owing to the permanent deformation of the steel components.

To properly optimise floor design, some authors proposed multi-objective optimisation. Van-Thai [84] optimised timber concrete composite floors with notched connectors by minimizing total thickness, weight, and material cost considering structural, vibration comfort, and especially, fire conditions constraints using the well-developed genetic algorithm (NSGA-II). It was found that the serviceability deflection and vibration constraints governed the designs of long-span concrete composite floors. The optimisation of Timber-Concrete Composite (TCC) floor system was also addressed by Movaffaghi et al. [85], who presented a Multi-Criteria Decision Analysis (MCDA) for comprehensive performance evaluation for the alternative floor design. The considered objectives are serviceability and sustainability performance with associated criteria such as (1) comfort class, (2) architectural quality, (3) CO_2 emissions, and (4) costs.

Vibration mitigation can also be achieved with specific design strategies. The reader can refer to Xue et al. [86], who addressed the dynamic effect of the bracing elements, and Suarez-Riestra [87], who estimated the effect of non-tensioning and self-tensioning configurations. As discussed by other researchers [88,89], the results show that an un-bonded prestressed bar hardly alters the eigenfrequency value compared with non-tensioned solutions. In this field, Shen et al. [90] considered wood truss joist floors as an alternative to solid timber joist floors in low-rise timber houses. Ebadi et al. [8] discussed the effects of span, support arrangement, beam spacing and the addition of non-structural topping materials on the vibration responses of floors. However, the effect of a composite action is discussed in the following sections.

3.5. Aspects related to specific floor typologies

The first subsections highlighted the general vibration aspects mainly valid for lightweight timber floors. However, within the broader context of timber floors, specific floor typologies, namely CLT floors and composite floors, have gained notable prominence in recent years. The increasing popularity of these typologies has positioned them as integral components of contemporary timber construction discussions. The following sub-sections comprehensively analyse the vibration aspects of these specific floor typologies.

3.5.1. CLT floors

Empirical design criteria for lightweight floors, shown in Table 1 based on static displacement and the fundamental natural frequency, were not validated against the dynamic response of CLT floors [91]. So far, no specific serviceability criteria have been proposed regarding CLT floors under multiple occupancy classifications. While traditional lightweight timber floors are prevalent in one-way systems, CLT floors exhibit a plate-like behaviour, being supported on all four sides. The scientific literature highlights two relevant aspects.

Some scholars affirm that using the current vibration criteria for the CLT floor design leads to conservative estimates; see Zhang et al. [92] and Hu et al. [93]. In this sense, Hu et al. [93] proposed a serviceability design criterion based on experimental tests on CLT strips behaving like simply-supported beams. According to Hu et al. [93], CLT strips can be considered the worst scenario since they neglect the effect of four-side support, see the recommendations of the CLT Handbook sponsored by the Canadian forest industry [94].

On the other hand, the human-induced dynamic response of CLT panels is associated with a significant contribution of higher modes, neglected by the EC5 formulation [95,96]. If all sides of the panel are supported, the number of participating modes can increase significantly up to 100 Hz [97]. This phenomenon is magnified by semi-rigid support conditions, intra-slab joints and a plan aspect ratio close to one. Recently, Milojevic et al. [98] numerically assessed the effect of connections, proving their stronger influence on high-frequency floors rather than low-frequency floors. Also, the effect of multiple people activities appears crucial for CLT floors. Wang [99] showed that the vibration amplitude of CLT floors under multi-person loadings was almost double that under single-person. Thus, multi-person activities are more likely to cause the occupants discomfort, although the serviceability criteria in Table 2 are satisfied. Kozar et al. [100] explored the vibrations caused by human action on five-layer cross-laminated timber panels considering different combinations of thicknesses and spans. The authors discussed the serviceability requirements, highlighting that if the minimum required natural frequency of the CLT panel is 8 Hz, the spans could go up to 6 m.

Most of the last years of research on CLT have been based on experimental tests. There are two mainstream: (i) the papers focused on dynamic characterization and (ii) those including serviceability metrics. In the first group (i), the authors consider the papers by Shahnewaz [19], Xin [20] Arnold [21], Huang [22] and Sun [23]. Shahnewaz [19] tested CLT glulam floors, showing that the connection types have negligible influence on the dynamic properties of the composite floor segments. Xin [20] identified the elastic constants of CLT floors based on the experimental modal parameters. Arnold [21] investigates whether Diagonal Laminated Timber (DLT) rotating each layer of the CLT panel to a certain angle increases its torsional stiffness, proving the increment of the serviceability performance. Huang [22] studied the effect of beam spacing, beam size and supporting conditions on the dynamic behaviours of CLT floors. Sun [23] developed a machine-learning method to determine the natural frequencies of CLT panels based on ANN networks. In the second group of papers (ii) falls the research by Huang et al. [101], and Koyama et al. [102,103]. Huang [101] tested CLT floors with hollow cores along the transverse direction, finding that the VDVs of CLT floors with hollow cores along the transverse direction were not more prominent than those of the solid CLT floor under walking excitation. Koyama [102] studied the influence of the finishing joist floor on walking vibration by comparing the dynamic performance of CLT floors without and with the joist floor. Koyama et al. [103] also measured the vibration response of a CLT floor under walking vibrations, investigating the influence of varying material properties and boundary conditions on the vibration performance of the floor.

Two additional aspects related to CLT floors were investigated: CLT floor optimisation and acoustics. Landmann et al. [104] were the sole who optimised the layup of CLT floors based on vibration criteria. Landmann et al. did a design optimisation for CLT floor panels under stress, deflection, and vibration constraints. In this case, the stiffness of the panel was the dominant parameter. It was concluded that the most effective way to optimise a CLT floor's layup is to adopt a configuration with a higher-grade outer lamination than the inner ones. In the period 2018–2022, Persson et al. [105], Qian et al. [106], Kawarza et al. [107], Morandi et al. [108] and Vardaxis et al. [109] addressed acoustic issues in CLT floors. Persson [105] attempted to improve the low-frequency vibroacoustic performance of CLT floor panels by an informed selection of wood material. Using laminations with stiffness properties typical for hardwoods ash, beech, and birch can significantly improve the performance of a CLT floor panel. Qian et al. [106] developed a vibroacoustic stochastic finite element prediction tool to quantify the uncertainties of material properties induced by the CLT panels' vibration performance. Kawarza [107] measured the vibration characteristics of a CLT floor in a residential building during three construction states. The calibrated model is used to evaluate the impact of various parameters of the floor construction on the low-frequency footfall sound insulation. Morandi et al. [108] benchmarked theoretical methods and experimental measurements to estimate when the transition from modal to diffuse field occurs in CLT panels. For this purpose, the diffuseness of the vibration field has been investigated through the experimental evaluation of the mode count and the modal overlap factor on a pilot CLT panel. Results of direct measurements performed up to 550 Hz show that the number of modes occurring in one-third of octave bands exceeds the standard threshold of 5 only at 500 Hz. In contrast, most modes' modal overlap factor is lower than the traditional threshold 1. This indicates that the vibration field is mainly non-diffuse in the mid-low frequency range due to the small number of modes combined with the low damping of the CLT plate. Vardaxis [109] tested twelve CLT floors adopting several indicators. An increase in sound insulation was achieved thanks to added total mass and thickness. They tested the following materials: wool insulation, gypsum boards, plywood, concrete screed, and wooden parquet floor. The results indicate that multilayered CLT floors can provide improvements of up to 22 dB for airborne sound and 32 dB for impact sound indicators compared with the bare CLT slab. Floating floor configurations with dry floor solutions (concrete screed) and wooden parquet floors are optimal. However, the parquet floor only provides a 1–2 dB improvement for impact sound indicators in floating floor setups (or higher in three cases).

CLT floors also received interest from structural mechanics. This is because CLT can be viewed as a layered plate-like continuum medium, which can be treated analytically. Among analytical studies, there are the ones by Furtmuller [110,111], Marjanović [112], Ussher et al. [113]. Furtmuller [111] developed an equivalent single-layer plate model with eight kinematic degrees of freedom. This model proved accurate for cross-ply laminates and elements oriented at any angle to the principal material axes. He also derived dispersion relations for the propagation of bending waves in the CLT panel [110]. Marjanović [112] developed an object-oriented computational framework for the 3D bending and free vibration analysis of multilayer plates based on Reddy's plate theory for laminated composites. Ussher et al. [113] derived explicit formulas for predicting the dynamics of orthotropic timber floor slabs. The formulation shows good agreement with numerical and experimental predictions. Finally, Sandoli et al. [114] studied the influence of the rolling shear deformation on the flexural behaviour of CLT panels. The results show that at the service limit states, the effect of the rolling shear can be significant when the aspect ratios become less than $l/h = 30$. Contrariwise, in the case of higher aspect ratios (slender panels), the deflections and stresses can be evaluated, neglecting the rolling shear influence, assuming the layers of boards as fully-connected.

While significant research has been conducted on the dynamics of CLT floors, some aspects still require further investigation. The current body of research has mainly focused on experimental testing, empirical design criteria, optimisation approaches, and some aspects of acoustics and structural mechanics. However, a few areas are relatively underexplored or warrant additional attention.

Among these is the validation of empirical design criteria. The existing empirical design criteria for lightweight floors, which are based on static displacement and fundamental natural frequency, have not been adequately validated against the dynamic response of CLT floors. More research is needed to assess the applicability and accuracy of these criteria, specifically for CLT floor systems.

Moreover, the classification of multiple occupancies is another overlooked aspect. Specific serviceability criteria tailored to CLT floors under multiple occupancy classifications have not been proposed. While traditional lightweight timber floors have primarily been studied in one-way systems, CLT floors exhibit plate-like behaviour and are supported on all four sides. Developing occupancy-specific criteria considering the unique characteristics of CLT floors would be beneficial.

The influence of higher modes on the dynamic response of CLT panels is another area deserving of further enquiry. The human-induced dynamic response of CLT panels is associated with a significant contribution of higher modes, which is not adequately considered in the current design codes and criteria. Further research is needed to investigate the effect of higher modes on the vibration behaviour of CLT floors and to develop appropriate design guidelines that account for these modes.

The interaction between CLT panels and supporting elements, including connections and support conditions, also plays a pivotal role in the dynamic behaviour of CLT floors. More studies are needed to understand and quantify the influence of these factors on the vibration response of CLT floors, including the effects of semi-rigid support conditions, intra-slab joints, and different connection types.

While experimental testing is prevalent in studying CLT floor dynamics, there is a demand for more research focusing on dynamic modelling and numerical simulations. Analytical models and numerical methods can provide valuable insights into the dynamic behaviour of CLT floors, allowing for parametric studies, optimisation, and assessment of various design strategies.

Lastly, a comprehensive assessment of CLT floor performance should consider factors beyond vibration-related aspects. This includes fire performance, sustainability, architectural quality, and cost. Therefore, more research is needed to devise multi-criteria evaluation methods that can holistically assess the performance of CLT floors, thereby informing design decisions.

Addressing these research gaps can enhance understanding of CLT floor dynamics and optimise the design and performance of these pioneering structural systems.

3.5.2. Composite floors

The dynamic response of timber floors regarding the fundamental frequency, peak velocities, and damping might improve under a combination of timber and other materials with complementary properties. Timber composite floors are generally made of wood products coupled with concrete, steel, glass or other wood products through a continuous or discontinuous connection [115,116]. A total composite action is achieved when the connection is rigid, and the assembly acts like a monolithic structure. Even in the case of partial composite action, composite floors might possess considerable advantages over traditional ones, including enhanced bending stiffness, load-bearing capacity, and dynamic response [10,115–117].

Upgrading an existing timber floor by adding a concrete layer increases bending stiffness. Nonetheless, the addition of concrete also increases the floor weight. Santos et al. [118] show that the additional mass due to the concrete layer leads to an advantage in reduced peak velocities under impulse loads. Still, adding concrete could also generate a significant decrease (44%) in the fundamental frequency. Casagrande et al. [119] tested CLT and timber-concrete composite floors in the same building. The comparison highlighted that, despite the lower stiffness of the CLT floor, there are no significant differences in first mode frequency due to the highest weight of the composite floor. In Gadami et al. [120], adding a 6.5 cm concrete topping to a laminated timber deck increased the frequency of the first mode from 11.4 Hz to 16.2 Hz. Also, Kozaric et al. [121] proved the improvement in the dynamic behaviour of an existing floor. In this case, the floor mass was reduced using lightweight concrete made with ground-expanded polystyrene (EPS).

Sometimes, the concrete slab is coupled with a CLT panel rather than wooden joists to save height. In [122], a 25% increase in frequency has been obtained by adding a 100 mm concrete topping to a 150 mm CLT panel. To compensate for the material waste in the previous approaches, Bukavaivade et al. [123] used plywood rib panels rather than CLT panels, resulting in a 73% lower cost and up to 71% smaller self-weight. Timber-steel hybrid structural systems are also widely applied to mid-rise construction [124,125], despite being prone to excessive and complex human-induced vibrations due to the low damping level [126]. Guan [127] tested full-scale cold-formed thin-walled steel-profiled steel sheet floors under dynamic and static loading. The study shows that casting gypsum-based self-levelling mortar on the profiled steel sheet reduced composite floors' fundamental frequency, damping ratio, and mid-span vertical deflection.

Connector stiffness is one of the parameters that could be most economically and efficiently varied to increase the fundamental frequency of a composite floor. Several papers proved its importance [10,118,128,129] based on parametric FE and experimental studies. For example, Thai et al. [57] found that the higher connector density might increase the stiffness and reduce the damping ratios. The most used fasteners are nails, steel bars, screws, inclined screws, split rings, toothed plates, steel tubes, notch, and steel plates glued to timber [117]. Screws perpendicular to the sliding plane are economical, quick and easy to install, and in the case tested by [121], a satisfactory fundamental frequency of 10 Hz was achieved. Furthermore, Owolabi et al. [124] obtained a high level of composite efficiency (98%) using inclined screws resulting in a 2.5-fold increase in the bending stiffness. The effectiveness of 45°-inclined screws in reaching a full composite action was also demonstrated by [122]. Full composite action in serviceability conditions can also be achieved through hybrid screwed-adhesive bond connections [115]. Notched connections are frequently used with screws to avoid uplift [55] and guarantee a high composite action. However, the notches' presence can impact the CLT panels' bending stiffness. A careful assessment is recommended if the notched connector density is higher than 5% of the panel surface, as advised in [57].

End restraints also play a significant role in the dynamic behaviour of the composite floor. According to [128], using fixed support in the TCC floor raises its fundamental frequency by 26.8% and reduces the peak acceleration by 37.5%. The numerical and experimental study conducted in [130] highlighted the influence of the flexibility of the support. It concluded that if uplift occurs in the floor edges, the vibration modes can significantly differ from the theoretical modes for supported plates. Floors supported on all four edges are characterized by significantly higher natural frequencies than those supported only at two opposite edges (45%) [130]. In this case, the CLT-to-CLT joint considerably influences the stiffness and dynamic behaviour of the composite floor. Even small gaps in the joints result in a lower natural frequency [126]. Splice joints with self-tapping screws, glued dovetails, or step joints can exploit the biaxial capacity of CLT floors [130].

Partitions, furniture, and occupants can limit the vibration spreading and increase damping. The floor in the actual structures has a critical damping ratio 6–9 times higher than that of the bare structure [131]. The in-depth investigation carried out by [128] revealed a significant influence of the walking path on peak acceleration. For a composite floor consisting of joists and a reinforcing plate, the maximum peak acceleration is obtained when the pedestrian walks transversely to the joists due to the lower out-of-plane stiffness in this direction. In the same study, it was concluded that peak acceleration of the floor increase with an increased number of pedestrians, step frequency, and walking regularity.

Finite element analysis can predict the natural frequencies, the modal shapes and the peak acceleration of composite floors [10]. Finite element modelling strategies for composite floors can be divided into two categories based on the level of complexity. The simplified approach consists in modelling the members with two overall dimensions as plate elements and the elements with one overall dimension over the others as beam elements. The interaction between elements is simulated with a rigid link in the out-of-plane direction and a linear elastic spring in the main shear direction. In glued connection, a rigid link is also used in the shear direction [57,115,118,126].

The more complex approach models the plate and the beam members with solid elements. This approach includes the friction effect between the sliding plane through surface contact interactions. In this case, the interaction between members could be reproduced by modelling the fastener itself [124,128,132].

Hybrid approaches were also proposed in literature [121,130]. Although numerical models can be very accurate in predicting the dynamic behaviour of composite floors, practitioners and codes demand simplified approaches. The most recurrent analytical approach for composite floors assumes the floor as a simply-supported beam with an equivalent bending stiffness determined according to the gamma method described in Eurocode 5. According to this approach, the bending stiffness is equal to the sum of the bending stiffness of each member plus a fraction of the Huygens-Steiner contribution dependent on the connection stiffness [119,128].

The method neglects the floor stiffness perpendicular to the direction of the joist. Therefore, it is unsuitable for floors supported on all four sides [118]. This approach usually leads to underestimating the performance of the composite floors [122].

Several parameters have to be considered in designing a composite floor. Existing literature highlighted how some of the parameters could positively influence some aspects of the dynamic floor response while negatively affecting some others; e.g. a reduction in the floor mass increases its natural frequency and at the same time, increases also peak velocities or an increase in the connection stiffness cause an increase in natural frequency while it could also reduce damping.

Although significant strides have been made in understanding the dynamics of composite timber floors, certain areas require further exploration. One of these areas is the long-term performance of these floors. Most research on composite timber floors focuses on their immediate dynamic response. However, long-term performance, including the effects of ageing, creep, and moisture content changes, is an important aspect that needs to be further studied.

The robustness and durability of composite floors under varying environmental conditions is another aspect that needs further study. These conditions include temperature variations, moisture exposure, and potential damage due to impacts or other external forces.

Furthermore, a deeper understanding of the dynamic interaction between composite floors and other building systems is crucial. Composite floors are part of a larger building system, and interactions with other building components, such as partitions, façade systems, or structural elements, can influence their dynamic behaviour. Understanding and quantifying these dynamic interactions are crucial for accurate predictions of floor performance.

While finite element analysis is commonly used to study composite floors, there is a call for more advanced multi-scale modelling techniques. These techniques should capture the complex behaviour at different length scales, considering the microstructural properties of timber and other materials, as well as the macroscopic response of the composite floor system.

Given the increasing interest in sustainability in construction, developing optimisation techniques that consider both the structural performance and environmental impact of composite timber floors is a growing need. This includes incorporating Life Cycle Assessment (LCA) and other sustainability metrics into the design process.

Finally, field monitoring and validation offer valuable data for validating numerical models and design approaches. Therefore, there is a need for more field studies to assess the actual dynamic response of composite floors under real-life conditions and compare them with predictions from analytical models.

Filling these research gaps would greatly contribute to a deeper understanding of composite timber floor dynamics and support the creation of more accurate design guidelines and performance-based standards for these systems.

3.6. Timber bridges

Timber bridges can be considered long-span floors (see [133]), which deserve specific attention. Wood had been the prevailing bridge material for centuries after being replaced by steel and concrete. However, in the previous decades, wood has regained ground as a bridge material, especially in northern European countries. This applies not only to pedestrian bridges but also to large road bridges for full traffic load. About 200 timber bridges are used today; see Kleppe et al. 2013 [134]. In Sweden, 817 timber bridges were built between 1994 and 2013; 501 were pedestrian, and 316 were full-traffic bridges. This accounts for roughly 25% of all bridges built in this period. In addition, approximately 40 timber bridges, mostly pedestrian and bicycle bridges, have been made annually since 1995 [135]. The spreading of timber bridges shows that wood is a cost-efficient, environmentally friendly, appealing, and long-lasting material in modern bridge design.

Timber bridges have three main drawbacks: durability, fire safety, and serviceability requirements [136]. The recent collapse of the Tretten bridge in Norway in August 2022 showed the importance of a correct design [137]. The revival of timber bridges also feeds research in dynamic assessment and serviceability requirements. Fiore et al. [138] discussed shape, structural and durability strategies for the design of timber pedestrian bridges, with a particular concern for vibration levels. In addition, the authors underlined the need to carry out dynamic analyses to ensure pedestrians' comfort and avoid the risk of dangerous coupled lateral–torsional oscillations. So far, no relevant applications of structural health monitoring (SHM) solutions for timber bridges exist. Recently, Walker [139] has emphasized the importance of monitoring the natural frequencies of timber bridges and environmental parameters (moisture content, e.g.) for SHM. Several papers explicitly address the serviceability performance of timber bridges. Since most timber bridges are pedestrian, the serviceability requirements involve the vibration comfort to the users [140]. The most recent and relevant researches are perhaps those by Hawryszkow et al. [141], Toyoda [142], and Garcia [72], detailed below. Hawryszkow et al. [141] carried out dynamic analyses of two untypical, modern footbridges made of glued-laminated timber. The in situ measurements confirm the high level of damping in footbridges made of glued-laminated wood, a significant and distinguishing feature not commonly recognized. The study also calls attention to timber choice as an advisable material for footbridges. This is not only for environmentally friendly and aesthetic reasons but also for providing satisfying vibration comfort for pedestrians.

The excellent damping of modern timber bridges was also proven by Toyoda [142]. After completion, the authors tested 23 modern timber pedestrian bridges' dynamic responses. The results clearly showed that the damping coefficient of timber bridges could be higher than those of steel and concrete bridges with similar structures due to the high damping capability of glulam itself and the effect of friction at the connections. Therefore the equation $c = 0.12/l^{0.5}$ commonly adopted for steel and concrete bridges provides a lower limit of the damping coefficient. This study highlighted that the fundamental vertical natural frequency was almost equivalent to general highway bridges. A comparison with experimental data has proven that the equation $f = 100/l$ (Hz) can roughly estimate the fundamental natural frequency for timber bridges. The experimental data also showed a significant decrease in structural rigidity after the first ten years of life. Therefore, the equation $S = 100(1 - e^{-0.0011t^2})$ is proposed to determine the percentage of decrease in structural rigidity.

Garcia [72] investigated the dynamic response of a short-span timber footbridge with uncertain mechanical properties under the action of a deterministic walking load model. The work aims to quantify uncertain material properties' influence on a short-span timber footbridge's natural and forced vibration problems. In some scenarios, the variation of the material properties can lead to unacceptable serviceability performances of the structure and a reduction in pedestrian comfort. The stochastic analysis highlighted that higher accelerations and smaller displacements characterize the footbridge compared to similar structures with the same natural frequency but different materials. According to the authors, this observation depends on the timber material's high stiffness/weight ratio.

The research on the vibration of timber bridges still has some gaps and areas that require further investigation. Here are some aspects that are missing or warrant more attention. Firstly, while some studies have examined the dynamic behaviour of timber bridges during their early years of service, there is a need for long-term monitoring and assessment. Understanding how the dynamic response of timber bridges evolves, considering factors such as moisture content, ageing, and environmental conditions, is crucial for ensuring their continued structural integrity and vibration performance.

Secondly, the robustness and resilience of timber bridges during extreme events such as earthquakes, strong winds, and heavy traffic loads should be evaluated. The effects of these events on the vibration behaviour of timber bridges, including the potential for excessive vibrations or structural failure, should be thoroughly studied.

Additionally, composite timber bridge systems that combine timber with other materials, such as steel or concrete, are an emerging field. Further research is needed to investigate these composite timber bridges' dynamic behaviour and vibration performance, including the interaction between different materials, connection details, and their impact on overall bridge response.

Furthermore, the application of SHM techniques for timber bridges remains relatively limited. More research is needed to develop effective and practical SHM systems tailored to timber bridges. This includes exploring sensor technologies, data analysis algorithms, and real-time monitoring techniques to assess the dynamic behaviour and detect potential structural issues in timber bridges.

Human-induced vibrations also warrant further study. Although some studies have investigated the comfort of pedestrians on timber bridges, more comprehensive research is needed to understand the effects of human-induced vibrations on the overall dynamic response of timber bridges. This includes considering various factors such as crowd loading, walking patterns, frequencies of human activities, and their influence on the vibration comfort and performance of timber bridge structures.

Lastly, there is limited development of comprehensive design guidelines and standards specifically addressing the vibration performance of timber bridges. It is crucial to establish clear criteria and recommendations for assessing and mitigating excessive vibrations in timber bridges, considering natural frequency, damping, comfort thresholds, and safety margins.

4. Building

Following the component-level classification adopted in this paper, this section deals with vibration issues affecting timber buildings. Specifically, three main topics are analysed in the corresponding subsections. The first subsection introduces readers to high-rise timber buildings and emphasizes the pivotal role different construction solutions play in influencing the vibration performance of these structures. The effectiveness of various lateral resisting systems in mitigating vibrations and ensuring the structural integrity of tall timber buildings is explored. The second subsection delves into the general serviceability criteria applicable to buildings. While serviceability requirements receive more attention at the individual floor level, there is a lack of specific standardization and design approaches at the building level. The focus is on wind-induced excitations and discussing the primary methods for modelling wind actions in timber buildings. The final subsection focuses on experimental investigations centred on vibration responses. These investigations primarily involve traditional dynamic identification techniques, damage identification methods, and model updating procedures. Through these experimental approaches, more profound insights are gained into the dynamic behaviour of timber buildings, enabling improvements in design and performance assessment.

4.1. Lateral resisting systems for high-rise timber buildings

As engineers strive to take multi-storey timber buildings to new heights, it is necessary to understand how existing structures and current construction systems behave in service and how their performance relates to what is predicted at the design stage. Predicting the dynamic behaviour of buildings is challenging due to non-linearities and the difficulty of modelling damping. Since tall timber buildings are relatively new on the construction landscape, understanding their behaviour needs to be improved compared to other structures. Most research on high-rise timber buildings focuses on the structural side (i.e., devising novel lateral resisting systems or experimental tests on actual buildings). To the authors' knowledge, no general papers provide comfort criteria related to the serviceability performance of high-rise timber buildings.

There are two prevalent structural solutions for high-rise timber buildings:

- Hybrid timber buildings;
- Purely timber buildings.

Fig. 9 provides a schematic representation of the main solutions for high-rise timber buildings.

Hybrid timber buildings exploit the coupling between multiple building materials to achieve high-rise structures. Generally, a timber structure is coupled with a concrete or steel lateral resisting system. The lateral resisting system can be either a concrete core or a steel frame. Entirely high-rise timber buildings are more challenging to design due to the lower structural mass and rigidity and more proneness to vibration issues [143].

There are two main construction systems for high-rise timber buildings:

1. Post and beams buildings (Moment-resisting frames);
2. Mass-timber panels buildings.

Moment-resisting frames are increasingly important in countries with no seismic hazard [144]. Therefore, the unique severe hazard is represented by the wind action. Thus, several studies were carried out to understand the behaviour of tall timber-framed buildings. Tulebekova [145,146] investigates the effects of connection flexibility and non-structural components on the wind-induced vibration behaviour of an existing, tall Glued Laminated Timber (GLT) framed timber building. For this purpose, a detailed finite element model, including non-structural elements, was established. The flexibility of the connections was accounted for by introducing "connection zones", whose stiffness could be tuned 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

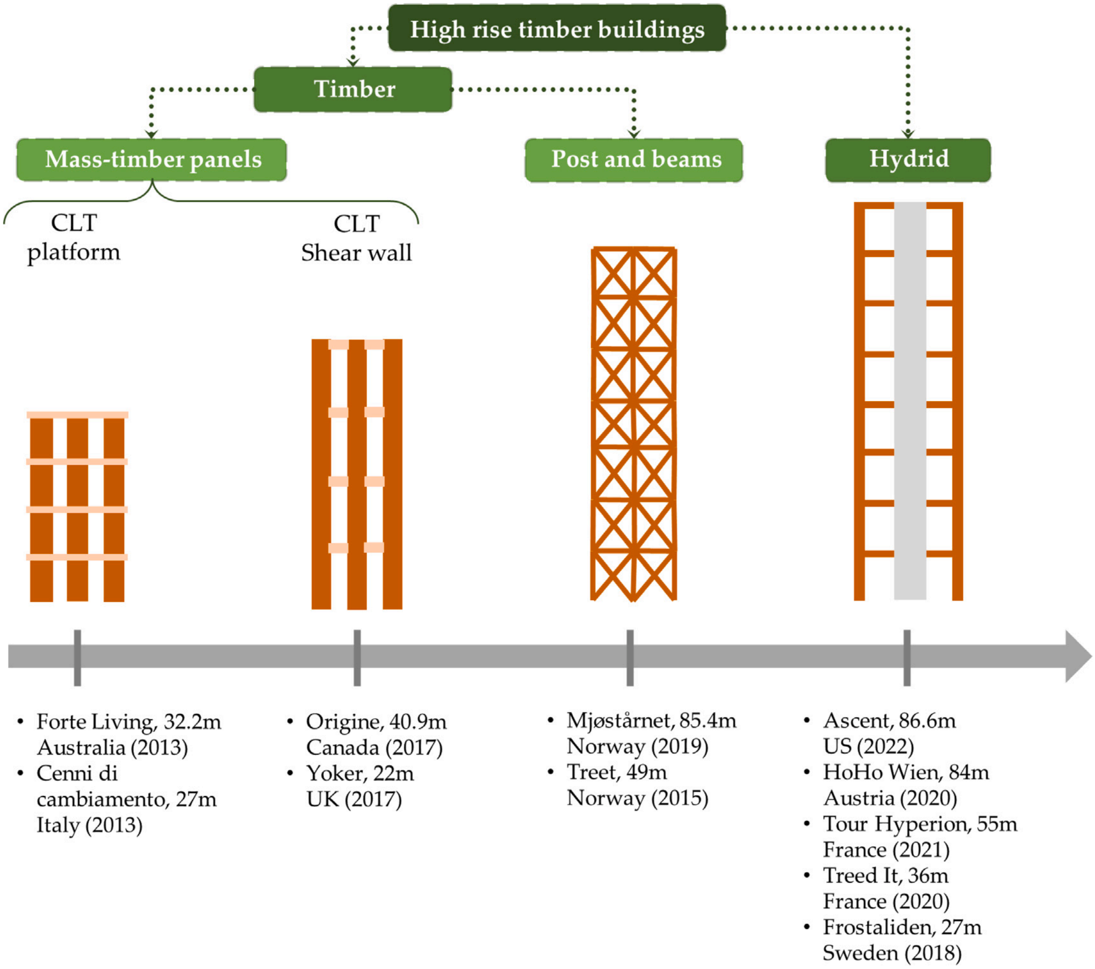

Fig. 9. Schematic representation of the main solutions for high-rise timber buildings.

were significantly affected by the non-structural partitions, making these two factors necessary for the accurate modelling of the building vibrations. In the same direction, Landel et al. [147] investigated the response of large laminated timber structures with mechanical joints exposed to wind excitation. They present vibration tests and model reduction approaches of a truss with dowel-type connections.

Mass-timber buildings are widespread in seismic-prone areas, where multiple structural systems were devised based on mass-timber products, particularly CLT. Talja et al. [148] summarize Eurocode design for wind-induced vibration and present some considerations for CLT buildings. The wind-induced response depends on the modal parameters. Therefore, many experimental pieces of research were carried out to understand the dynamic characteristics of mass-timber buildings [149–151]. Recently, within the DynaTTB research programme [143], Abrahamsen et al. (2020) performed several dynamic tests on tall timber buildings to estimate damping. In addition, Medel-Vera [152] proposed predictive models for the fundamental period of vibration of CLT buildings for seismic design.

It must be remarked that there are also more advanced approaches for reducing vibration discomfort in tall timber buildings through damping devices. A few deal with the vibration control of timber buildings. Das et al. [153] proposed a shape memory alloy (SMA)-based damped outrigger system for vibration control of tall timber buildings. However, most refer to the ultimate limit state and the vibration control during seismic excitation [154,155]. Other scholars proposed alternative solutions to improve the vibration performance of tall timber buildings using flexible lateral stiffening systems. For example, Binck et al. [156] followed the tube-in-tube concept. The internal tube consists of a braced timber core, and the outer tube consists of a frame structure with semi-rigid beam–column joints in the façade. In the same direction, Hahn et al. [157] present the design, manufacture and installation of a truss tower whose top segment was composed of moulded wooden tubes. The article includes all project steps, from the basic idea of the wood moulding technology to the calculation of the structure and the connections towards the final assembly of the structure.

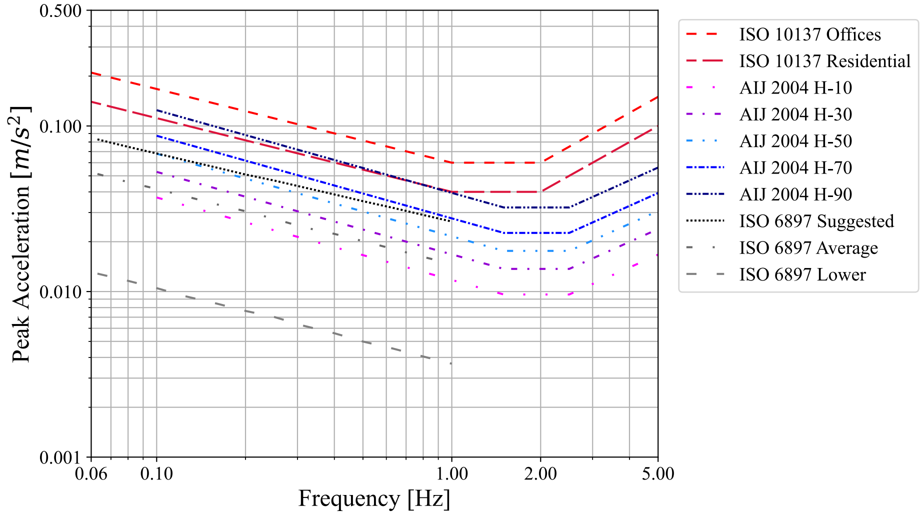

Fig. 10. Comparison between different curve perception (RMS values from ISO 6897 are multiplied by $\sqrt{2}$ to be comparable with peak acceleration limits).

4.2. Serviceability criteria and modelling approaches

It is well-acknowledged that as the height of a building increases, wind forces tend to become the controlling design loads. Moreover, due to wood's inherent low mass and relatively low stiffness, timber buildings are more prone to wind-induced oscillations that might cause discomfort to the occupants than buildings made of concrete and steel. For these reasons, serviceability issues related to wind-induced vibration are considered a hindering factor for the design of tall timber buildings. In tall, slender and flexible structures, serviceability is more critical than in low-rise buildings, where strength is usually the governing design criterion.

Serviceability limit states, however, define the functional performance and behaviour of a building; they set a level of quality of the structure or element and involve the perceptions and expectations of the owner or user. Since they are not directly related to safety, professional committees and code bodies seem reluctant to codify serviceability issues rigidly. This reluctance is probably due to the different opinions on the purpose of building codes: protection for life safety or the establishment of complete minimum design standards. However, the fact that serviceability limit states are usually not codified should not diminish their importance. While safety is usually not an issue in this optic, the economic consequences can be substantial.

Whereas the research on the seismic response of timber buildings has progressed rapidly, wind performance of mid and high-rise timber buildings has been studied more scarcely. There is no specific research on wind-related human discomfort in tall timber buildings. The main reason is manifest: there is no significant sample of tall timber buildings for a meaningful statistical evaluation. Therefore, the wind modelling and the comfort criteria originate from past studies on other structural systems, see [158]. However, the lack of specific studies on timber buildings does not affect comfort criteria limits, which depend on the interaction between human perception and building dynamics and are not directly related to the building material.

Current criteria to evaluate comfort are based on users' perception of motion, which is assessed through acceleration curves. The base curves represent either the threshold of motion perception or the limit for probable adverse comments by the occupants [159, 160]. They depend on the natural vibration frequency of the structural system and the orientation of the vibration relative to the human body axes. Firstly a performance indicator (e.g. running root-mean-square, peak acceleration) is calculated from the acceleration signal induced by the wind action. This indicator is compared to the base perception curves to evaluate the system's performance. Some of the most relevant standards containing serviceability criteria related to motion perception of the occupants are hereby listed and reported in Fig. 10:

- ISO 10137 (2007) [159]. The standard recommends the serviceability criteria for the building's vibrations. Annex D provides a method for evaluating the human response to wind-induced motions in buildings, giving acceptable limits in peak acceleration and natural frequency in the building's principal direction (along-wind, cross-wind, torsion). The peak acceleration should be calculated for wind speed with a one-year return period and a 10-min average.
- ISO 6897 (1984) [160]. The standard cover building, whose frequency is 0.063 Hz–1 Hz, gives limit values of root mean square (RMS) accelerations for buildings used for general purposes. The limits are based on the worst ten consecutive minutes of a wind storm with a return period of at least five years.
- AIJ (2004) [161]. The Japanese guidelines provide five curves: H-10, H-30, H-50, H-70 and H-90, where the number of each curve indicates the perception probability, expressed as a percentage of people who can perceive the given vibration level. The guidelines recommend no specific limit, which is to be decided by the owner and the designer. The one-year-recurrence peak acceleration is to be applied for the evaluation.

The dynamic response of tall buildings to wind loads is a complex phenomenon, as the wind loads vary significantly in speed, force and direction over time. To achieve simplification, building codes treat wind loads as quasi-static loads. The gust effect is also included as a turbulence factor added to the quasi-static component for high slender structures. Furthermore, the effect of the wind on a building will be affected by its exposure, the roughness of the terrain around it as well as the shape and height of the building. The gust load factor approach originates from the work of Davenport [162] and is a simplified frequency-domain method in which the wind load's standard deviation and the dynamic response's amplitude are multiplied by a peak factor to obtain the peak response. The standard deviation of the response and a peak factor is obtained based on random vibrations theory. Because of its simplicity, the gust factor method has received widespread acceptance worldwide and is employed in wind loading codes and standards in almost all major countries. According to the method in Annex B of EN 1991-1-4, for instance, the characteristic wind-induced acceleration, in the along-wind direction, for a point at height z, is calculated as:

$$a_{peak}(z) = K_p \cdot b_b \cdot h_b \cdot q_{z,ref} \cdot c_{fw} \cdot \Phi_{1,x}(z) \cdot \frac{1}{M_1} \cdot R \tag{13}$$

The definition of all symbols in Eq. (13) is given in the initial list of symbols and notations. The peak response obtained can be compared with peak acceleration criteria, such as ISO 10137 [163]. However, the response of buildings subjected to wind loads can be estimated more precisely with time-domain analysis using in-situ wind measurements or wind tunnel experiments, but also with methods combining spectral analysis and time-domain analysis [164–166]. The wind is described in a frequency-domain wind spectrum, and then a time series is generated. The dynamic response of the structure can be computed through numerical integration of the modal equation of motion.

Most of the research work carried out during the last years deals with numerical studies where different structural systems (e.g. post-and-beams, CLT, etc.) are analysed throughout case studies and parametric analyses [6,166–174]. Specifically Johansson et al. [167] study the response of two archetypes (i.e. CLT buildings, Glulam post-and-beam with a concrete shaft) to wind-induced acceleration according to EN 1991-1-4 and compare the results of the simplified analytical calculations with the limits of ISO 10137. Then they extend the analysis to a 48 m (16 storeys) high building where they study the effect of doubling and tripling the mass, stiffness and damping ratio. In [168], the authors analyse 22-storey structures having an internal CLT core and a post-and-beam structure at the perimeter. They model the structure with FE software for more reliable results regarding natural frequencies and mode shapes. Edskär and Lindelöw [169] perform a parametric analysis on the FE model of a CLT structure varying the footprint, height, damping ratio, wall stiffness, wall density and additional surface loads to study the influence of these parameters on the dynamic response of the building. In [170], the authors extend the parametric analyses to a post and beam type of structure and compare it to the response of a CLT one. In the same direction, Zhao et al. [6,171] perform parametric studies on the peak accelerations of CLT and glulam frames buildings, respectively. The structures were assumed to be located in Glasgow and have 30 storeys. Furthermore, the varied parameters were the timber material properties and building masses. In these papers, the accelerations are also calculated according to the Eurocodes, and the response is evaluated concerning ISO 10137 limits. Landel et al. [172] compare four procedures to evaluate the along wind accelerations on four existing tall timber buildings, highlighting high variations between the different codes. Cao and Stamatopoulos [166] deliver a numerical investigation on the response of moment-resisting frames subject to wind loads. They performed over one million simulations on planar frames where several parameters (e.g. floor height, floor number, beam stiffness) were varied. The response of the planar frames is evaluated with the simplified gust approach but also performing time-domain analyses explicitly considering the time series of the wind force. A quite interesting finding is that the gust factor approach might underestimate the response for frames with up to 10–12 floors while overestimating the accelerations for frames with more than 10–12 storeys [166]. Bezabeh et al. [173] examined the dynamic response and serviceability performance of five case study tall mass-timber buildings varying in height (10-, 15-, 20-, 30-, and 40-storey). Bezabeh et al. [164,165] propose a probabilistic procedure to assess the serviceability performance of tall mass-timber buildings, applying the complete framework to a case study consisting of a 102-m tall building. The framework incorporates uncertainties at each step of the wind-loading chain. The design process consists of a preliminary strength design using building code provisions. Then serviceability checks are performed using wind loads obtained from aerodynamic wind tunnel tests. Finally, the detailed probabilistic performance assessment is performed with structural reliability analysis using Monte Carlo sampling to propagate the uncertainties through the wind loading chain. The results from reliability analysis are used to develop fragility curves for wind vulnerability estimations. Lazzarini et al. [174] studied the comfort assessment of the 18-storey "Mjøstårnet" building in Norway, applying computational fluid dynamic (CFD) analyses to simulate the wind flow around the building. The results of the CFD analysis are then used to extrapolate detailed pressure data, which is applied to a generalized model and a reduced model to obtain accurate evaluations of wind-induced motions.

While significant progress has been made in the research on the serviceability of tall timber buildings, several research gaps still exist. These gaps include:

There is still a need for developing specific comfort criteria for tall timber buildings. Currently, few studies focus on wind-related human discomfort in tall timber buildings. The absence of a significant sample size of tall timber buildings hinders the development of specific comfort criteria tailored to these structures. More research is needed to investigate the relationship between wind-induced vibrations and human perception in tall timber buildings.

Despite rapid progress in researching the seismic response of timber buildings, the wind performance of mid and high-rise timber buildings has been relatively overlooked. Further studies are needed to enhance our understanding of the dynamic behaviour of tall timber buildings subjected to wind loads, including the characterization of their modal parameters, natural frequencies, and mode shapes.

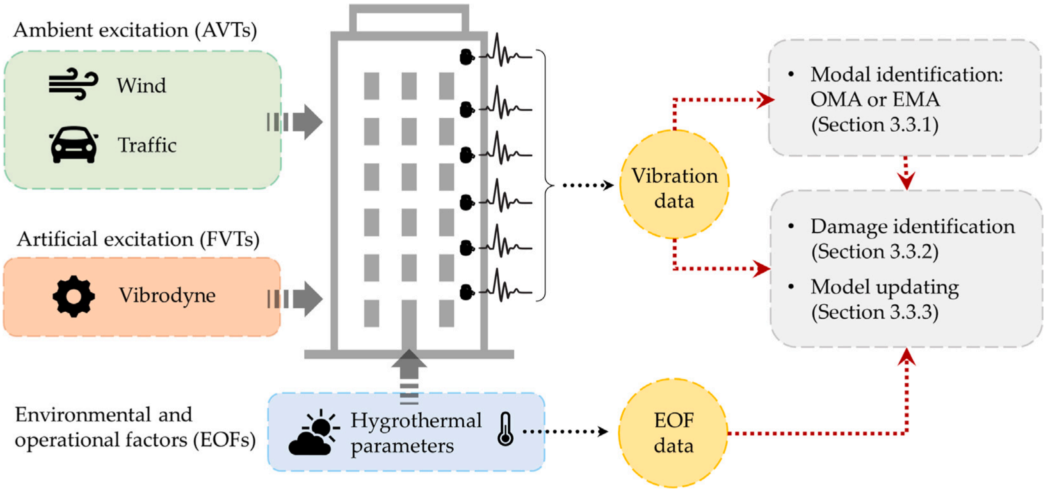

Fig. 11. General overview on vibration-based monitoring.

Analytical models and numerical studies have significantly contributed to the understanding of tall timber building serviceability, but there is an emerging need for experimental validation. Conducting comprehensive experimental tests on tall timber buildings under real wind conditions will help validate and refine the analytical models, providing more accurate predictions of their dynamic behaviour.

Another area of interest is the investigation of damping mechanisms and damping devices. Damping is crucial in mitigating vibrations and improving the comfort of tall timber buildings. Further research is required to explore the damping mechanisms specific to timber structures and investigate the effectiveness of various damping devices, such as tuned mass dampers and viscoelastic materials, in reducing wind-induced vibrations.

Lastly, the current design guidelines and standards for tall timber buildings often rely on simplified approaches and codes applicable to other structural systems. This necessitates the development of more specific and robust design guidelines to accommodate the unique characteristics and challenges of tall timber buildings. These include their lightweight nature, lower stiffness, and increased susceptibility to wind-induced vibrations.

4.3. *Experimental investigations*

The dynamics of buildings is governed by their stiffness, mass, and damping characteristics. Therefore, analysing their dynamic responses can provide indirect information on such properties. A field of great importance relates to identifying the modal properties of buildings, i.e., modal frequencies, modal shapes, and damping factors. Ambient Vibration Tests (AVTs) and Operational Modal Analysis (OMA) techniques exploit vibrational responses under operational excitations. In contrast, Forced Vibration Tests (FVTs) and Experimental Modal Analysis (EMA) techniques use vibrational responses under artificial excitations [175]. Typical dynamic loads acting on buildings in operational conditions include vehicular traffic, wind, human actions, rotating machines, and earth tremors. Artificial excitations can be generated by devices such as vibrodynes. The dynamic properties of structures are typically influenced by Environmental and Operational Factors (EOFs).

In addition to better understating the structural behaviour to improve building codes and, ultimately, the design of new constructions, vibrational response data might be exploited to identify damage to existing structures in operational conditions or after a disaster or to calibrate numerical models, for instance, for structural safety assessment. These two activities rely on the modal parameters identified through AVTs or FVTs. In Fig. 11, a general overview of vibration-based monitoring of buildings is provided.

Hence, it is crucial to establish how far research on analysing the dynamic behaviour of timber buildings has gone to highlight critical issues and knowledge gaps. The literature on this topic is reviewed, highlighting similarities and differences to other structures and identifying future research needs and directions. First, an overview of the modal identification of timber buildings is provided. After that, the state of the research on damage identification and model calibration is investigated.

4.3.1. *Modal identification*

The literature on AVTs and FVTs on civil structures is vast. They are commonly performed on civil structures such as bridges [176], dams [177], stadia [178], historic structures [179]. Nevertheless, applications for timber buildings are still limited. According to the authors' knowledge, the first AVT on a timber building was performed by Ellis and Bougard in 2001 [180]. 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 them 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. [150,181], Feldmann et al. [149]) using OMA methods. The research conducted by Reynolds and colleagues constitutes probably the largest AVT database performed on European timber structures to date. They tested different timber structural archetypes: post and beam, timber-framed, pure CLT and hybrid timber-concrete structures. It is also worth mentioning the tests performed in Germany and Austria on eight timber observation towers (with a height of up to 45 m), a 100 m tall wind turbine and three multi-storey residential timber buildings (with a height of up to 26 m). The findings of all these testing campaigns have allowed for assessing the simplified relationship between height and natural frequency for multi-storey buildings given in Eurocode 1. In North America, where there is a deeply-rooted tradition of wooden frame housing, efforts have been made to understand the dynamic behaviour of smaller low-rise residential buildings, see Mugabo et al. [182], and all the infield investigations on light-frame wood buildings by Hafeez et al. [183–185]. Kim et al. [186] combined vibration and force measurements. They used load cells between the column and foundation stone to measure axial column force, and ambient vibration tests were performed to measure natural vibration frequency and mode shape.

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 [145]. Nevertheless, extensive dynamic tests on mid-rise and high-rise timber structures represent a missing part. This will aid in learning important lessons and enhance the engineering community's confidence towards using this material.

4.3.2. Damage identification

Damage, such as cracks and reduction of cross sections in structural members, can modify the dynamic response of structures [187]. Thus, vibration data are processed to extract Damage-Sensitive Features (DSFs) and ultimately obtain damage indices which alert about variations of DSFs between a reference and the current state of the structure [188]. According to the available resources (e.g., the number and location of sensors), different levels of damage identification can be attained [189], namely: (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). The dynamic properties of a structure do not vary only due to the occurrence of damage. EOFs can modify the properties of healthy structures. This is a major concern in damage identification. Variations of EOFs might hide the effect of structural anomalies and hamper damage identification. Besides, 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 understood and considered for damage identification purposes.

Extensive research on the effect of environmental factors, such as hygrothermal parameters, has been carried out on concrete [187], steel [190], and masonry structures [191] including earth buildings [192]. Most of the investigations show that modal frequencies are susceptible to variations in temperature. Specifically, increasing temperatures lead to decreasing modal frequencies. This effect is generally more evident for concrete structures rather than steel ones. In turn, modal shapes are generally not influenced by temperature, whereas the relation between damping and temperature has not yet been fully understood [193]. Masonry structures can present more complex relations with environmental factors, including relative air humidity, see, e.g. [191,194]. Operational factors extensively studied include, for instance, human actions and vehicular traffic, see, e.g., [195]. In addition to temperature and relative air humidity, one of the main concerns in the case of timber buildings is the Moisture Content (MC), which influences several properties of timber, such as strength, density, and elastic modulus. To the authors' knowledge, Larsson et al. [196] were the first to monitor a hybrid timber building long-term and investigated the relationship between environmental factors and the dynamic response of a hybrid timber-concrete building. The results of this experimental campaign were published in 2022. The authors have tracked the modal parameters, i.e., modal frequencies, modal shapes, and damping ratios, 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. Furthermore, it is observed that the modal frequencies decrease in the first year after construction due to the drying out of timber elements. In [197], the results of a 3-years monitoring campaign on a Pres-Lam building are presented. In this case, the results show that temperature, relative humidity, and post-tensioning losses do not affect the structure's dynamic behaviour. While damage identification in timber buildings has seen some progress, numerous research gaps still exist and require further exploration.

In terms of damage detection methods, although there have been advances in this area, there is a pressing need to develop more robust and reliable techniques specifically adapted for timber structures. Unlike other construction materials, timber displays unique characteristics and behaviour patterns, demanding the creation of methods tailored to these specific properties.

The impact of environmental factors on damage detection is another area that needs further study. Environmental factors, such as temperature, humidity, and moisture content, can significantly affect the dynamic behaviour of timber structures. However, their influence on damage detection and the ability to differentiate between damage-induced changes and environmental variations are poorly understood. Further research is needed to investigate the impact of environmental factors on damage detection in timber structures.

The ageing effects on timber structures and the importance of long-term monitoring are also crucial areas for further research. Ageing processes can change material properties and structural behaviour over time. Long-term monitoring of timber structures is crucial to understand the effects of ageing on the dynamic response and developing reliable damage detection methods that can account for these changes.

Another underexplored area is the integration of multiple data sources. Damage detection in timber structures can benefit from integrating multiple data sources, such as vibration data, visual inspections, and other sensing technologies. The fusion of data from different sources can improve the accuracy and reliability of damage identification and characterization.

Lastly, it is essential to validate the performance of damage detection methods through experimental testing on real-scale timber structures. Large-scale experimental campaigns introducing controlled damage and the subsequent detection and assessment of the damage using different techniques can provide valuable insights into the effectiveness and limitations of various damage detection methods.

4.3.3. Model calibration

Developing representative numerical models of structures can be challenging. This is even truer for innovative structural systems or historical buildings, which are generally affected by even more uncertainty concerning ordinary buildings. In [198], the authors discuss the differences between numerical and experimental modal properties of the ETH House of Natural Resources (HoNR), an innovative timber building. In [199], the authors develop a FE model of historical timber mosques in Turkey using data available in the literature and compare the results of a modal analysis with modal shapes and frequencies identified through AVTs. Even though a good agreement between modal shapes was found, the difference between frequencies exceeded 30%.

The calibration of numerical models may rely on deterministic or probabilistic approaches. Deterministic approaches minimize the difference between the response of numerical models and experimental data. To this purpose, single or multi-objective functions are generally defined and minimized using iterative optimisation algorithms [200,201]. The calibration can be carried out manually or through automatic optimisation algorithms. In [202], the model developed in [199] is calibrated manually by updating the elastic modulus of timber until the difference between identified and numerical frequencies is lower than 5%. Min et al. [203] used identified natural frequency to determine the storey stiffness of a heritage timber building in Korea. Aloisio et al. [204], and Kurent et al. [205] presented the FE modelling and model updating of two CLT buildings based on the minimization of the error between the numerical and experimental value of frequencies and MAC values. Specifically, Aloisio et al. [204] estimated the minimum of the objective function by evaluating the objective function in a discretized domain. In contrast, Kurent et al. [205] employed a multi-objective genetic algorithm. Both studies show that CLT floors can be considered a rigid diaphragm for fundamental modes and that the effect of connections is not relevant under low vibration levels (perfect bond between CLT panels is assumed). Probabilistic methods aim to obtain updated probability distributions of unknown structural parameters based on experimental data. This problem is generally formulated in a Bayesian framework accounting for different sources of uncertainties, e.g. in material properties and experimental data [206,207]. Bayesian updating of the timber structure is presented in [208,209]. Leyder et al. investigated the model updating of the HoNR. First, they performed a sensitivity analysis to identify the critical model parameters. Then, the posterior distribution of such parameters was estimated using a Bayesian updating implementation called BASIS. In [209], Kurent et al. extended the work presented in [205] by developing a surrogate-based Bayesian update of the model parameter.

5. Conclusions

This paper extensively reviews current research investigating vibration issues in timber structures. Through bibliometric analysis, crucial themes in this field have been identified and classified. These findings, summarized below, provide valuable insights for researchers, designers, and regulatory bodies involved in designing and evaluating timber structures subject to vibrations.

The major challenges related to vibration are primarily encountered at the floor and building levels due to the lightweight nature and lower stiffness of timber. Significant progress in predicting floor vibrations has resulted in the inclusion of modified serviceability criteria and evaluation methods for timber floors in the Eurocode 5 draft. Moreover, the potential of hybrid timber floors, particularly those combining timber and concrete, in mitigating vibration levels has been underlined.

Despite these advancements, certain areas warrant further investigation. The dynamic behaviour of CLT floors, differing considerably from traditional one-way timber floors, needs a more thorough understanding. A revision of the serviceability criteria based on such insights might be necessary. Continued research into hybrid timber-based solutions and material coupling strategies is encouraged, as these areas hold promise for innovative approaches to comfort issues caused by vibrations.

At the building level, vibrations in high-rise timber structures due to wind forces remain a significant concern. Although lateral resisting systems for these buildings have seen innovative development, the limited number of tall timber buildings worldwide impedes a robust statistical evaluation of human comfort perception concerning vibrations. Therefore, more research in this domain is highly recommended.

The value of experimental tests in enhancing the understanding of timber building behaviour over the past two decades is acknowledged. Yet, vibration-based monitoring remains relatively underexplored in the field of timber engineering. More case studies and research are needed to ascertain the potential and limitations of this monitoring approach. Despite these challenges, research and innovation in timber structures continue to progress, tackling the critical issue of vibrations in these structures. It is paramount to build upon this body of knowledge to encourage the wider adoption of timber buildings and to continue to innovate in vibration mitigation strategies in timber engineering.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] J. Smith, Sustainability and environmental impacts of timber structures, J. Sustain. Constr. 5 (2) (2017) 45–58.
[2] E. Jones, Mitigating wind effects in high-rise timber buildings, J. Timber Eng. 12 (3) (2020) 123–136.
[3] A. Opazo-Vega, F. Muñoz-Valdebenito, C. Oyarzo-Vera, Damping assessment of lightweight timber floors under human walking excitations, Appl. Sci. (Switzerland) 9 (18) (2019).
[4] A. Homb, S. Kolstad, Evaluation of floor vibration properties using measurements and calculations, Eng. Struct. 175 (2018) 168–176.
[5] Z. Zhang, S. Wang, H. Zhou, Effects of stud partitions on the vertical vibration performances of metal plate connected timber, J. Forestry Eng. 7 (2) (2022) 167–173.
[6] X. Zhao, B. Zhang, T. Kilpatrick, I. Sanderson, Numerical analysis on global serviceability behaviours of tall clt buildings to the eurocodes and uk national annexes, Buildings 11 (3) (2021).
[7] M. Ebadi, G. Doudak, I. Smith, Evaluation of floor vibration caused by human walking in a large glulam beam and deck floor, Eng. Struct. 196 (2019).
[8] M. Ebadi, G. Doudak, I. Smith, Vibration responses of glulam beam-and-deck floors, Eng. Struct. 156 (2018) 235–242.
[9] M. Robertson, D. Holloway, A. Taoum, Vibration of suspended solid-timber slabs without intermediate support: assessment for human comfort, Aust. J. Struct. Eng. 19 (4) (2018) 266–278.
[10] N. Perković, V. Rajčić, J. Barbalić, Analytical and numerical verification of vibration design in timber concrete composite floors, Forests 12 (6) (2021) 707.
[11] Y. Yokoyama, Y. Koyama, S. Nishitani, S. Fukuda, Effect of deflection on evaluation of walking vibration of long-span timber floor from the viewpoint of habitability, J. Environ. Eng. (Japan) 87 (797) (2022) 379–390.
[12] D. Yeoh, M. Fragiacomo, D. Carradine, Fatigue behaviour of timber–concrete composite connections and floor beams, Eng. Struct. 56 (2013) 2240–2248.
[13] G.H. Kyanka, Fatigue properties of wood and wood composites, Int. J. Fract. 16 (1980) 609–616.
[14] M. Chaplain, Z. Nafa, M. Guenfoud, Damage of glulam beams under cyclic torsion: Experiments and modelling, in: Damage and Fracture Mechanics: Failure Analysis of Engineering Materials and Structures, Springer, 2009, pp. 349–356.
[15] L.P. Hansen, A. Rathkjen, Fatigue of laminated wood beams, 1994.
[16] K.J. Yeo, D.E. Yeoh, Stiffness and strength degradation of timber concrete composite under fatigue loading, in: IOP Conference Series: Materials Science and Engineering, Vol. 713, IOP Publishing, 2020, 012024.
[17] L. Yang, A. Chen, J. Zhou, G. He, H. Wang, C. Li, Flexural fatigue behaviour of glulam beams connected with steel splints and bolts, Buildings 13 (5) (2023) 1218.
[18] S. Nesheim, K. Malo, N. Labonnote, Competitiveness of timber floor elements: An assessment of structural properties, production, costs, and carbon emissions, Forest Prod. J. 71 (2) (2021) 111–123.
[19] M. Shahnewaz, C. Dickof, J. Zhou, T. Tannert, Vibration and flexural performance of cross-laminated timber – glulam composite floors, Compos. Struct. 292 (2022).
[20] Z. Xin, H. Zhang, C. Guan, J. Liu, F. Liu, Y. Gong, H. Li, Y. Shen, Determining elastic constants of full-size cross laminated timber panel supported on four nodes using a vibration method, Constr. Build. Mater. 323 (2022).
[21] M. Arnold, P. Dietsch, R. Maderebner, S. Winter, Diagonal laminated timber—Experimental, analytical, and numerical studies on the torsional stiffness, Constr. Build. Mater. 322 (2022).
[22] H. Huang, Y. Gao, W.-S. Chang, Human-induced vibration of cross-laminated timber (CLT) floor under different boundary conditions, Eng. Struct. 204 (2020).
[23] J. Sun, J. Niederwestberg, F. Cheng, Y. Chui, Frequencies prediction of laminated timber plates using ann approach, J. Renew. Mater. 8 (3) (2020) 319–328.
[24] Guide to the Application of the European Directive Relating to the Assessment and Management of Environmental Noise, Tech. Rep., European Committee for Standardization, 2008.
[25] Guide to Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Repeated Shock, British Standards Institution, 1987.
[26] Mechanical Vibration and Shock–Evaluation of Human Exposure to Whole-Body Vibration, International Organization for Standardization, 1997.
[27] W. Nering, J. Jabben, Annoyance caused by environmental noise and vibrations: A systematic review and meta-analysis, Environ. Impact Assess. Rev. 83 (2020) 106425.
[28] K. Nering, A. Kowalska-Koczwara, Determination of vibroacoustic parameters of polyurethane mats for residential building purposes, Polymers 14 (2) (2022) 314.
[29] H.V. Howarth, M.J. Griffin, Annoyance caused by vibration and noise from construction sites, J. Sound Vib. 145 (3) (1991) 411–422.
[30] K. Fossen, E. Björn, Acoustics in timber buildings–a design guide, J. Build. Apprais. 4 (4) (2008) 323–336.
[31] A. Olsson, Acoustic performance of timber-framed multi-storey residential buildings: A literature review, Build. Environ. 149 (2019) 216–226.
[32] M. Caniato, M. Machimbarrena, S. Schelfhout, D. Torfs, Design for acoustic performance of lightweight buildings: A state-of-the-art review, Build. Environ. 205 (2022) 108395.
[33] Building Acoustics–Estimation of Acoustic Performance of Buildings from the Performance of Elements–Part 12: Laboratory Measurement of the Impact Sound Insulation of Floors, International Organization for Standardization, 2017.
[34] J. Olsson, A. Linderholt, Low-frequency impact sound of timber floors: A finite element–based study of conceptual designs, Build. Acoust. 28 (1) (2021) 17–34.
[35] D. Wang, M. Abrahamsen, K.-J. Høeg, A. Ruud, C. Sinadinovski, M. Sjödahl, J. Bačova, R. Čajka, A. Sternheim, J. Varela, et al., Predicting impact forces, structural vibration and radiated sound power of timber joist floors, Build. Environ. 186 (2020) 107307.
[36] C. Fox, M. Nakamura, Vibration prediction in light timber floors with air cavity using a composite model structure, Build. Environ. 157 (2019) 831–839.
[37] R. Paolini, G. Perillo, M. Masoero, V. Bignozzi, Prediction of airborne sound transmission through multi-layered thin elastic components by using a computational mesh-free method, Build. Environ. 153 (2019) 23–36.
[38] F. Ljunggren, A. Ågren, Elastic layers to reduce sound transmission in lightweight buildings, Build. Acoust. 20 (1) (2013) 25–42.
[39] M. Lietzen, Effect of floor coverings on impact sound insulation, Build. Environ. 198 (2022) 122221.

[40] J. Negreira, R. Irusta, H. Astigarraga, F. Alday, A. Garcia, Characterisation of elastic insulating layers for the reduction of impact sound insulation of lightweight timber floors, Appl. Acoust. 86 (2014) 112–119.
[41] F. Reichelt, P. Strecker, S. Winter, Characteristics of the acoustic performance of elastic wood wool cement boards, Appl. Acoust. 104 (2016) 105–114.
[42] X. Huang, X. He, H. Fan, Y. Lv, T. Zhou, P. Ren, Performance of elastic cushion materials for impact sound insulation of timber floors, Build. Environ. 202 (2021) 108329.
[43] B. Azinović, M. Dolšek, I. Planinc, G. Klančar, Influence of flexible insulation layers on seismic performance of cross-laminated timber walls, Eng. Struct. 243 (2021) 112876.
[44] S. De Santis, G. Boscato, D. Cigana, M. Fragiacomo, Timber screwed connections with elastic interlayer: Analytical model for stiffness prediction, Eng. Struct. 244 (2021) 112869.
[45] M. Kržan, E. Govekar, G. Turk, Cyclic response of insulated steel angle brackets for CLT connections, Eng. Struct. 242 (2021) 112507.
[46] BS 6472:2008, Guide to Evaluation of Human Exposure to Vibration in Buildings, Standard, BS - BRITISH STANDARD, London, UK, 2008.
[47] ISO 2631-1:1997, Mechanical Vibration and Shock — Evaluation of Human Exposure to Whole-Body Vibration — Part 1: General Requirements, Standard, ISO, Geneve, CH, 1997.
[48] ISO 10137:2007, Bases for Design of Structures — Serviceability of Buildings and Walkways Against Vibrations, Standard, ISO, Geneve, CH, 2007.
[49] B.M. Basaglia, Dynamic Behaviour of Long-Span Timber Ribbed-Deck Floors (Ph.D. thesis), 2019.
[50] W. Chang, T. Goldsmith, R. Harris, A new design method for timber floors – peak acceleration approach, INTER - Int. Netw. Timber Eng. Res. 51-20-1 (2018).
[51] P. Hamm, A. Richter, S. Winter, Floor vibrations – new results, WCTE - World Conf. Timber Eng. Riva del Garda (2010).
[52] P. Hamm, J. Marcroft, T. Toratti, Vibrations of floors – comparison of measured data and suggested design, INTER - Int. Netw. Timber Eng. Res. 53 - 20 - 1 (2020).
[53] I. Abeysekera, P. Hamm, T. Toratti, A. Lawrence, Development of a floor vibration design method for eurocode 5, INTER - Int. Netw. Timber Eng. Res. 51-20-2 (2018).
[54] EN12512, Timber structures. Test methods. Cyclic testing of joints made with mechanical fasteners, 2022.
[55] J. Jaaranen, G. Fink, Experimental and numerical investigations of two-way LVL–concrete composite plates with various support conditions, Eng. Struct. 256 (2022) 114019.
[56] T. Akter, A. Miyamoto, T. Tomonari, Stiffness and vibration characteristics of cross-laminated timber (CLT) floor diaphragms considering wall-to-floor connections, J. Build. Eng. 41 (2021) 102680.
[57] H.T. Thai, S. Maas, X. Dai, Z. Wu, L. Dai, Improving measurement technique for estimating bending stiffness of timber floors, Materials 14 (15) (2021) 4240.
[58] N. Labonnote, A. Rønnquist, K. Malo, Experimental evaluations of material damping in timber beams of structural dimensions, Wood Sci. Technol. 47 (5) (2013) 1033–1050.
[59] M. Ebadi, G. Doudak, I. Smith, Finite-element modeling and parametric study of glulam beam-and-deck floors, J. Struct. Eng. (US) 143 (9) (2017).
[60] B. Basaglia, J. Li, R. Shrestha, K. Crews, Response prediction to walking-induced vibrations of a long-span timber floor, J. Struct. Eng. (US) 147 (2) (2021).
[61] M.R. Willford, P. Younge, A Design Guide for Footfall Induced Vibration of Structures, Tech. Rep., Concrete Society, Surrey, UK, 2006.
[62] T.M. Murray, D.E. Allen, E.E. Ungar, D.B. Davis, Steel Design Guide 11: Vibrations of Steel-Framed Structural Systems Due to Human Activity, Tech. Rep., second ed., American Institute of Steel Construction, Chicago, IL, 2016.
[63] A.L. Smith, S.J. Hicks, Design of Floors for Vibration: A New Approach, Tech. Rep., Steel Construction Institute, Ascot, UK, 2009.
[64] M. Feldmann, Human-Induced Vibration of Steel Structures, Tech. Rep., Luxembourg, 2008.
[65] K. Baumann, H. Bachmann, Durch menschen verursachte dynamische lasten und deren auswirkungen auf balkentragwerke, Bericht / Inst. Baustatik Konstruktion ETH Zürich 7501 (3) (1988).
[66] Z. Muhammad, P. Reynolds, O. Avci, M. Hussein, Review of pedestrian load models for vibration serviceability assessment of floor structures, Vibration 2 (1) (2019) 1–24.
[67] Z. Xie, X. Hu, H. Du, X. Zhang, Vibration behaviour of timber-concrete composite floors under human-induced excitation, J. Build. Eng. 32 (2020) 101744.
[68] D. Casagrande, I. Giongo, F. Pederzolli, A. Franciosi, M. Piazza, Analytical, numerical and experimental assessment of vibration performance in timber floors, Eng. Struct. 168 (2018) 748–758.
[69] H.A.T. Nguyen, N. Lythgo, E. Gad, J. Wilson, N. Haritos, Development of dynamic load factors for human walking excitation for floor vibration design, Int. J. Appl. Mech. Eng. 27 (3) (2022) 103–114.
[70] A.S. Mohammed, A. Pavic, V. Racic, Improved model for human induced vibrations of high-frequency floors, Eng. Struct. 168 (2018) 950–966.
[71] M. Willford, C. Field, P. Young, Improved methodologies for the prediction of footfall-induced vibration, 2006, pp. 1–15.
[72] M. García-Diéguez, V. Racic, J.L. Zapico-Valle, Complete statistical approach to modelling variable pedestrian forces induced on rigid surfaces, Mech. Syst. Signal Process. 159 (2021) 107800.
[73] F. Pancaldi, E. Bassoli, M. Milani, L. Vincenzi, A statistical approach for modeling individual vertical walking forces, Appl. Sci. 11 (21) (2021) 10207.
[74] Z.O. Muhammad, P. Reynolds, Probabilistic multiple pedestrian walking force model including pedestrian inter- and intrasubject variabilities, Adv. Civ. Eng. 2020 (2020) 1–14.
[75] E. Bassoli, K. van Nimmen, L. Vincenzi, P. van den Broeck, A spectral load model for pedestrian excitation including vertical human-structure interaction, Eng. Struct. 156 (2018) 537–547.
[76] G. Piccardo, F. Tubino, Equivalent spectral model and maximum dynamic response for the serviceability analysis of footbridges, Eng. Struct. 40 (2012) 445–456.
[77] T.F. Ferrarotti A, Equivalent spectral model for pedestrian-induced forces on footbridges: a generalized formulation, 2015.
[78] H. Han, D. Zhou, T. Ji, J. Zhang, Modelling of lateral forces generated by pedestrians walking across footbridges, Appl. Math. Model. 89 (2021) 1775–1791.
[79] C. Wang, W.-S. Chang, W. Yan, H. Huang, Predicting the human-induced vibration of cross laminated timber floor under multi-person loadings, Structures 29 (2021) 65–78.
[80] A.S. Mohammed, A. Pavic, Simulation of People's Movements on Floors Using Social Force Model, Springer, 2019, pp. 39–46.
[81] P. Jelusic, S. Kravanja, Optimal design and competitive spans of timber floor joists based on multi-parametric MINLP optimisation, Materials 15 (9) (2022).
[82] C. Malaga-Chuquitaype, J. Ilkanaev, Novel digitally-manufactured wooden beams for vibration reduction, Structures 16 (2018) 1–9.
[83] H. Huang, W.-S. Chang, Application of pre-stressed SMA-based tuned mass damper to a timber floor system, Eng. Struct. 167 (2018) 143–150.
[84] M. Van Thai, P. Galimard, S. Elachachi, S. Ménard, Multi-objective optimisation of cross laminated timber-concrete composite floor using NSGA-II, J. Build. Eng. 52 (2022).
[85] H. Movaffaghi, I. Yitmen, Multi-criteria decision analysis of timber–concrete composite floor systems in multi-storey wooden buildings, Civ. Eng. Environ. Syst. 38 (3) (2021) 161–175.
[86] S. Xue, Z. Zhang, Z. Zhang, H. Zhou, Y. Shen, Effects of strongbacks and strappings on vibrations of timber truss joist floors, Shock Vib. 2021 (2021).

[87] F. Suárez-Riestra, J. Estévez-Cimadevila, E. Martín-Gutiérrez, D. Otero-Chans, Experimental, analytical and numerical vibration analysis of long-span timber-timber composite floors in self-tensioning and non-tensioning configurations, Constr. Build. Mater. 218 (2019) 341–350.
[88] E. Hamed, Y. Frostig, Natural frequencies of bonded and unbonded prestressed beams–prestress force effects, J. Sound Vib. 295 (1–2) (2006) 28–39.
[89] A. Aloisio, Aspects of vibration-based methods for the prestressing estimate in concrete beams with internal bonded or unbonded tendons, Infrastructures 6 (6) (2021) 83.
[90] Y. Shen, H. Zhou, S. Xue, J. Zhang, A comparison on numerical simulation models for vibrational performances of the wood truss joist floor system, Shock Vib. 2021 (2021).
[91] E. Ussher, K. Arjomandi, J. Weckendorf, I. Smith, Predicting effects of design variables on modal responses of CLT floors, in: Structures, Vol. 11, Elsevier, 2017, pp. 40–48.
[92] S. Zhang, J. Zhou, J. Niederwestberg, Y. Chui, Effect of end support restraints on vibration performance of cross laminated timber floors: An analytical approach, Eng. Struct. 189 (2019) 186–194.
[93] L. Hu, Serviceability of Next Generation Wood Buildings: Laboratory Study of Vibration Performance of Cross-Laminated-Timber (CLT) Floors, Project 301006159: Report 2012/13, 2013.
[94] S. Gagnon, C. Pirvu, CLT handbook, special pub. SP-528E, 2011.
[95] J. Weckendorf, I. Smith, Dynamic characteristics of shallow floors with cross-laminated-timber spines, 1 (2012) 176–185.
[96] S. Maldonado, Y. Chui, Effect of end support conditions on the vibrational performance of cross-laminated-timber slabs, in: Proceedings of 13th World Conference on Timber Engineering, 2014.
[97] J. Weckendorf, T. Toratti, I. Smith, T. Tannert, Vibration serviceability performance of timber floors, Eur. J. Wood Wood Prod. 74 (3) (2016) 353–367.
[98] M. Milojević, V. Racic, M. Marjanović, M. Nefovska-Danilović, Influence of inter-panel connections on vibration response of CLT floors due to pedestrian-induced loading, Eng. Struct. 277 (2023) 115432.
[99] C. Wang, W.-S. Chang, W. Yan, H. Huang, Predicting the human-induced vibration of cross laminated timber floor under multi-person loadings, Structures 29 (2021) 65–78.
[100] L. Kozaric, M. Purcar, S. Zivkovic, Vibrations of cross-laminated timber floors [vibracije križno lameliranih drvenih međukatnih panela], Drvna Ind. 70 (3) (2019) 307–312.
[101] H. Huang, X. Lin, J. Zhang, Z. Wu, C. Wang, B. Wang, Performance of the hollow-core cross-laminated timber (HC-CLT) floor under human-induced vibration, Structures 32 (2021) 1481–1491.
[102] Y. Koyama, Y. Ohashi, S. Fukuda, Y. Yokoyama, Fundamental study on walking vibration of cross laminated timber floor with finishing joist floor, J. Environ. Eng. (Japan) 85 (777) (2020) 791–801.
[103] Y. Koyama, S. Fukuda, Y. Yokoyama, Presentation of example of span table of cross laminated timber floor from the viewpoint of walking vibration, J. Environ. Eng. (Japan) 84 (761) (2019) 623–633.
[104] A. Landmann, M. Mahamid, O. Amir, Cost optimisation of cross-laminated timber panels in one-way bending, Eur. J. Wood Wood Prod. (2022).
[105] P. Persson, O. Flodén, H. Danielsson, A. Peplow, L. Andersen, Improved low-frequency performance of cross-laminated timber floor panels by informed material selection, Appl. Acoust. 179 (2021).
[106] C. Qian, S. Ménard, D. Bard, J. Negreira, Development of a vibroacoustic stochastic finite element prediction tool for a CLT floor, Appl. Sci. (Switzerland) 9 (6) (2019).
[107] M. Kawrza, T. Furtmüller, C. Adam, Experimental and numerical modal analysis of a cross laminated timber floor system in different construction states, Constr. Build. Mater. 344 (2022).
[108] F. Morandi, A. Prato, L. Barbaresi, A. Schiavi, On the diffuseness of the vibrational field of a cross-laminated timber plate: Comparison between theoretical and experimental methods, Appl. Acoust. 159 (2020).
[109] N.-G. Vardaxis, D. Bard Hagberg, J. Dahlström, Evaluating laboratory measurements for sound insulation of cross-laminated timber (CLT) floors: Configurations in lightweight buildings, Appl. Sci. (Switzerland) 12 (15) (2022).
[110] T. Furtmüller, C. Adam, An accurate higher order plate theory for vibrations of cross-laminated timber panels, Compos. Struct. 239 (2020).
[111] T. Furtmuller, C. Adam, A higher-order plate theory for the analysis of vibrations of thick orthotropic laminates, Acta Mech. (2022).
[112] M. Marjanović, G. Meschke, E. Damnjanović, Object-oriented framework for 3D bending and free vibration analysis of multilayer plates: Application to cross-laminated timber and soft-core sandwich panels, Compos. Struct. 255 (2021).
[113] E. Ussher, K. Arjomandi, I. Smith, Explicit vibration formulas applicable to timber plates with free and simply supported edges, Struct. Eng. Int. 28 (4) (2018) 506–517.
[114] A. Sandoli, B. Calderoni, The rolling shear influence on the out-of-plane behaviour of CLT panels: A comparative analysis, Buildings 10 (3) (2020).
[115] T. Tannert, A. Gerber, T. Vallee, Hybrid adhesively bonded timber-concrete-composite floors, Int. J. Adhes. Adhes. 97 (2020).
[116] M. Stepinac, I. Šušteršič, I. Gavrić, V. Rajčić, Seismic design of timber buildings: Highlighted challenges and future trends, Appl. Sci. 10 (4) (2020) 1380.
[117] M.K. Skaare, Vibrations in Composite Timber-Concrete Floor Systems (Master's thesis), Institutt for konstruksjonsteknikk, 2013.
[118] P.G.G.d. Santos, C.E.d.J. Martins, J. Skinner, R. Harris, A.M.P.G. Dias, L.M.C. Godinho, Modal frequencies of a reinforced timber-concrete composite floor: Testing and modeling, J. Struct. Eng. 141 (11) (2015) 04015029.
[119] D. Casagrande, I. Giongo, F. Pederzolli, A. Franciosi, M. Piazza, Analytical, numerical and experimental assessment of vibration performance in timber floors, Eng. Struct. 168 (2018) 748–758.
[120] N. Gadami, N. Abd Ghafar, D. Chuan, M. Rahimi, N. Aziz, Pilot study on the vibration behaviour of TCC laminated deck systems, Int. J. Integr. Eng. 13 (3) (2021) 244–252.
[121] L. Kozaric, D. Varju, M. Vojnic Purcar, S. Bursac, A. Ceh, Experimental investigations and numerical simulations of the vibrational performance of composite timber-lightweight concrete floor structures, Eng. Struct. 270 (2022).
[122] K. Quang Mai, A. Park, K. Nguyen, K. Lee, Full-scale static and dynamic experiments of hybrid CLT–concrete composite floor, Constr. Build. Mater. 170 (2018) 55–65.
[123] K. Buka-vaivade, D. Serdjuks, L. Pakrastins, Cost factor analysis for timber–concrete composite with a lightweight plywood rib floor panel, Buildings 12 (6) (2022).
[124] D. Owolabi, C. Loss, Experimental and numerical study on the bending response of a prefabricated composite CLT-steel floor module, Eng. Struct. 260 (2022).
[125] S. A.L. Hunaity, H. Far, A. Saleh, Vibration behaviour of cold-formed steel and particleboard composite flooring systems, Steel Compos. Struct. 43 (3) (2022) 403–417.
[126] A. A. Chiniforush, M. Makki Alamdari, U. Dackermann, H. Valipour, A. Akbarnezhad, Vibration behaviour of steel-timber composite floors, part (1): Experimental and numerical investigation, J. Construct. Steel Res. 161 (2019) 244–257.
[127] Y. Guan, X.-H. Zhou, S.-J. Wei, Y. Shi, Study on vibration performance and static deflection of cold-formed thin-walled steel composite floors, Gongcheng Lixue/Eng. Mech. 35 (5) (2018) 131–142.
[128] Z. Xie, X. Hu, H. Du, X. Zhang, Vibration behaviour of timber-concrete composite floors under human-induced excitation, J. Build. Eng. 32 (2020).
[129] L. Zhang, J. Zhou, Y. Chui, G. Li, Vibration performance and stiffness properties of mass timber panel-concrete composite floors with notched connections, J. Struct. Eng. (US) 148 (9) (2022).

[130] J. Jaaranen, G. Fink, Experimental and numerical investigations of two-way LVL–concrete composite plates with various support conditions, Eng. Struct. 256 (2022).
[131] A. Hassanieh, A. Chiniforush, H. Valipour, M. Bradford, Vibration behaviour of steel-timber composite floors, part (2): Evaluation of human-induced vibrations, J. Construct. Steel Res. 158 (2019) 156–170.
[132] H. Movaffaghi, J. Pyykkö, Vibration performance of timber-concrete composite floor section –verification and validation of analytical and numerical results based on experimental data, Civ. Eng. Environ. Syst. 39 (2) (2022) 165–184.
[133] L. Kollar, Z. Pap, Modal mass of floors supported by beams, Structures 13 (2018) 119–130.
[134] O. Kleppe, H. Kepp, T. Dyken, Contribution to structural details on timber bridges, in: 2nd International Conference on Timber Bridges, Wood Products Council Las Vegas, NV, 2013.
[135] A. Gustafsson, Cluster wooden bridges, 2014.
[136] K.-C. Mahnert, U. Hundhausen, A review on the protection of timber bridges, Wood Mater. Sci. Eng. 13 (3) (2018) 152–158.
[137] S. Vegvesen, Blokkutriving etter overbelasting felte tretten bru, 2022.
[138] A. Fiore, M. Liuzzi, R. Greco, Some shape, durability and structural strategies at the conceptual design stage to improve the service life of a timber bridge for pedestrians, Appl. Sci. (Switzerland) 10 (6) (2020).
[139] K. Walker, T. Miller, R. Gupta, A. Shariati, T. Schumacher, Development of virtual visual sensor applications for wood structural health monitoring, J. Test. Eval. 46 (1) (2018).
[140] Z. Wang, X. Li, J. Yi, Q. Li, Human-induced vibration and optimal control of long-span glulam arch bridges, Tumu Gongcheng Xuebao/China Civ. Eng. J. 54 (4) (2021) 79–94.
[141] P. Hawryszkow, J. Biliszczuk, Vibration serviceability of footbridges made of the sustainable and eco structural material: Glued-laminated wood, Materials 15 (4) (2022).
[142] A. Toyoda, H. Honda, S. Kato, Static and dynamic structural performance of modern timber bridges, J. Japan Soc. Civ. Eng. 8 (1) (2020) 26–34.
[143] R. Abrahamsen, M.A. Bjertnaes, J. Bouillot, B. Brank, L. Cabaton, R. Crocetti, O. Flamand, F. Garains, I. Gavric, O. Germain, et al., Dynamic response of tall timber buildings under service load: The dynattb research program, in: EURODYN 2020, XI International Conference on Structural Dynamics, Athens, Greece, 22–24 June 2020, National Technical University of Athens, 2020, pp. 4900–4910.
[144] A. Vilguts, Moment-Resisting Timber Frames with Semi-Rigid Connections, NTNU, 2021.
[145] S. Tulebekova, K.A. Malo, A. Rønnquist, P. Nåvik, Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings, Eng. Struct. 261 (2022) 114209.
[146] S. Tulebekova, K. Malo, A. Rønnquist, P. Nåvik, Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings, Eng. Struct. 261 (2022).
[147] P. Landel, A. Linderholt, Reduced and test-data correlated FE-models of a large timber truss with dowel-type connections aimed for dynamic analyses at serviceability level, Eng. Struct. 260 (2022).
[148] A. Talja, L. Fülöp, Evaluation of Wind-Induced Vibrations of Modular Buildings, VTT Technical Research Centre of Finland, 2016.
[149] A. Feldmann, H. Huang, W. Chang, R. Harris, P. Dietsch, M. Gräfe, C. Hein, Dynamic properties of tall timber structures under wind-induced vibration, in: World Conference on Timber Engineering (WCTE 2016), 2016.
[150] T. Reynolds, R. Harris, W. Chan, Dynamic response of tall timber buildings to wind load, in: 35th Annual Symposium of IABSE/52nd Annual Symposium of IASS/6th International Conference on Space Structures, London, 2011.
[151] R. Verhaegh, M. Vola, J. Jong, Haut - a 21-storey tall timber residential building, Int. J. High-Rise Build. 9 (3) (2020) 213–220.
[152] C. Medel-Vera, M. Contreras, Resilience-based predictive models for the seismic behaviour of mid-rise, base-isolated CLT buildings for social housing applications in Chile, J. Build. Eng. 44 (2021).
[153] S. Das, S. Tesfamariam, Multiobjective design optimisation of multi-outrigger tall-timber building: Using SMA-based damper and Lagrangian model, J. Build. Eng. 51 (2022).
[154] K. Ishikawa, Y. Wakashima, R. Fujioka, H. Shimizu, D. Matsubara, A. Kitamori, Contributions of plywood shear walls and plasterboad on seismic response reductio of timber structures using wood friction-based dampers, AIJ J. Technol. Des. 27 (65) (2021) 166–171.
[155] M. Shinohara, H. Isoda, Seismic design method based on spectrum capacity procedure for timber semi-rigid frame with oil damper, J. Struct. Constr. Eng. 85 (769) (2020) 355–365.
[156] C. Binck, A. Cao, A. Frangi, Lateral stiffening systems for tall timber buildings–tube-in-tube systems, Wood Mater. Sci. Eng. (2022).
[157] B. Hahn, T.-E. Werner, P. Haller, Truss segments made of moulded wood tubes as support structure of small wind power plants [konstruktion einerwindkraftanlage mit fachwerksegment aus faserbewehrten formholzrohren], Bauingenieur 96 (1–2) (2021) 11–18.
[158] S. Lamb, K.C. Kwok, D. Walton, A longitudinal field study of the effects of wind-induced building motion on occupant wellbeing and work performance, J. Wind Eng. Ind. Aerodyn. 133 (2014) 39–51.
[159] International Organization for Standardization, Bases for Design of Structures–Serviceability of Buildings and Walkways Against Vibrations, ISO, 2007.
[160] ISO 6897, Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low-frequency horizontal motion (0.063 to 1hz), 1984.
[161] A. Aij, Guidelines for the evaluation of habitability to building vibration, AIJ (2004).
[162] A. Davenport, How can we simplify and generalize wind loads? J. Wind Eng. Ind. Aerodyn. 54 (1995) 657–669.
[163] A. Kareem, Synthesis of fluctuating along wind loads on buildings, J. Eng. Mech. 112 (1) (1986) 121–125.
[164] M. Bezabeh, G. Bitsuamlak, M. Popovski, S. Tesfamariam, Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads: Part I - structural design and wind tunnel testing, J. Wind Eng. Ind. Aerodyn. 181 (2018) 85–103.
[165] M. Bezabeh, G. Bitsuamlak, M. Popovski, S. Tesfamariam, Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads: Part II - structural reliability analysis, J. Wind Eng. Ind. Aerodyn. 181 (2018) 112–125.
[166] A. Cao, H. Stamatopoulos, A theoretical study of the dynamic response of planar timber frames with semi-rigid moment-resisting connections subjected to wind loads, Eng. Struct. 240 (2021).
[167] M. Johansson, A. Linderholt, Å. Bolmsvik, K. Jarnerö, J. Olsson, T. Reynolds, Building higher with light-weight timber structures-the effect of wind induced vibrations, in: 44th International Congress and Exposition on Noise Control Engineering, INTER-NOISE 2015, 2015.
[168] M. Johansson, A. Linderholt, K. Jarnerö, P. Landel, Tall timber buildings—A preliminary study of wind-induced vibrations of a 22-storey building, in: Proceedings of the WCTE, 2016.
[169] I. Edskar, H. Lidelow, Wind-induced vibrations in timber buildings-parameter study of cross-laminated timber residential structures, Struct. Eng. Int. 27 (2) (2017) 205–216.
[170] I. Edskär, H. Lidelöw, Dynamic properties of cross-laminated timber and timber truss building systems, Eng. Struct. 186 (2019) 525–535.
[171] X. Zhao, B. Zhang, T. Kilpatrick, I. Sanderson, D. Liu, Numerical analysis on global serviceability behaviours of tall glulam frame buildings to the eurocodes and UK national annexes, J. Civ. Eng. Constr. 10 (3) (2021) 109–122.
[172] P. Landel, M. Johansson, A. Linderholt, Comparative study of wind-induced accelerations in tall timber buildings according to four methods, in: WCTE 2021, World Conference on Timber Engineering, Santiago, Chile, 9-12 August, 2021.
[173] M. Bezabeh, G. Bitsuamlak, M. Popovski, S. Tesfamariam, Dynamic response of tall mass-timber buildings to wind excitation, J. Struct. Eng. (US) 146 (10) (2020).

[174] E. Lazzarini, G. Frison, D. Trutalli, L. Marchi, R. Scotta, Comfort assessment of high-rise timber buildings exposed to wind-induced vibrations, Struct. Des. Tall Special Build. 30 (12) (2021).
[175] C. Rainieri, G. Fabbrocino, Operational Modal Analysis of Civil Engineering Structures, Springer New York, NY, 2014.
[176] F. Magalhães, Á. Cunha, E. Caetano, Vibration based structural health monitoring of an arch bridge: From automated OMA to damage detection, Mech. Syst. Signal Process. 28 (2012) 212–228.
[177] S. Pereira, F. Magalhães, Á. Cunha, C. Moutinho, J. Pacheco, Modal identification of concrete dams under natural excitation, J. Civ. Struct. Health Monit. 11 (2) (2021) 465–484.
[178] A. Cigada, A. Caprioli, M. Redaelli, M. Vanali, Vibration testing at meazza stadium: Reliability of operational modal analysis to health monitoring purposes, J. Perform. Constr. Facil. 22 (4) (2008) 228–237.
[179] R. Alaggio, A. Aloisio, E. Antonacci, R. Cirella, Two-years static and dynamic monitoring of the Santa Maria di Collemaggio basilica, Constr. Build. Mater. 268 (2021) 121069.
[180] B. Ellis, A. Bougard, Dynamic testing and stiffness evaluation of a six-storey timber framed building during construction, Eng. Struct. 23 (10) (2001) 1232–1242.
[181] T. Reynolds, A. Feldmann, M. Ramage, W. Chang, R. Harris, P. Dietsch, Design parameters for lateral vibration of multi-storey timber buildings, in: International Network on Timber Engineering Research Proceedings (INTER 2016), 2016.
[182] I. Mugabo, A. Barbosa, M. Riggio, Dynamic characterization and vibration analysis of a four-story mass timber building, Front. Built Environ. 5 (2019).
[183] G. Hafeez, G. Doudak, G. McClure, Effect of nonstructural components on the dynamic characteristics of light-frame wood buildings, Can. J. Civil Eng. 47 (3) (2020) 257–271.
[184] G. Hafeez, G. Doudak, G. McClure, Dynamic characteristics of light-frame wood buildings, Can. J. Civil Eng. 46 (1) (2019) 1–12.
[185] G. Hafeez, G. Doudak, G. McClure, Establishing the fundamental period of light-frame wood buildings on the basis of ambient vibration tests, Can. J. Civil Eng. 45 (9) (2018) 752–765.
[186] Y.-M. Kim, Y.-M. Kim, H.-J. Kim, T.-U. Ha, E.-M. Shin, W.-J. Kim, Analysis of roof load and dynamic characteristics of traditional timber building considering column axial force and ambient vibration measurement, J. Archit. Inst. Korea 37 (11) (2021) 271–280.
[187] B. Peeters, G. De Roeck, One-year monitoring of the Z24-bridge: environmental effects versus damage events, Earthq. Eng. Struct. Dyn. 30 (2) (2001) 149–171.
[188] C.R. Farrar, K. Worden, An introduction to structural health monitoring, Phil. Trans. R. Soc. A 365 (1851) (2007) 303–315.
[189] A. Rytter, Vibrational based inspection of civil engineering structures, 1993.
[190] D. Yang, D. Youliang, L. Aiqun, Structural condition assessment of long-span suspension bridges using long-term monitoring data, Earthq. Eng. Eng. Vib. 9 (1) (2010) 123–131.
[191] L.F. Ramos, L. Marques, P.B. Lourenço, G. De Roeck, A. Campos-Costa, J. Roque, Monitoring historical masonry structures with operational modal analysis: two case studies, Mech. Syst. Signal Process. 24 (5) (2010) 1291–1305.
[192] G. Zonno, R. Aguilar, R. Boroschek, P.B. Lourenço, Analysis of the long and short-term effects of temperature and humidity on the structural properties of adobe buildings using continuous monitoring, Eng. Struct. 196 (2019) 109299.
[193] Y. Xia, B. Chen, S. Weng, Y.-Q. Ni, Y.-L. Xu, Temperature effect on vibration properties of civil structures: a literature review and case studies, J. Civ. Struct. Health Monit. 2 (1) (2012) 29–46.
[194] F. Ubertini, G. Comanducci, N. Cavalagli, A.L. Pisello, A.L. Materazzi, F. Cotana, Environmental effects on natural frequencies of the San Pietro bell tower in Perugia, Italy, and their removal for structural performance assessment, Mech. Syst. Signal Process. 82 (2017) 307–322.
[195] W.-H. Hu, Á. Cunha, E. Caetano, R.G. Rohrmann, S. Said, J. Teng, Comparison of different statistical approaches for removing environmental/operational effects for massive data continuously collected from footbridges, Struct. Control Health Monit. 24 (8) (2017) e1955.
[196] C. Larsson, O. Abdeljaber, Bolmsvik, M. Dorn, Long-term analysis of the environmental effects on the global dynamic properties of a hybrid timber-concrete building, Eng. Struct. 268 (2022).
[197] G. Granello, A. Palermo, Monitoring dynamic properties of a pres-lam structure: trimble navigation office, J. Perform. Constr. Facil. 34 (1) (2020) 04019087.
[198] C. Leyder, F. Wanninger, A. Frangi, E. Chatzi, Dynamic response of an innovative hybrid structure in hardwood, Proc. Inst. Civ. Eng. Constr. Mater. 168 (3) (2015) 132–143.
[199] A.C. Altunişik, O.Ş. Karahasan, F.Y. Okur, E. Kalkan, K. Özgan, Ambient vibration test and modelling of historical timber mosques after restoration, Proc. Inst. Civ. Eng. Struct. Build. 173 (12) (2020) 956–968.
[200] N.F. Alkayem, M. Cao, Y. Zhang, M. Bayat, Z. Su, Structural damage detection using finite element model updating with evolutionary algorithms: a survey, Neural Comput. Appl. 30 (2) (2018) 389–411.
[201] A. Teughels, J. Maeck, G. De Roeck, Damage assessment by FE model updating using damage functions, Comput. Struct. 80 (25) (2002) 1869–1879.
[202] A.C. Altunisik, O.S. Karahasan, F.Y. Okur, E. Kalkan, K. Ozgan, Finite Element Model Updating and Dynamic Analysis of a Restored Historical Timber Mosque Based on Ambient Vibration Tests, ASTM International, 2019.
[203] K.-W. Min, J. Kim, S.-A. Park, C.-S. Park, Ambient vibration testing for story stiffness estimation of a heritage timber building, Sci. World J. 2013 (2013).
[204] A. Aloisio, D. Pasca, R. Tomasi, M. Fragiacomo, Dynamic identification and model updating of an eight-storey CLT building, Eng. Struct. 213 (2020) 110593.
[205] B. Kurent, B. Brank, W.K. Ao, Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing, Struct. Infrastr. Eng. (2021) 1–19.
[206] J.L. Beck, L.S. Katafygiotis, et al., Updating models and their uncertainties. I: Bayesian statistical framework, J. Eng. Mech. Proc. ASCE 124 (4) (1998) 455–462.
[207] N. Shirzad-Ghaleroudkhani, M. Mahsuli, S.F. Ghahari, E. Taciroglu, Bayesian identification of soil-foundation stiffness of building structures, Struct. Control Health Monit. 25 (3) (2018) e2090.
[208] C. Leyder, E. Chatzi, A. Frangi, Vibration-based model updating of a timber frame structure, Procedia Eng. 199 (2017) 2132–2139.
[209] B. Kurent, N. Friedman, W. Ao, B. Brank, Bayesian updating of tall timber building model using modal data, Eng. Struct. 266 (2022).