Faircloth et al. Journal of Wood Science (2025) 71:71
https://doi.org/10.1186/s10086-025-02247-4

Journal of Wood Science

REVIEW ARTICLE

Open Access

Global state of knowledge on human-induced sound and vibration events: defining future research directions for mass timber products

Adam Faircloth[1,2*], Hassan Karampour[1], Patricia Hamm[3], Theresa Müller[4], Aleksandar Pavic[5,6,7], Paul Reynolds[5], Benoit P. Gilbert[1], Stefan Schoenwald[8], Haoyu Huang[9], Philippe Grönquist[4], Johannes Ruf[3], Loic Brancheriau[10] and Chandan Kumar[2]

Abstract

Despite the rise in mass timber buildings globally, challenges remain with timber's limitations in low-frequency sound and vibration. This is due to timber's lower density compared to concrete and steel, leading to natural frequencies more susceptible to disturbances from footfall vibrations. This study identifies areas for further research in floor sound and vibration through a combined analysis of practitioner consultations and systematic review. A total of 112 discussions across 13 countries captured varying perspectives from producers of mass timber products through to designers of mass timber structures, as well as researchers of these different approaches. Of those consulted, 75% of producers noted increased mass timber product demand alongside a need for more design data, with 61% of designers and builders facing challenges related to sound and vibration. In addition, 17% of builders reported receiving tenant complaints over sound and vibration-related concerns, with 44% of practitioners noting concerns over sound and vibration performance. Several standards/design guides were analysed and ranked through the systematic review and practitioner consultation finding FprEN 1995-1-1, CCIP-016, and BS 6472-1 to be highly ranked from both analysis approaches. However, there were several cases, where standards ranked highly through the literature analysis approach were not highly ranked through the analysis of practitioner responses. Three under-researched areas were identified: (1) long-span floor systems, (2) the influence of mass timber product material properties, and (3) the undefined relationship between lab and in-situ performance. Furthermore, 71% of practitioners highlighted that the perception of comfort by occupants is under-represented in current research.

Keywords Low frequency, Vibration, Sound insulation, Occupant comfort, Perception, Serviceability, Timber floors

*Correspondence:
Adam Faircloth
Adam.Faircloth@dpi.qld.gov.au
Full list of author information is available at the end of the article

Introduction

In 2018, the United Nations Sustainable Development Goals were created, identifying 17 areas having an elevated influence on the changing climate conditions globally [1]. One of these 17 areas is the built environment which contributes close to 40% of the global greenhouse gas (GHG) emissions [2]. Methods to reduce the GHG emissions generated by the built environment are of high priority for governments and researchers globally with timber or timber composite products considered a potential solution [3]. Recent innovations in mass timber products (MTPs) such as cross-laminated timber (CLT), glued laminated timber (GLT or glulam), and composites present opportunities to compete with conventional building materials such as concrete and steel on a low-to-mid-rise scale [4–7]. MTPs offer comparable structural performances to concrete and steel (based on a strength to weight ratio), solutions for timbers' material stability concerns, cost-effective design, easy installation, and often less trade on site [8–10]. MTPs are also a natural carbon sink, allow for rapid installation, often require a smaller building foundation/footprint, and a host of biophilic benefits that come with working/living in 'green spaces' [4, 8, 10, 11].

An area that still generates significant interest for MTPs is their performance against occupant induced vibration and sound [12–16]. Due to timber's low density (relative to concrete and steel), it often exhibits limitations in resisting low-frequency vibration and sound events, such as those commonly excited by footfall loading (walking vibrations) and other impacts [17]. These limitations can lead to design challenges, such as excessive dynamic deflections, uncomfortable or continuous structural motions, and transmission of low-frequency impact sound between adjacent floors and rooms as well as across various storeys [15, 17], which is perceived as very annoying by building occupants [16]. Several articles have documented these limitations, and designers and builders still seek additional information to confidently use MTPs and overcome the noted challenges with respect to low-frequency vibration and sound insulation [18–20]. The desire for design information from these practitioners comes from the lack of clarity that exists globally on the use of MTPs in construction due to limited research on their in-situ application [15, 21]. Researchers who have significantly contributed to this through product-focused research, however, often do not capture the specific challenges of today's mass timber industry and newer timber composite product options. These challenges include (but are not limited to) design-specific information for new material types, validated parameters that can be measured that relate to human perception and comfort, and the validated influence of each contributing stage of a floor's development. In 2023, literature related to vibration serviceability made up only 4.5% of available mass timber literature and sound insulation research made up a smaller 1.5% worldwide [22]; however, practitioner concern over these themes continues to grow.

The authors of this article hold a positive view that the concern is not for risk of 'bouncy' or non-conformant floors, but an opportunity to increase material efficiency and deliver future structures with enhanced vibration and noise performance. This article presents a combined literature analysis and practitioner consultation to define challenges being faced by designers, producers, and researchers with respect to occupant induced vibration and sound insulation of MTPs. The article has consolidated global research to date through a comprehensive systematic review of 118 articles, standards, design guides, and website publications that have been summarised in the Background section. The outcomes of 112 conversations with mass timber practitioners from 13 different countries are presented in the Practitioner Conversations section which identified priority areas on the Product and System Design requirements, the Product Performance Evaluation, and Regional Variations sections. The Theme Comparison section then compares the general themes identified through the systematic review with the priority areas raised by the consulted practitioners to define potential gaps or underdeveloped linkages between ongoing research and industry concerns.

Background

This section contains the summarised key findings from the review of 118 articles specific to vibration and sound insulation in MTPs. The section first describes the literature selection, Systematic Review, process through an analysis of the reviewed articles and breakdown of article types. Following this, two main literature themes are presented and summarised as (1) Product and Design Requirements, and (2) Product Performance Evaluation.

Systematic review

Using keywords such as "vibration", "sound insulation", "occupant induced", "serviceability", "comfort", "mass timber construction" and "mass timber floors," several targeted studies were reviewed and are discussed below. The articles were selected with a focus on mass timber construction challenges related to vibration and noise caused by occupants. Additional terms such as "perception", "challenges", and "barriers to increased use" were combined with specific keywords to identify relevant studies on mass timber floors and solutions for excessive vibration or inadequate sound insulation. Where publications were insufficient, online articles, technical reports, and international standards were included. The search identified 118 articles, standards, design guides, and website publications. Using a "keyword co-occurrence", Fig. 1 was generated to show the linkages between co-occurring or paired keywords across the selected articles. Figure 1 shows more consistently paired keywords as larger bubbles and bigger text compared to those that are less commonly linked.

The data from the 118 articles was also analysed through a publication timeline (Fig. 2), showing an increase in the use of keywords over time. Figure 2a highlights the lack of research on MTPs before the early 2000's, likely due to missing terms such as "mass timber panels" or "cross laminated timber" along with phrases such as "serviceability", "comfort", and "perception" as related to human interactions with timber structures. This aligns with CLT's market introduction in the early 1990's [4, 22, 23]. After CLT's conception in the 1990's research grew, with significant expansion from 2010 onward, focusing on comfort-specific topics (Fig. 2b). This reflects both the increasing research in the field and a shift toward in-situ product performance.

Reviewing 118 articles revealed that 42.2% of the literature focuses on floor vibration and serviceability research, covering testing of bare materials composites, and hybrid constructions. Vibration analysis and design methods, linked with floor stiffness, are well-represented, with 42.2% of the literature having this theme (Fig. 2b). The rise of new products suggests a need for consistent testing methods. The literature analysis identified 27 floor/building standards and design guides (16 on vibration, 11 on sound insulation) but only 35.3% have been assessed against or mention MTPs, with limitations, such as spans and fundamental natural frequency constraints [24, 25]. These conservatisms, especially with long-span floor systems (LSFS—where the literature defines this as greater than ~ 8 m), often lead to over-designed floors, limiting the use of MTPs and slowing research into LSFS (9.2% of the literature) [15, 26–28]. Sound insulation research, though closely linked to vibration, represents just 26.6% of the studies, focusing mostly on laboratory

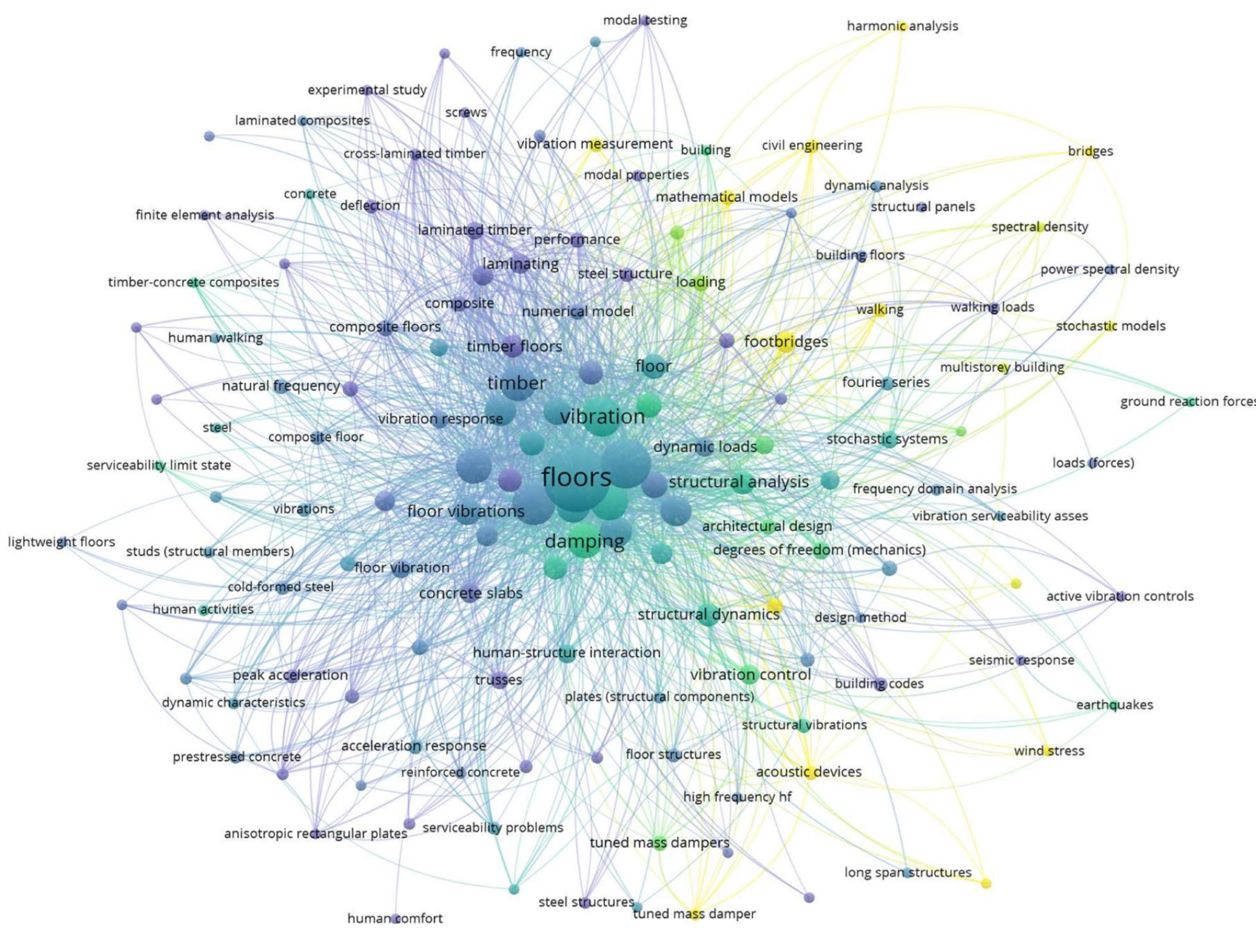


Fig. 1 Word cloud of keywords extracted from reviewed literature (VOS viewer: https://www.vosviewer.com/)

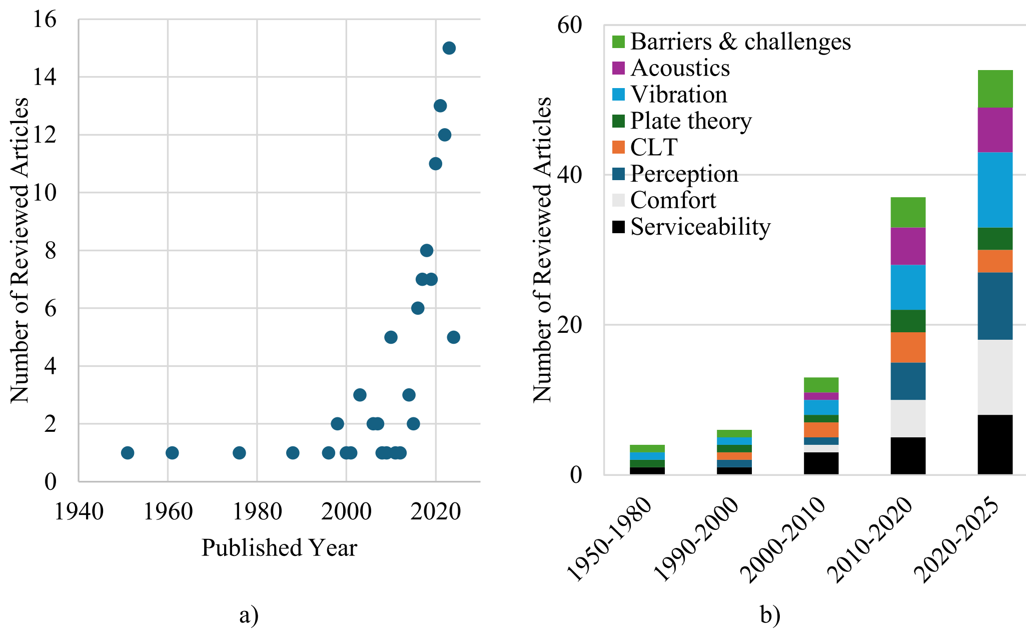


Fig. 2 **a** Timeline distribution of 118 articles reviewed, **b** proportion of keyword mentions against year ranges

testing with limited in-situ or perception-related works [16, 29–32]. Given the anecdotal interest from industry being more aligned to vibration, this study has focused more so on vibration-related works and topics with some sound insulation information still reported, but to a lesser extent.

It should be noted that standards on sound insulation requirements and methods for sound insulation testing are material independent. Furthermore, standards for the control of excessive noise (such as ISO 12354 series [33, 34]) are general in nature and targeted to the audible noise range for occupants (200–20,000 Hz) with low-frequency noise (below 50 Hz) remaining underexplored. Further material characteristic data on the effect various material layers and configurations can have on the control of excessive noise is considered needed for better solutions. Only 16.5% of studies address occupant perception, and many rely on bench testing rather than in-situ analysis [16, 24, 35–38]. Footfall experiments reveal inconsistencies between measured vibration and sound insulative floor performance and perception, suggesting inconsistencies between conformant design and favourable vibration and sound insulation perception. From the literature analysed in this section, 18 topical themes have been extracted and examined. Similar to the connections developed in Fig. 1, linkages between these themes have been analysed and proposed. Figure 3 maps research themes that are developed and underdeveloped as measured through the amount of or lack of literature related to these themes based on the keyword co-occurrence analysis performed previously in this section. From the literature analysis summarised, two broad umbrella themes have been developed and discussed further as key contributors to the successful development of MTP floor systems; (1) Product and System Design, and (2) Product Performance Evaluation. These two themes have been selected due to their broad and all encapsulating definitions relating to the future focus of the study; human induced sound and vibration events in mass timber structures. These have been explored below with noteworthy findings discussed.

Product and system design

Understanding product properties, capabilities, and limitations is crucial in floor design and product selection [39–41]. Designers must consider how products may perform under expected activities, in-service, and within anticipated boundary conditions (enforced through floor structural details) [39–43]. Through the consultation and tours undertaken, the three most common construction approaches for mass timber structures are shown in Fig. 4. Solid CLT walls provide advantages for lateral loading and bracing but use more materials (Fig. 4a). Open plan spaces, such as offices or schools, typically use a ‘post-and-beam’ configuration with non-load bearing partitioning walls and large spans allowing flexibility (Fig. 4b). More common in medium scale residential design is the combination of CLT floors with light weight framed walls (Fig. 4c).

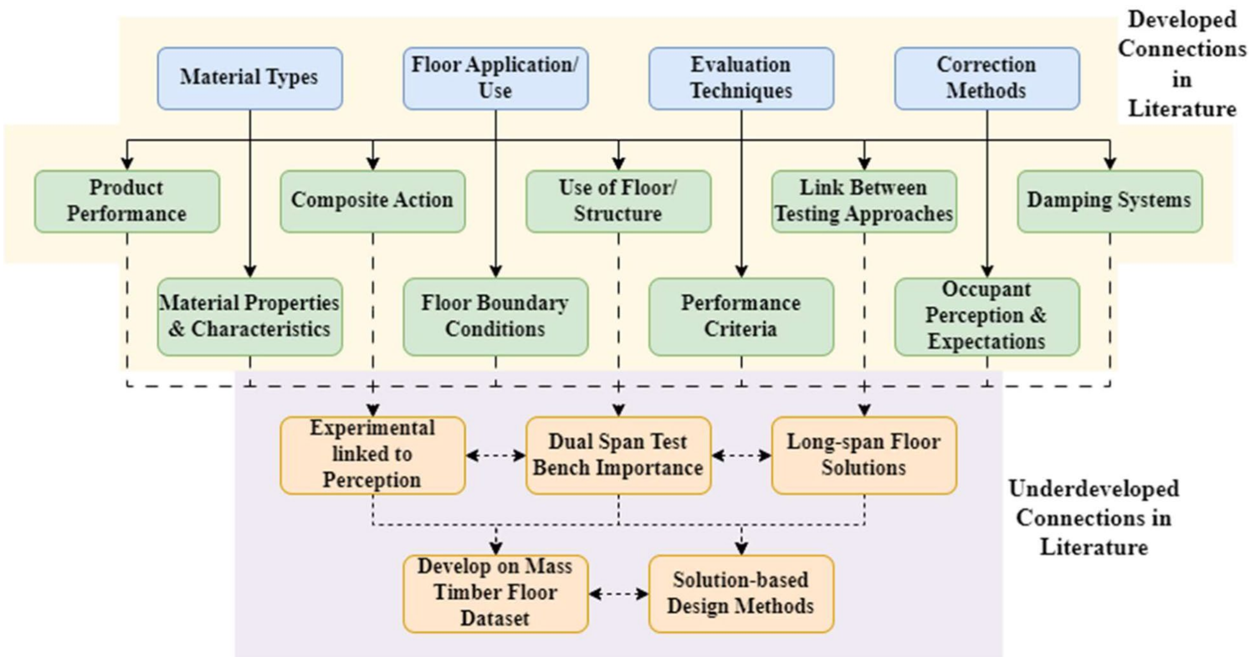
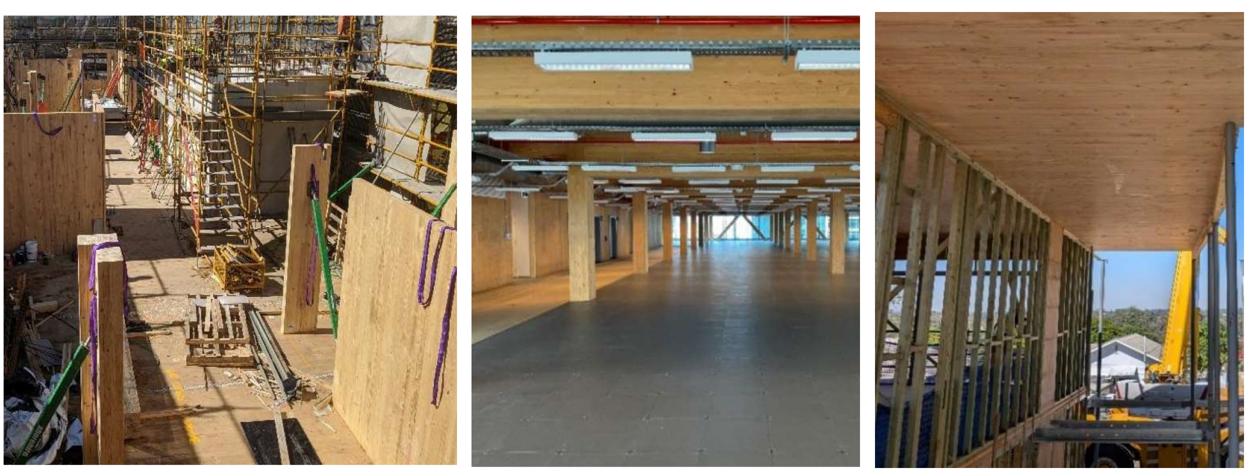


Fig. 3 Summary of review literature linkages as well as connections considered as needing further definition. The box colours refer to the separation of the broad categories governing changes to performance (the blue), the themes available through the literature (the green), and the less addressed (or not addressed) themes (the orange)



a) b) c)

Fig. 4 Three common mass timber building construction methods viewed: **a** solid wall option, **b** post-and-beam design, and **c** solid mass timber (CLT) floor with light weight framing walls

Different floor plan configurations that use framing, solid mass timber walls, or posts and beams significantly affect overall floor vibration and sound insulation performance due to the affected boundary conditions, whether load bearing or not [44–48]. These configurations can lead to misleading measurements during construction and are difficult to replicate in the laboratory. Kawrza et al. [45] evaluated a CLT floor in three stages: (1) bare CLT floor, (2) CLT floor with non-structural partitions, and (3) an added 175 mm thick screeded concrete floor to (2). While the added mass decreased the fundamental natural frequency [49–51], the damping ratios surprisingly yielded the following trend (1) = 5.1%, (2) = 8.1%, and (3) = 2.1%, respectively. Kawrza et al. [45] attributed these irregular damping ratios to the lightweight floor in (1) and the partitioning walls altering the boundary conditions in (2). The screeded concrete floor mass in (3) normalized the damping ratio. This and other studies highlight the possibility to use damping as a detection method for installation defects or poorly jointed panels [44, 47, 52].

The Council on Tall Buildings and Urban Habitat (CTBUH) reported that in 2022, there were 139 mass timber buildings globally (greater than 8 storeys) with 45% all timber, 35% timber concrete composite (TCC), 12% concrete–steel–timber, and 8% steel–timber construction [53]. Though 55% were constructed with hybrid construction methods, most finished floors are considered hybrid due to added layers for services and aesthetics [31, 44, 50]. The most common hybrid category according to the 2022 report was TCC structures and floors. The design of these composite floor systems must account for their purpose, such as using concrete to increase mass and damping ratios or relying on the composite action to improve stiffness; however, as shown above, it is clear this is not always the case. An important theme of research for TCC floors is ongoing to optimise performance versus environmental sustainability [31, 54–56]. Studies on TCC panel thickness show that as concrete thickness increases, damping ratios will decrease but fundamental natural frequencies will increase. Damping ratios and the fundamental frequency were seen to fluctuate between 3.9 and 13.1%, respectively, as concrete thickness increases when compared to bare MTPs of comparable thickness [57–59]. Müller et al. [31] and Zhou et al. [60] address the challenges of designing for both sound insulation and vibration comfort, with sound insulation solutions often requiring disconnection and cavities, while vibration improvements require stiffening through composite action [31, 55, 60, 61]. Despite a 20% improvement in sound insulation measured through reduced sound transmission and increases in damping ratios from concrete screeds and cavities, low-frequency noise (below 50 Hz) remains a concern for designers. This is coupled with the growing demand for sustainable construction solutions, and relying on concrete to solve design challenges is not always the optimum approach. Based on this, it could be said that sound insulation improvement measures appear directly related to the overall environmental impact depending on the materials used [20, 31, 61–63]. The main difference between TCC and concrete screeded solutions is the relationship between mass, stiffness, and damping [54]. Mass, stiffness, and damping are key parameters in predicting a building elements' vibration performance, directly affecting product performance and guiding design [52].

Hollow type mass panel constructions offer a potential alternative to solid CLT allowing for longer clear spans, minimising panel mass, and maintaining a relatively slender cross section [32, 64]. Huang et al. [64] explored a hollow-core CLT design, removing every second board in the inner layers of three- and five-layer CLT panels (105 mm and 175 mm thick, respectively), and tested its response to footfall excitation. The hollow-core CLT measured 3.1% (three-layer) and 10.4% (five-layer) lower damping ratios, and fundamental natural frequencies 10.6% (three-layer) and 39.5% (five-layer) lower compared to solid CLT panels. These frequency reductions likely stem from more decreased stiffness than mass. Interestingly, acceleration values for both solid and hollow-core CLT panels were similar. This highlights possible variations in acceptability depending on which design standard is used with different standards prioritising different parameters.

Challenges in new product designs can often come from a disconnect across disciplines. Research from a holistic design approach shows greater success in achieving interdisciplinary exchange, relevant to this hollow box system. Krtschil et al. [65] with the University of Stuttgart (Stuttgart, Germany) have and continue to investigate how the impact sound transmission can be positively influenced by reducing the amount of material used in design through hollow box panelised systems. Not only does the design explored by Krtschil et al. [65] allow for 24% less material to be used compared to a solid CLT alternative, it also achieves structural decoupling between layers, reducing impact sound transmission by 12% when compared to a solid CLT alternative [32]. Structural decoupling is deliberately built into the hollow box system targeting a change in stiffness [32, 64]. This approach offers a viable alternative for concrete constructions and addresses the lack of integration of sound insulation requirements in the design and construction of timber buildings [32]. This balance between reduced mechanical capacity (thus raising acceleration) and air gaps (lowering it) highlights the potential for hollow-core and hollow-box CLT and other variations to standard design for both vibration and sound insulation benefits.

The majority of reviewed floor designs both in laboratories and in-situ have been restricted to a tested span of ~ 6 m. This may not be representative as conventional mass timber floor systems struggle to achieve compliant measured values of fundamental natural frequency, acceleration, response factors (RF) and damping ratios at spans longer than 6 m. Methods to overcome restricted spans include layered construction types, where the added mass or air cavities improve damping ratios, natural frequency (if composite action is achieved), and sound absorption. Limiting designed spans to ~ 6 m nominally has also become industry standard rather than considering alternative long-span floor designs, which is a missed opportunity. Designs exceeding this unenforced limit often require additional data to justify the variation from common practice.

Product performance evaluation

Three main approaches exist for evaluating the mass timber floor vibration and sound insulation performance: (1) laboratory testing, (2) in-situ testing, and (3) subjective perception [54, 66]. The growing demand for knowledge-based solutions in floor system design stems from insufficient clarity in existing standards for MTPs with respect to proven data sets outlining their performance for the different product options that exist [37, 67, 68]. To refine standards efficiently, experimental testing must mimic in-situ applications, emphasising laboratory tests that replicate spans in both orthogonal directions and floor build-ups for sound transmission [51, 54, 56, 66, 69–72]. Studies have also highlighted significant variation between laboratory and in-situ testing for both vibration and sound insulation assessments [45, 54, 66, 73–75]. Given that CLT is an orthotropic material and can span in two directions, research using orthogonal (or dual) span test benches may enhance the understanding of its vibration performance and strengthen the correlation between laboratory and in-situ performance. Table 1 displays a selection of reviewed studies and details of the tested floor systems. In most of the single and short span cases, the natural frequencies are relatively high compared to the longer span or dual spanning test benches [51, 54, 66]. This is especially present in those studies with a large span-to-depth ratio, leading to lower natural frequencies and smaller differences between natural frequencies [38]. It is important to consider that for a number of design standards (such as Eurocode 5 and FprEN 1995-1-1), the floors' first natural frequency is limited to 8 Hz minimum (below which a more rigorous analysis is required), which as the select floor examples below indicate, longer spanning and alternative material conditions can influence this acceptance criteria. It should also be noted that the floor results presented below were conducted in a laboratory environment, using a simply supported boundary condition for all floor systems.

Hamm et al. [38] assessed a dual spanning test bench 12.5 (L) × 12.5 (W) m with various floor configurations. Comparisons between the bare CLT floor supported by glulam beams condition and those with added layers (sound insulation, screed, pavers) showed damping ratios remain largely unchanged, while fundamental natural frequencies were reduced by 32%. Although some studies note the natural frequency to be sensitive to added mass, the authors suggest the mass increase is insufficient to affect the damping ratio significantly. A substantial increase in mass could lower the damping but can also reduce frequency (unless a significant increase in stiffness also occurs). Low damping ratios and low natural frequencies can lead to resonance, potentially causing discomfort to prolonged vibrations, which aligns with standards focusing on properties other than the damping ratio (such as the clear spanning length which has been shown to reduce damping also [38]).

The literature identified prominently used standards in a similar way to the co-occurrence analysis conducted on keywords in the Background for both vibration analysis and sound insulation properties in floor systems. While the acoustic methods appeared to be more focused on material testing and, therefore, somewhat consistent in their approach, vibration assessments varied greatly. To give some perspective on the many differences of approach that exist for vibration evaluation and design, the standards and design guides identified specific to vibration are listed in Table 2. Here, 16 standards have been tabulated, along with a description of the standard, its classification as either a design or evaluation type standard, and its developer origin. It can be noted that

Table 1 Results of floor vibration assessments compiled on test bench investigations (data sourced from [38, 44, 50, 51, 54, 66]). The thickness (T) is reported for the CLT only, not including the supporting beams

Material (plate and supports)	Plate dimension (L, W, T) m	1st freq (Hz)	2nd freq (Hz)	3rd freq (Hz)
Uncovered CLT floor with steel beams	9.0 × 6.6 × 0.12	7.9	14.6	32.0
Uncovered CLT floor with steel beams	6.0 × 5.6 × 0.11	5.2	7.9	14.4
Uncovered CLT floor with steel beams	6.0 × 2.4 × 0.11	18.2	23.0	26.8
Uncovered CLT with glulam beams	4.2 × 2.9 × 0.19	13.3	15.7	32.6
Uncovered CLT with glulam beams	5.5 × 1.5 × 0.07	14.9	20.3	20.2
Uncovered CLT with glulam beams	12.5 × 12.5 × 0.03	6.2	7.4	8.6
CLT floor with concrete screed topping	12.5 × 12.5 × 0.19	4.2	5.0	5.1

Table 2 Description of standards and design guides highlighted through regular occurrence in literature (data sourced from [24, 25, 27, 35, 36, 77–89])

Standard	Type	Origin	Standard	Type	Origin
FprEN 1995–1-1	Design	Europe	CCIP-016	Design	UK
AISC DG11	Evaluation	America	ISO 10137	Evaluation	Europe
ISO2631.1/AS2670.1	Evaluation	Europe	SCI-P354	Design	UK
AS/NZS 1170.0	Design	Australia	BS 6472-1	Evaluation	UK
HIVOSS	Evaluation	Europe	CSA 086:19	Design	Canada
AS/ISO 2631.2	Evaluation	Australia	Canadian CLT DG	Design	Canada
ISO 18324	Evaluation	Europe	WS DG 49	Design	Australia
ISO/TR 21136	Evaluation	Europe	AISC DG 37	Design	America

the classification of standards shows a relatively even split between the two types with 8 design and 8 evaluation type standards/design guides. A general observation of Table 2 is the suggestion that design and evaluation type standards are not harmonised [76]. Chang et al. [76] proposed a harmonised approach allowing the incorporation of multiple parameters to more accurately predict floor performance. This harmonised method suggests a staggered approach using response factors obtained as in CCIP-016 [35] and vibration dose values (VDVs) calculated from ISO 10137 to then estimate the total number of allowable events according to the SCI P354 [77].

The differences of approach for these 16 vibration standards are separately discussed in the following sections: performance variables, vibration events, and perception evaluation. It is worth highlighting that as noted previously, design and evaluation type standards are not material specific; rather, they are general in nature. The challenge MTPs face comes from the lack of calibration data available to validate the use of these design and evaluation standards and design guides on timber structures. Therefore, it is important to analyse the various approaches, their role in design or evaluation, and what properties they consider most important.

Performance variables

Acceleration is a key factor in floor vibration, with peak limits outlined in various standards [82, 83, 87]: 0.5%g for quiet spaces, 1.5%g for shopping malls, and 5.0%g for outdoor areas [68, 87]. Peak Acceleration or RMS (root mean squared) acceleration, vibration dose value (VDV), and maximum transient vibration value (MTVV), are key assessment parameters in a number of standards, linking them to building classifications and perceived comfort. Often, where these values are lower the perceived performance from occupants is more positive. The fundamental natural frequency is an indirect way of limiting vibration response. The limits vary, with the 2004 version of EN 1995-1-1, and AS 1170.0 targeting 8 Hz, while the revised FprEN 1995-1-1 suggests a threshold of 4.5 Hz. Frequencies between 4 and 8 Hz are associated with negative perceptions [35, 82]. AISC DG 37 [89] sets a lower limit of 3.0 Hz, and HIVOSS recommends avoiding 1.3–4.6 Hz, respectively. Hamm [90] applied prEN 1995-2 to bridge design, showing that spans up to 12 m typically maintain frequencies of 4–5 Hz.

Prescribed damping ratios also vary, with Wood Solutions Design Guide 49 (used in Australia) [27] consolidating limits from various standards. FprEN 1995-1-1 suggests 1 to 3.5%, ISO 10137 indicates 2 to 3%, and HIVOSS allows up to 6% for bare wooden floor systems in open plan office spaces. Accurately measuring the damping ratio is challenging at the best of times, particularly if testing conditions differ from final in-situ conditions. Consequently, various standards and design guides propose different thresholds for frequency and damping ratios, which can create confusion for designers trying to determine which standards and/or design guides to follow and when to apply them. Establishing a more consistent, unified guide would help clarify these differences and support more informed decision-making. Some prescriptive standards such as ISO 10137 and BS EN 6472-1 have not been revised or had more recent test information introduced to them for some time (last revisions were 2007 and 2008, respectively). New information drawn from recently published and ongoing research could be integrated to revise such standards.

Vibration events

Response factors (RFs) predict a floor's conformance based on measured and perceived indicators [35]. RFs can be estimated from predicted natural frequency values for theoretical floor design modelling and are included in the new FprEN 1995-1-1. However, since RF limits originate from work focused on concrete and composite floor systems (dating back to the 1980s), its relevance to mass timber is unknown and yet to be fully explored. Similarly, SCI-P534 [77] and the OS-RMS90 [85] methods assess allowable excitation events before complaints arise, but differing methods yield varying results. Muhammad et al. [91] tested a multi-storey office with steel–concrete composite floors and found discrepancies across several predictive methods for RFs when compared to actual values. The type of excitation, especially from multiple walkers, is another contributor which can significantly impact assessment [92]. Wang et al. [93] showed that multiple walkers could raise VDV by 30%. This factor is factored into the standards for design of pedestrian bridges but often neglected in standards for design of floors [35, 54, 94].

Perception evaluation

Quantitative interpretation of comfort from qualitative data is complex, as many standards link perception to measured values [37, 95]. Comfort is influenced by the vibro-acoustic environment which is normally undefined. Hence it is not surprising that Pavic [37] noted that compliant structures often fail to satisfy floor users. Although 35% of the reviewed standards address occupant perception, only 17% of studies reviewed in this paper focus on it. Responses to vibration are highly subjective, and perceived performance data are less readily available than measured value data for mass timber floors. The response amplitude significantly influences vibration perception, with a baseline perceivable acceleration limit of approximately 0.5%g according to ISO 10137 to WoodWorks [94]. Both CCIP-016 [35] and WoodWorks [94] indicate that small changes in acceleration are hard to detect, with noticeable changes requiring double the amplitude. Acceleration at 0.5%g within 4–8 Hz is often perceived as particularly uncomfortable, while the same acceleration within 3–15 Hz is considered ‘transitional’ and less predictable [35, 82, 94]. RFs are effective for assessing perceived performance and occupant comfort [35, 36]. FprEN 1995-1-1 defines eight floor classifications based on RFs, from low to unrestricted vibrations. VDVs as detailed in SCI-P354 [77], take into account both duration and magnitude of vibration exposure, and can indicate the likelihood of adverse comments if limits are exceeded, with high tolerances for evenings versus daytime events. ISO 21136 includes a perception assessment process, where occupants answer questions about their personal vibration tolerances, walk across the floor, and provide feedback. ISO 21136 acknowledges that perception may vary across cultures and serves as a framework for developing region-specific perception testing standards. Environmental expectations also influence perceived vibration and sound insulation [96]. Virtual reality (VR) studies by Huang et al. [96] showed that occupants have lower vibration tolerances in private settings by ‘removing’ them from the laboratory and simulating different environments. These findings suggested that VDV metrics may correlate better with comfort than RFs. Finally, the interaction between occupants and floor materials affects perception also [92, 97]. Considering the linkage between vibration events and sound insulation, Ljunggren et al. [16] found footfall noises particularly annoying in lightweight timber and CLT structures, while concrete was less problematic. Understanding loading profiles and the influence of additional layers is crucial for assessing perceived comfort, as some studies indicate these materials may be ineffective at reducing noise below certain frequencies [16, 17, 62, 63, 98–100]. Overall, this section attempts to highlight the limited perception data that exists in this field and for this material type while also overlaying the importance refined perception information introduces into design. From the somewhat outdated design criteria referenced in the previous sub-sections, perception presents a clear path toward refinement.

Practitioner conversations

The following sections summarise the insights gathered from conversations with various experts in the processing, manufacture, design, evaluation, and use of mass timber products. The section first reviews the location of the practitioners and their respective roles, Scoping of Practitioner Concerns. The conversation information has then been separated into the three main product implementation groupings of Product and System Design requirements, Product Performance Evaluation, and Regional Variation. The aim of this component of the study has been to consolidate the wider perceived concerns for the industry.

Scoping of practitioner concerns

One hundred and twelve practitioners were engaged across 13 countries (Fig. 5) over 2 years by the first author. The map legend in Fig. 5 indicates regions, where greater numbers of practitioners were selected. The consultations were conducted in person and consisted of discussions specific to product and building design details and challenges the practitioner(s) had faced regarding vibration and sound insulation measurement, mitigation, and correction. The practitioners were selected due to their position within the supply chain for the use of MTPs in the built environment. The distribution of the roles these practitioners held has been described further in Fig. 6.

The consultations generally aimed at determining perceived barriers to the increased use of MTPs in the built environment, and design and mitigation methods

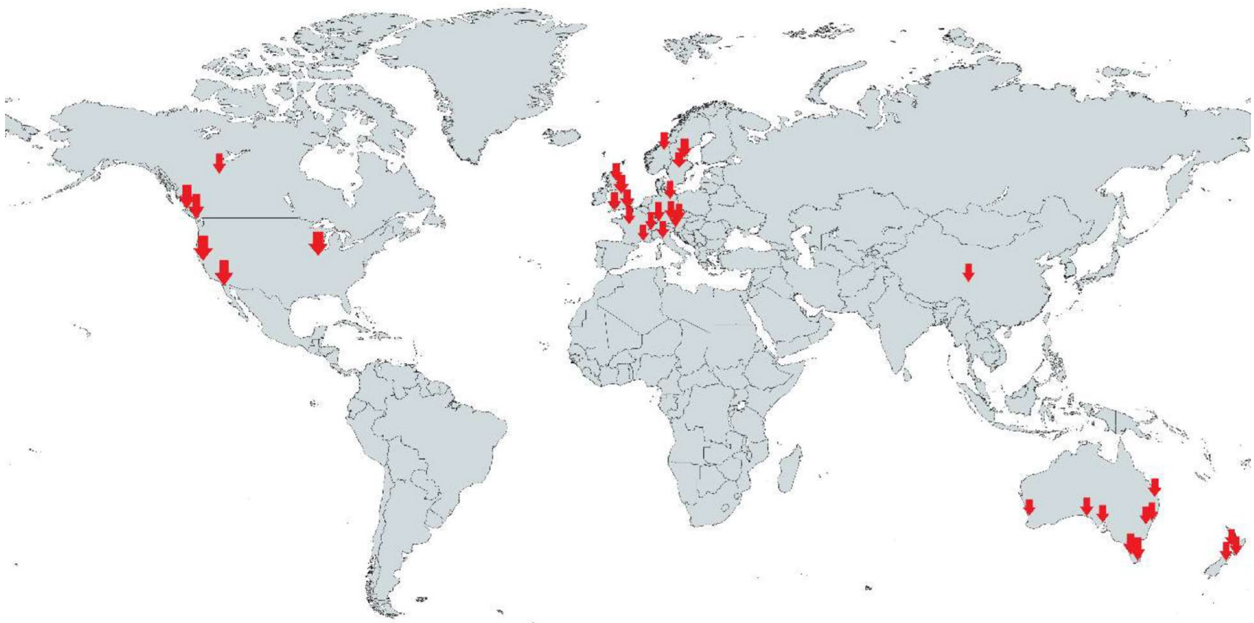


Fig. 5 World map indicating the participating practitioner's location of origin (produced with https://www.mapchart.net)

considered suitable for vibration and sound insulation in MTPs. Responses to the perceived barriers (Fig. 7a) indicated 27% of the practitioners believe confusion due to the number of standards and their variations in detail presents a major barrier for MTPs. Another considerable barrier identified is that of occupant vibration/sound insulation comfort/perception with 26% of practitioners concerned with struggling to ensure occupant comfort is high and negative responses due to sound transmission or floor vibration are low.

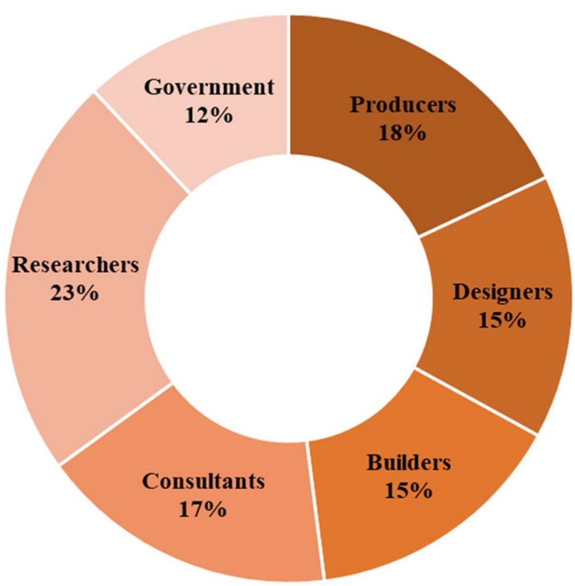


Fig. 6 Roles of consulted practitioners considered in this study

While vibration and sound insulation perception are addressed in some standards and design guides, the sheer number of practitioners concerned with it warranted its separate inclusion (Fig. 7b). A shared component influenced by both perception and standard complexity is the poor design information specific to MTPs that received 19% of the responses. This reflects discussions regarding a desire from builders/designers to have a greater level of information available for new and evolving product types as well as the performance of alternative structure design. A common example is the use or ability to design for longer spans while using MTPs, as this presents a number of perceived challenges regarding standard requirements, market perception, and performance limits.

Twenty-nine percent (29%) of practitioners suggested that being able to comply with the prescribed standards and design guides for vibration and sound insulation noted in Table 2 presents a means of overcoming the perceived design information barrier. Scaled/laboratory (24%) and in-situ testing (19%) are considered useful ways of mitigating challenges with perception, developing design information, reducing potential corrective costs, and defining product limitations early. However, staggered in-situ or scaled testing is not always possible.

From the practitioner responses, areas of concern were classed as floor systems (63%), connections and junctions (mainly linked with vibration and sound energy transfer, i.e., flanking) (27%), building services (7%), and other

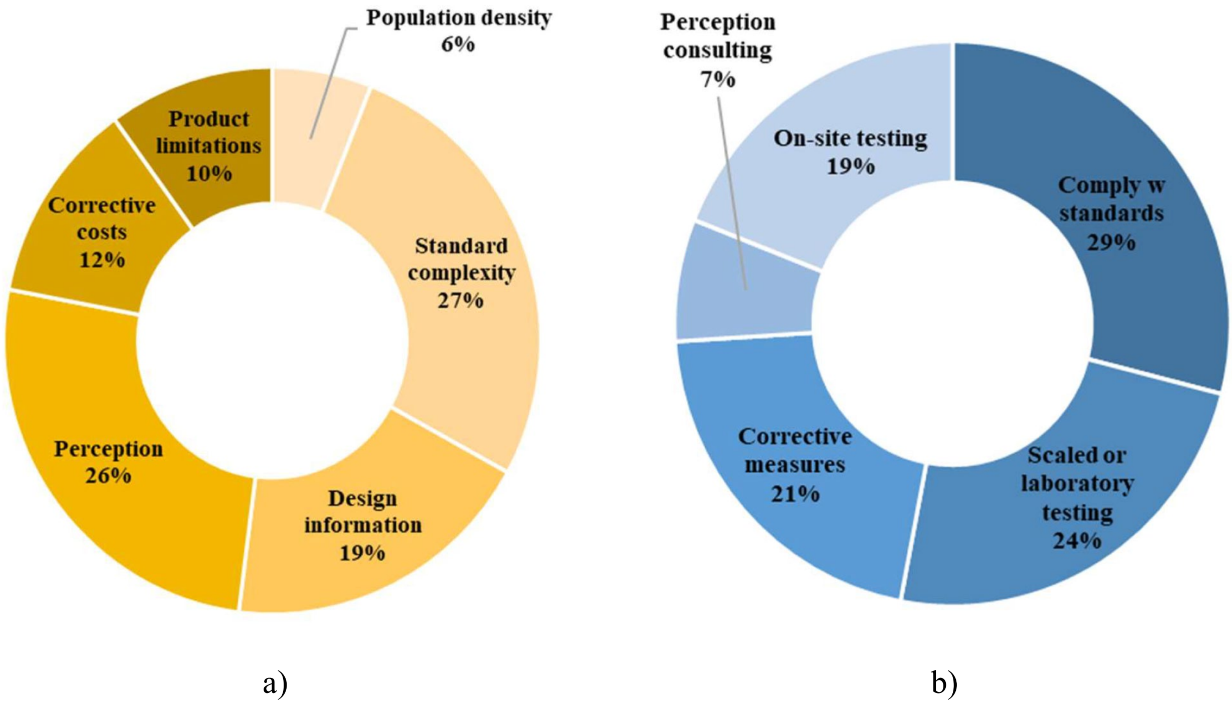


Fig. 7 Focal area responses indicating the **a** perceived barriers to increased use of MTPs, and **b** strategies for mitigating vibration and sound insulation challenges

(3%). As an area that consumed most of the concern and/or demand for research focus from the majority of those consulted, floor systems have been considered as the focal point of the remainder of this review focusing on areas, such as building and product design/application, evaluation methods and approaches, and corrective measures. Considering the range of practitioners included (Fig. 6) and the focal areas highlighted in Fig. 7a, b, the analysis of discussions has been separated into three key groups: (i) product and system design, (ii) product performance evaluation, and (iii) regional variations.

Product and system design

This section describes the summarised findings from discussions specific to those who are involved in the product design process with MTPs. Within this section, there are two subsections which detail these observations with respect to the Production and Manufacturing, and the Designers and Builders.

Production and manufacturing

From the regions visited during the consultation period (Australasia, North America, Europe, Asia), all but one (Asia, China) were actively producing MTPs, at the time of writing/visiting. The lack of MTP production in China, while anecdotal from the practitioners consulted, appears to indicate the local industry is not yet ready to accept the substitution of common construction materials for MTPs. To avoid challenges related to the scale of production, a range of MTP producers were visited varying in scale to capture and identify challenges that are inherent to MTP production only. Challenges specific to those that relate to vibration and sound insulation performance have been reported in this section. Challenges have been classed as either global or local with global challenges being those that are echoed across regions, and local challenges being ones that are isolated to a specific region or country.

Several global challenges are summarised as follows:

- *Complexity of standards*: Producers of MTPs are facing growing calls to design for vibration serviceability with builders seeking materials that can meet an increasing demand for open plan office spaces, school halls, and parking garages. Given the proven capabilities of MTPs in regard to strength, durability, and fire resistance, vibration serviceability continues to affect the increased use of MTPs in the built environment with the challenges beginning with product design. A continuing challenge related to product design becomes the varying details between regional standards and prescribed requirements for different regions, making design challenging when using regional guides with less detail than others. By expanding the data set available for a range of MTPs and applications, the pressure on producers to provide advice on design and usage can be minimised.

- *Added material influence*: A part of MTP design for vibration serviceability that complicates vibration performance prediction accuracy is the final floor systems' performance, as an uncovered CLT panel will very rarely be the floors surface finish. Each functional but non-structural layer added, for example, carpet, screeded concrete, access ceilings, will influence the performance of the finished floor through either dissipating energy with air cavities, or dampening of impact sound through added dead load mass or interlayer materials to absorb foot fall load responses. However, vibration serviceability and floor design standards do not accurately capture and/or distinguish the performance attributes of these added materials.

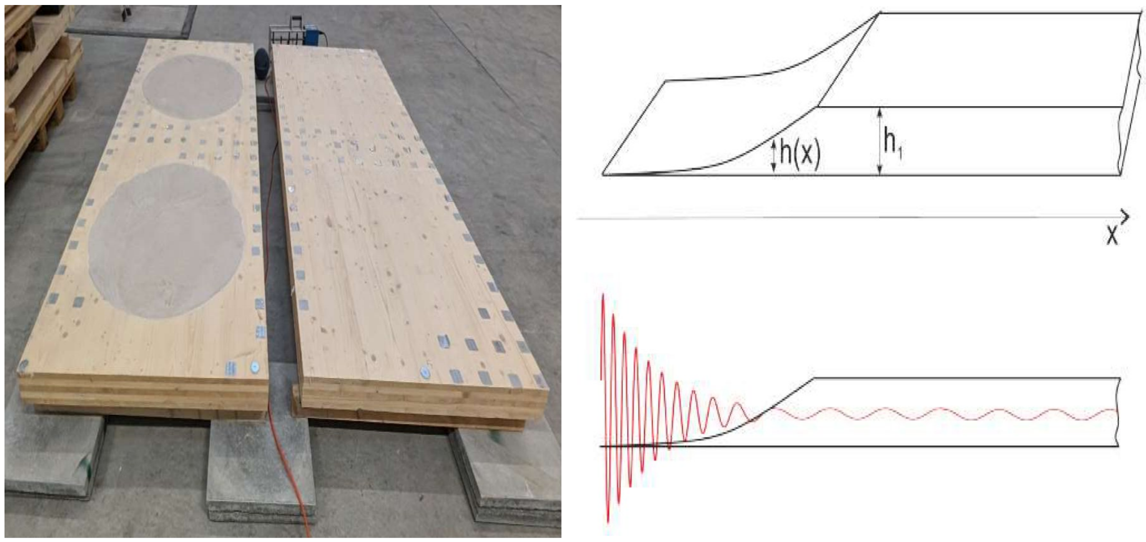
Several local challenges are summarized as follows:

- *Material properties*: Different timber species and access to them are the biggest cause for product performance differences between regions. The growing conditions, seasonal aspects, and rotation ages are often the biggest variables (outside of species) that contribute to varying material properties, such as density and stiffness between Europe, North America, and Australasia. An added challenge is also in access to these materials whether this be due to seasonal weather challenges or government policy decisions. These constraints are considered business specific, i.e., not addressed through research.
- *Conditioning*: Timber being hygroscopic, means its performance differs with moisture content variation. To overcome this introduced variability most European-based producers would condition their feedstock prior to manufacturing. However, this level of control is not observed in most Australasian production facilities. As a result, manufacturing tolerances must allow for these anticipated changing environmental effects.

Of the 20+timber producers consulted, around 75% noted a stronger demand for the supply of their 'product' to include design-related information, such as installation details and product application details. This is a strong contrast to the commodity-type format timber processors provide as 'off the shelf' raw materials. Comments received from producers suggested the reasoning behind the increased demand for information is partly due to the global challenge defined above as "standard complexity" meaning difficulty had in aligning performance requirements with the material. Some producers commented that this demand for information is linked to a lack of experience in working with MTPs coming from designers and builders. Conversations continued to suggest that consequently, performance targets are overconservative leading to overly thick panels, shorter clear spans, and/or lower ceilings (due to excessive ceiling cavities) to address concerns over occupant-induced vibration and sound insulation. A challenge with both global and local contexts is design standards, referred to as "standard complexity" linked to the lack of validated MTP data. While the reasoning behind each of these is described above, broadly, the two classifications apply limitations on the material, leading to the conservatism prescribed in specifying MTPs. While these prescribed limitations appear challenging to address, research viewed during the consultation period on product development appears focused on methods to overcome some of the limited characteristics, such as stiffening floor panels and improving timber's poor sound insulation performance at low frequencies.

The Institute for Health in the Built Environment (IHBE), at the University of Oregon (Portland, Oregon, USA) developed a micro-acoustic test chamber to explore rapid sound insulation assessment of larger material types at a reduced section size [101]. This technique allowed for the sound insulation characterisation of unscaled materials or new floor/wall layering's as a screening alternative to costly large-scale testing. The current system is limited to the mid-to-high audible frequency range (1,000–5,000 Hz) with the low range (below 1,000 Hz) still considered unattainable. This presents some of the limited research into addressing literature gaps noted in Fig. 3 on linking in-situ performance to laboratory scale testing. Schoenwald et al. [102] and the Swiss Federal Laboratories for Materials Science and Technology (EMPA, Zurich, Switzerland) took an alternative approach to addressing sound insulation performance of conventional CLT constructions by introducing acoustic black holes (ABHs) (Fig. 8). Filling just the ABH indentations with gravel as opposed to covering the whole CLT surface, reduced the floor's total mass by 50% and reduced measured impact sound by up to 10 dB (measured at 100 Hz). However, noted challenges of this study are the translation of these laboratory scale experiments and specimens to their in-situ, large scale performance [31, 63].

Product design and performance often begins at the laboratory stage (conception stage). The challenges in benchmarking product design in controlled experimental (laboratory) conditions are the difficulty in practically developing the same test environment in the laboratory that would be expected in the field (in-situ). While some



a) b)

Fig. 8 **a** laboratory images of (left) CLT panel with acoustic black holes (ABH) introduced, and (right) control panel, **b** schematic of theory for ABH, where red line shows sound waves interacting with ABH indentation [102]

activities are ongoing with respect to linkages between laboratory and in-situ performance, this challenge still appeared to resonate with all the 25 researchers consulted through this study specific to mimicking floor boundary conditions, building loads (live loads, uniformly distributed loads, static deflection occurrences), and experimental size/scale. A solution for this challenge could allow for more specific laboratory experiments and data to be fed into prescriptive standard design and revision.

Designers and builders

The information in Table 3 presents data specific to the visited practitioner geographic areas regarding their population [103], number of mass timber structures (8 + storeys [53, 104]), and MTP production and import volume at the time of writing [105–107]. The production and import volumes have been restricted to CLT only and are based on assumed full capacity operations. The accuracy of the building numbers tabulated is based on both the CTBUH report from 2022 [53], and the WoodWorks mass timber mapping system [104]. While Table 3 shows Europe/UK to have more volume of mass timber in construction, the population per number of MTP buildings suggests Australia/New Zealand are becoming more progressive regarding the use of mass timber in the built environment.

Of the developments witnessed during the consultation period across Australia and New Zealand, there is a large emphasis on mid-scale commercial developments often used for office spaces with many from 10 stories and greater. Those visited include: 25 King St (10 stories [108]), Brisbane, Queensland; T3 (14 stories [109]), Collingwood, Victoria; WS2 (12 stories [110]), Perth, Western Australia. These structures all presented a different design approach and reason behind the use of MTPs to meet structural and vibration serviceability specific goals. This included reinforced glulam beams with laminated veneer lumber (LVL) to increase stiffness requirements around extrusions (25 King St, Brisbane,

Table 3 Statistics for the continents and regions highlighted through Fig. 1 (data sourced from [53, 103–107])

Continent	Population (millions)	Production and import volumes of CLT (m^3)	Number of mass timber projects (8 + Storeys)	Ratio of population to completed Proj. (buildings/million)
Australia/New Zealand	31.12	200,000	8	0.26
United States/Canada	372.2	300,500	37	0.10
Europe/UK	449.2	1,200,000	60	0.13
Asia	1,412	Not available	3	< 0.01

Australia), extending existing building heights while limited by current spans and loading limits (T3, Melbourne, Australia), and reduced floor panel thickness due to loading limits requiring alternative dampening solutions (WS2, Perth, Australia). These structures and their unique approaches show a willingness of the local industry to pursue innovation in challenging applications. Conversely, the practitioner consultation showed a greater emphasis on low-rise (1 to 3 stories) and mid-rise (3 to 9 stories) mass timber structures across most of the visited countries in Europe (Norway, Sweden, Germany, Austria, Italy, Switzerland, France). This trend continues when considering building levels below 8 stories using the WoodWorks mass timber mapping tool for North America which notes 1,132 mass timber buildings ranging from 1 + stories [104]. This suggests the ratio in Table 3 may not be a strong indicator of a population's perception for the usage of MTPs. While the authors acknowledge the vastly different construction techniques often employed between low-rise and mid-rise structures, given the focus of this study has been the theme of floor system performance, the two have been analysed together rather than separating. Similar to observations from Australia/New Zealand, these developments appear to focus more on commercial office use with fewer residential applications. Figure 9 presents three example buildings visited during the practitioner consultation, where 9a) and 9b) were below eight stories.

While there may be a greater number of low-rise and mid-rise structures across the visited countries in Europe, of the large-scale structures that exist at the time of writing, Europe is their home also. One such structure is Mjøstårnet (Brumunddal, Norway) often referred to as "The Timber Hotel". The 18-storey timber hotel, completed in 2019, was a focal point for the consultation period to understand hurdles that were overcome to produce the tallest timber building in the world (at the time of writing). The majority of builders and designers consulted suggested that through the incorporation of vibration and sound insulation design specialists, concerning aspects of performance or perception can be (for the most part) minimized or mitigated due to experiences noted to date. An interesting anecdotal comment and observation during practitioner conversations noted that the large dimension timber (glulam) supporting columns were able to "carry" small amounts of sound transmission through them and into nearby floor levels. This is often a phenomenon known as "flanking", where noise reaches an adjoining space through an indirect path [99, 111].

Analysing the responses from the 50 participants from designers (17), builders (17), and consultants (16), some of the more notable conversation topics included:

- *Floor vibration serviceability challenges*: Of the 34 designers and builders consulted, approximately 61% noted encountering challenges when designing floor systems with MTPs at one point through their career. This was often concentrated to the design stages and assumptions made in appropriating standards originally designed for steel/concrete sub-structures for MTP floor design. Following this, 44% of the 16 consultants had raised observations about mass timber structures nearing completion suggesting vibration serviceability criteria were being consistently exceeded.
- *Vibration and sound insulation perception*: 17% of the builders and designers consulted, conceded to receiving negative comments from occupants of structures (irrespective of material type) in relation to excessive vibration complaints. This is in struc-

a) b) c)

Fig. 9 **a** Rothoblass mass timber facility in Trento, Italy, **b** TX real estate headquarters mass timber building, Zurich, Switzerland, **c** Mjøstårnet (the timber hotel), Brumunddal, Norway tures that met and/or exceeded the performance requirements of the relative design standard for the intended occupant application. This is contrary to the former suggestion that floors may be over-designed. Perception studies referenced through the Product Performance Evaluation section have mostly been isolated to laboratory testing, where the challenges in mimicking performance in-situ have already been raised. There is not sufficient data for mass timber floor systems to confidently suggest that the buildings which received poor comments would be likely to be MTPs. Considering the importance of occupant comfort to vibrations, 71% of consulted practitioners suggested perception is under-represented in the vibration serviceability criteria, often due to lack of completed studies or reliable data sets.

The discussion results of "floor serviceability challenges" complement the findings of Pavic [37] from 2019 which reported ~ 30% of surveyed practitioners experienced vibration serviceability problems for structures while in use. While a worrying statistic, it highlights that the need for knowledge regarding corrective or additive solutions to rectify such cases still exists. Additional layers such as those discussed in the previous sections provide some improved performance; however, research has highlighted the inability of these materials to significantly impact perceived change [112–114].

Product performance evaluation

As highlighted through the practitioner consultation, defining the role that each of these 16 standards and design guides (introduced in Table 2) can play in designing mass timber floors is critical to support those using them. Table 4 lists these standards and assigns them two ranks, both from '1' to '5', where '1' is considered "highly useful" and '5' is "lowest use". The ranking is based on the frequency of use through the reviewed articles in the Product Performance Evaluation section (referred to as "Literature"), and the discussions with practitioners regarding preferred standards to use in design (referred to as "Practitioner"). Therefore, for standards more frequently used through the reviewed studies, their ranking approaches '1'; for standards referenced by practitioners during discussions as more appropriate than others, these standards also approach '1'.

The rankings show areas, where literature and practitioner preferences align, such as FprEN 1995-1-1, CSA 086, and ISO 10137. However, other such trends observed from the consultations indicate standards such as HIVOSS [84], ISO 21136, and CSA 086 experience a significant (a change of 2 or more rank points) upward or downward trend when compared to the literature. Suspected reasons for this noted from the practitioners originated from the two main classes of standards in Table 4: deterministic and probabilistic. While deterministic approaches prescribe performance through calculated values, probabilistic ones consider a range of performances that can be achieved [85, 115]. Considering the variability that comes with floor design, a probabilistic approach appears more appropriate to some practitioners, where this proportion appears to be growing greater than those of researchers, at the time of writing. The standards listed in Table 4 present varying levels of detail, with some prescribing several material properties to either design for, or act as, a threshold for conformance. Other standards, however, may only prescribe a single design parameter. This suggestion alludes to the cause for the design complexity noted by 27% of all practitioners in selecting appropriate standards to design mass timber floors. This challenge was not isolated to industry professionals with a number of researchers also sharing their confusion in appropriate standard selection.

Table 4 Vibration serviceability and material property standards and relevant design guides (data sourced from [24, 25, 27, 35, 36, 77–89])

Standard name	Type	Ranking (1 to 5)		Standard name	Type	Ranking (1 to 5)	
		Literature	Practitioner			Literature	Practitioner
FprEN 1995-1-1	Design	1	1	CCIP-016	Design	1	1
AISC DG11	Evaluation	4	4	ISO 10137	Evaluation	2	2
ISO2631.1/AS2670.1	Evaluation	3	3	SCI-P354	Design	2	3
AS/NZS 1170.0	Design	4	4	BS 6472–1	Evaluation	1	1
HIVOSS:2007	Evaluation	4	2	CSA 086:19	Design	1	3
AS/ISO 2631.2	Evaluation	3	3	Canadian CLT DG	Design	4	4
ISO 18324	Evaluation	2	2	WS DG 49	Design	3	3
ISO/TR 21136	Evaluation	3	1	AISC DG 37	Design	3	4

A light rapid transit (LRT) system in Chongqing, China that passes through the centre of a mixed use (residential and commercial) building generates a significant amount of public interest. The surrounding levels to the station as well as buildings in close proximity are predominantly residential [95]. Xie et al. [95] conducted a survey of residents who occupy this building for their perception of the vibration and sound coming from the LRT system. Sound insulation measurements exceeded the limits in the national regulations by > 15 dB, while resident complaints highlighted that less than 20% have mitigating solutions such as double-glazed windows installed. Researchers consulted in the region were aware of the structure and many others like it across the vastly densified city. Due to rapid expansion, the buildings were constructed around the LRT system to make use of what available space existed. This exemplar structure highlights the extreme importance of considering both the use of the structure as well as the perceived comfort. The structure also touches on the importance of optimised and refined design guides that incorporate both vibration performance and perceived comfort measurements. A critical challenge with vibration and sound insulation perception assessments from most studies reviewed in the Product Performance Evaluation section was the difficulty in ensuring it resembles the actual floor system in situ. This is, as expected, challenging to achieve from a measurement point of view and equally difficult from a perceived environment point of view with participants often perceiving the test environment differently to how they would perceive an actual office or residential space.

Several researchers from the 25 consulted are actively looking at novel methods to capture perceived comfort of floor systems by either (i) addressing the environment that occupant views through VR and AR alternatives (H. Karampour, et al., Griffith University, Australia), (ii) monitoring neural activity (X. Zhang, et al., Chongqing University, China), or (iii) considering the affected range across a long span floor (P. Hamm et al., Biberach Universität, Germany). However, ensuring the floor space is performing as intended still remains challenging. The VSimulator experimental facility at Exeter University (Fig. 10) can physically simulate measured and most complex floor dynamic responses allowing researchers to mimic floor response factors, accelerations, and damping ratios from either intended design calculations or from real measurements taken from other test facilities. The VSimulator testing facility, co-founded by Professor Aleksandar Pavic is currently conducting tests measuring objectively cognitive deterioration of test participants subjected to realistic floor vibration levels [100]. This research is expected to contribute significant linkages between perceived and measured responses of floor vibrations.

A team led by Professor Aleksandar Pavic in 2024 performed, to the knowledge of the reviewers, the first experiment on the effects vertical vibrations can have on human cognition [100]. A total of 12 test subjects (two groups of 6) participated in the experiments with the participants asked to complete a standard visual search (VS) task while seated at a desk for 112 min. Pavic et al. [100] observed a strong relationship between the time taken for the test subjects to complete the VS and the level of floor vibration with no vibration (RF = 0) taking an average of 3.68 s up to 7.36 s for a RF of 8. This study highlights the challenge in assigning a binary pass–fail criterion to floor systems with even a moderately acceptable RF level of 8, causing significant differences in task completion.

Regional variations

As addressed in the Product and System Design section, the use of MTPs continues to increase across most of the visited regions other than Asia (China). Comments received from practitioners consulted in China suggested that local industry perceives MTPs to be not yet suitable in displacing current construction materials, such as concrete and steel. A comment which should not be taken out of context is that while perception of the materials' performance is one key reason, the construction landscape in China differs greatly from other regions that were visited, emphasising regional variation as previously mentioned. This appears in part due to the differing construction landscape in China compared to other countries, such as Australia and New Zealand. With varying populations, resources, and historic construction methods, the construction landscape in Australia and New Zealand was founded through light weight framed developments since colonisation. China, however, as a result of a largely expanding population crowds its sky with tall skyscrapers for residential and commercial use; a scale MTPs have not yet been tested for. Analysing the discussions with practitioners noted several consistent themes that were discussed and appeared heavily influenced due to the regional variation. Application of the various design standards from Table 4 (1), regional weighting of perception (2), and local industry capacity and innovation (3) are some of the themes that were discussed. Table 5 summarises the regional responses for the previously mentioned discussion topics.

Theme comparison

For such a paper with the intention to draw specific conclusions on focal fields of research, it is important to highlight the limitations of the study. The first of which is related to the sample size of the practitioners consulted.

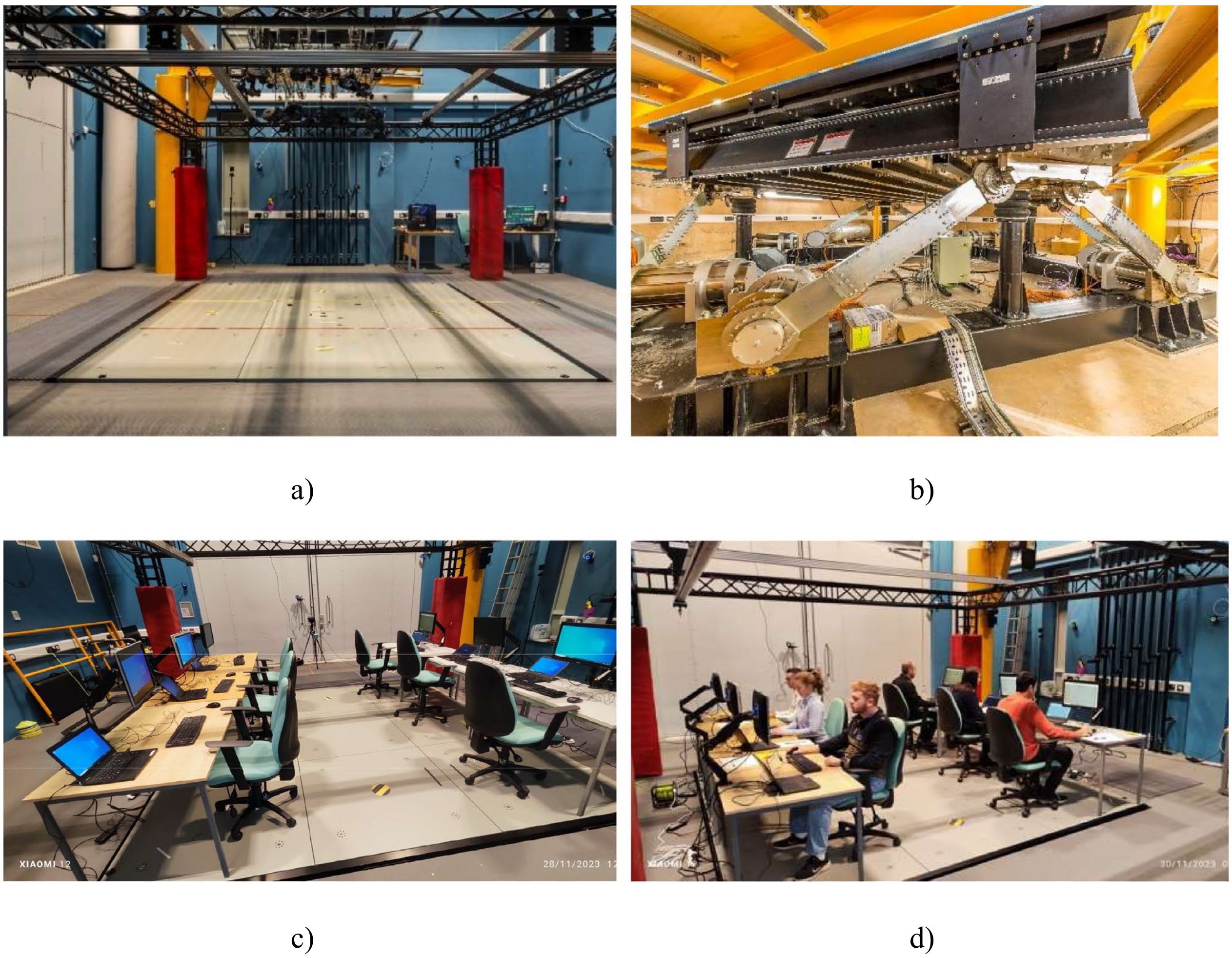


Fig. 10 Exeter University, UK. VSimulator experimental floor facility: **a** view of the floor system, **b** under-view of the floor system. Images **c** and **d** show the experimental setup for the cognitive assessments described in the text (all images supplied by A. Pavic [100])

While efforts have been made to ensure primary experts have been targeted, regions and some experts were not part of the study due to travel limitations. This study, however, presents a suitable cross section of participants from a range of regions, where MTPs are being used or considered actively, and therefore, challenges are being identified, considered, and addressed. Another limitation of the study has been the selected articles used to define the flowchart literature themes presented in Fig. 3. While more literature exists, specifically articles targeting more detailed understandings of sound insulation in MTP systems, the reviewed studies appear to show more relevance to the concerns and desires of the consulted practitioners. This suggests the background literature provides a suitable foundation for considering the state of knowledge with respect to challenges the MTP industry is facing and those of which academia is working on. While some important topics such as environmental influence or sustainability have not been specifically addressed through this study, it is not to suggest that this is not a priority for the industry; however, the practitioner consultation was focused on the specific challenges related to vibration and/or sound insulation performance of MTPs in the built environment.

Comparing the identified key themes in the background literature to the practitioner conversations, some strong relationships appear between those areas considered critical from the wider industry to the research being conducted as depicted in Fig. 3. These include research topics such as composite systems, effects of connections, and boundary conditions and how these contribute to vibration and sound insulation performance in MTPs. However, some areas became apparent that show little or no focus from researchers yet ranked highly by the practitioners. These research topics include long spanning floor systems, linkages

Table 5 Regionally sensitive practitioner responses

Region	Responses
(Australasia) Australia/New Zealand	(1) Table 4 shows that 24% of the standards were developed in Australia/New Zealand. However, the national vibration serviceability standard was last reviewed in 2000. As a result, 53% of practitioners reported using international standards and/or design guides in their designs (2) Practitioner consultations highlighted several perception studies conducted across the region, focusing on extracting meaningful data from subjective measurements rather than adhering to standardized layouts. In addition, 71% of practitioners felt that perception was undervalued in the design process (3) Excluding the standards and design guides, literature from this region accounted for 19% of the reviewed works mentioned in the Background section. Industry consultations also revealed a strong local interest in solutions for long-span floors
(North America) America/Canada	(1) This region contributed to 16% of the standards listed in Table 4, spanning from 1951 to 2024. Serviceability related to vibration was the primary focus, with sound insulation being a slightly lower priority. This trend has also been observed in other regions, as vibration events are often linked to sound insulation discomfort (2) While most practitioners considered perception important, some believed that current design standards adequately capture occupants' perceived comfort. However, this view conflicted with the majority, who felt that the standards only target the performance of the bare system. With additional material layers added during finishing, performance is generally expected to exceed the design target (3) Of the reviewed articles in the Background section, 22% were published from this region. Practitioners expressed a strong interest in exploring alternatives to current design standards to support the growing mass timber sector and its increasing number of projects
(Europe) UK/Norway/Sweden/Germany/Austria/Italy/Switzerland/France	(1) Since 1996, Europe has led the development of international standards, particularly with the revision of FprEN 1995-1-1, focusing on floor vibration serviceability, perception frameworks, and probabilistic design approaches. Europe has been responsible for 60% of the standards listed in Table 4. However, for mass timber design standards, the primary references remain FprEN 1995-1-1 and HIVOSS [84] (2) Perception is highly emphasized across the region, with many countries encouraging, or even requiring, the inclusion of vibration and sound insulation expertise in structural design and planning to ensure appropriate measures are taken. Despite this, challenges persist, particularly in defining the relationship between laboratory and in-situ performance (3) Of the regionally produced background literature, 51% of the total papers originated from European countries. This reflects strong industry support, significant research efforts, and a unified approach to performance criteria
(Asia) China	(1) As mentioned earlier, mass timber is not widely used in China at the time of writing. Therefore, discussions with local practitioners focused on comfort design protocols for all building materials. In terms of design standards, practitioners rely on locally developed regulations, though these were not accessible for review (2) While perception was considered important by local practitioners, it was difficult to confirm this through local publications. Relevant studies on vibration and sound insulation comfort often reported discrepancies between expected and measured performance (3) Despite mass timber's limited use and production in China, local research efforts are increasing, highlighting the material's effectiveness in various structural applications. These efforts aim to encourage greater investment from local industry and government by showcasing the benefits of mass timber. As a result, 8% of the background literature originated from studies conducted in this region

between laboratory and in-situ performance, and influence of material properties. To accurately visualise these different themes and the varying levels of attention they receive, the 18 themes from the flow chart in Fig. 3 have been plotted on the below Venn diagram in Fig. 11. The figure should be interpreted by considering perfect alignment between the "Practitioner Areas of Concern" extracted from the Practitioner Conversations section, and "Literature Linkages" from the Background section as examples of good collaboration and interaction between industry and academia. Following this, points that land further to the left on the diagram into the "Literature Linkages" section are considered saturated research fields, where this is less of a priority for industry based on the practitioners consulted. Finally, for the points that land to the right of the figure in "Practitioner Areas of Concern", these are themes that appear of greater interest and concern for the practitioners consulted and appear to be less focused on by the published or ongoing research efforts.

Figure 11 shows research topics such as "composite action", "boundary conditions" of floor systems, "performance criteria", and floor "damping systems" align with the concerns raised by consulted practitioners. Areas like "damping systems" (meaning layered materials and damping tools) are positioned near the overlap boundary, suggesting that existing literature may not fully address practitioners' concerns. This is reinforced by studies on additive floor layering materials that often conclude these systems fail to address the relevant frequency ranges [16, 17, 98, 116]. Other topics like the "link between testing approaches" are just outside the overlap boundary, indicating that while research is being conducted in this area, it remains a significant concern for practitioners, as previously mentioned. Topics such as the research into long spanning floors ("long-span floor solutions"), the link

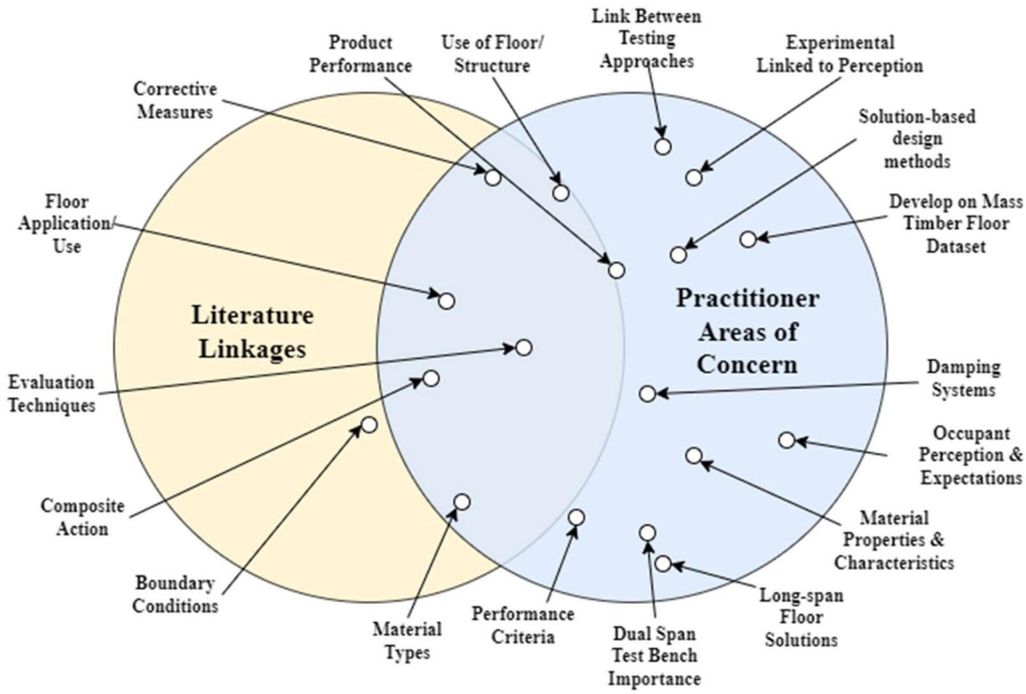


Fig. 11 Venn diagram of literature linkages and practitioner focal areas with highlighted key themes

between perception and experimental data ("experimental linked to perception") and the importance of research on floor scale floors ("dual-span test bench research") are further from the overlap boundary, indicating that while research may be ongoing, they are areas of growing concern and/or interest for practitioners.

Another area of specific interest identified by practitioners, but inadequately covered in the literature, is the "material properties and characteristics." This refers to the discrete performance of mass timber products (MTPs), including the effects of layering, the influence of hybrid material stages, and variations in adhesives and board properties. Practitioners are particularly interested in more defined prediction methods for MTP performance, with a focus on understanding how each stage contributes to overall performance.

Conclusion

The purpose of this study has been to update the current state of knowledge on aspects that contribute to the performance of, or criteria to measure conformance of, MTPs with respect to vibration and sound insulation. The study consists of a systematic review of 118 articles, standards, design guides, and website publications compared against analysis of discussions had with 112 practitioners located across 13 countries. The findings have been summarised based on the following themes:

- *Specific concerns for producers*: Manufacturers and producers of MTPs noted standard complexity as one of the leading concerns for them with a greater demand being felt from designers for specific material property information on MTP performance. Of the manufacturers and producers consulted, 75% noted demand increase for MTPs globally with local challenges appearing more nuanced such as feedstock conditioning capabilities.
- *Specific concerns from developers*: 61% of designers and builders conceded to encountering challenges in the design stage for mass timber builds with 17% of them expressing receiving complaints regarding occupant comfort related to vibration and sound insulation in finished structures. 44% of the consultants noted raising detected issues part way through construction specific to vibration and/or sound insulation.
- *Regional variations*: The practitioner analysis for the various regions showed variation based on design standard quality with regions lacking specifics in local design protocols adopting international alternatives. A large proportion of the practitioners highlighted FprEN 1995-1-1, HIVOSS, and CCIP-016 as the top standards recommended for mass timber floor vibration and sound insulation serviceability design. However, 71% of the consulted practitioners noted vibration perception to be the least understood

criteria for floor vibration and sound insulation serviceability with a strong contribution toward occupant comfort and cognitive performance.

- *Literature and practitioners*: The study defined a number of literature linkages through the review and also specified some linkages which appeared underdeveloped due to minimal or lack of research in these fields. From the practitioner conversations several complimentary areas between published literature and concerns from practitioners were defined, suggesting the research is both impactful and focused on practitioner concerns. However, several topics were identified as still having strong practitioner concern and lack of focus. These included focused research on long spanning mass timber floor systems, dual spanning test benches, developed linkages between experimental and perceived performance, and discrete material properties.

Acknowledgements
The authors would like to acknowledge the funding support provided by the Gottstein Trust (Gottstein Fellowship: America, Canada, United Kingdom, Norway, Sweden, Germany, Austria, Italy, Switzerland, France, and China) and Timber Queensland (Kennedy Timbers, Growth Scholarship: New Zealand and Australia) which facilitated the comprehensive study tours and extensive network engagements with a range of practitioners. The support of the Queensland, Department of Primary Industries (DPI), Forest Product Innovations (namely, Dr William Leggate and Dr Robert L. McGavin) team has been an instrumental aspect of conducting these engagement type campaigns. Networking support and supervision provided by Griffith University and the research community developed by the ARC funded Advanced Timber Hub (IH220100016) is also acknowledged. For their specific contributions and guidance, Dr Arash Behnia of Robert Bird Group (RBG) and Dr Ali Habibi from Northrop Consulting Engineers are acknowledged and thanked. A major focus of this review document has been its collaboration and engagement with the 112 researchers, practitioners and industry professionals; therefore, the support of each and every person that welcomed the primary author is thanked for their welcoming nature and willingness to share their perspective on the topic of vibration and sound insulation in mass timber structures.

Author contributions
Adam Faircloth: funding acquisition, project development, literature review, methodology development, consultation, analysis, and writing. Hassan Karampour: supervision, writing, reviewing, editing, practitioner contact support. Patricia Hamm: writing, reviewing and editing with respect to large scale and long spanning floor vibration and standards information. Theresa Müller: writing, reviewing and editing with respect to long spanning floor vibrations and material sound insulation analysis information. Alex Pavic: writing, reviewing and editing with respect to perception analysis and linkages between laboratory and in-situ performance context. Paul Reynolds: writing, reviewing and editing with respect to theory definitions and application of the various standards relevant to floor vibration serviceability. Benoit P. Gilbert: supervision, writing, reviewing, editing, practitioner contact support. Stefan Schoenwald: writing, reviewing and editing with respect to sound insulation information on materials and assessment methods in both the laboratory and in-situ environments. Haoyu Huang: writing, reviewing and editing with respect to the perceived vibrational performance of floor systems and how this integrates into floor system selection/ranking. Phillipe Gronquist: writing, reviewing and editing with respect to composite and hybrid MTP systems as well as contributing factors to design that need to be accounted for. Johannes Ruf: writing, reviewing and editing with respect to the screening and ranking of particular standards referenced through the article. Loic Brancheriau: writing, reviewing and editing with respect to non-invasive vibration systems knowledge and expertise. Chandan Kumar: supervision, project development, writing, reviewing, editing, practitioner contact support.

Data availability
Data will be made available upon request.

Declarations

Competing interests
The authors declare no competing interests.

Author details
[1]School of Engineering and Built Environment, Griffith University, Gold Coast, Australia. [2]Department of Primary Industries, Salisbury Research Facility, Brisbane, Australia. [3]Biberach University of Applied Sciences, Biberach, Germany. [4]University of Stuttgart, Stuttgart, Germany. [5]CALMFLOOR, University of Exeter, Exeter, UK. [6]University of Exeter, Exeter, UK. [7]Full Scale Dynamics Ltd., Exeter, UK. [8]Empa, Dübendorf, Switzerland. [9]Newcastle University, Newcastle, UK. [10]UPR BioWooED, CIRAD, University of Montpellier, Montpellier, France.

Received: 4 August 2025 Accepted: 20 November 2025
Published: 27 November 2025

References

1. Nations U (2016) The Sustainable Development Goals Report. Accessed 05/05/2024. https://unstats.un.org/sdgs/report/2016/
2. MECLA (2000) MECLA Innovative Building Materials Challenge. Materials and Embodied Carbon Leaders' Alliance. Accessed 09/08/2023. https://mecla.org.au/innovative-building-materials-challenge/
3. Greene JM, Hosanna HR, Willson B, Quinn CJ (2023) Whole life embodied emissions and net-zero emissions potential for a mid-rise office building constructed with mass timber. Sustain Mater Technol. https://doi.org/10.1016/j.susmat.2022.e00528
4. McGavin RL, Dakin T, Shanks J (2020) Mass-timber construction in Australia: is CLT the only answer? BioResources 15:4642–4645. https://doi.org/10.15376/biores.15.3.4642-4645
5. Puettmann M, Pierobon F, Ganguly I, Gu H, Chen C, Liang S, Wishnie M (2021) Comparative LCAs of conventional and mass timber buildings in regions with potential for mass timber penetration. Sustainability. https://doi.org/10.3390/su132413987
6. Abed J, Rayburg S, Rodwell J, Neave M (2022) A review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures. Sustainability. https://doi.org/10.3390/su14095570
7. Duan Z, Huang Q, Zhang Q (2022) Life cycle assessment of mass timber construction: a review. Build Environ. https://doi.org/10.1016/j.buildenv.2022.109320
8. Kremer P, Symmons M (2018) Perceived barriers to the widespread adoption of mass timber construction: an Australian construction industry case study. Mass Timber Constr J 1:1–8
9. Kontis C, Tsichlas C, Kolaitis DI, Founti MA (2020) Fire performance of CLT members: A detailed review of experimental studies across multiple scales. Paper presented at the Proceedings of the 9th International Conference (3–6 May 2020), Štrbské Pleso, Slovakia
10. Lehmann S, Kremer P (2023) Filling the knowledge gaps in mass timber construction: where are the missing pieces, what are the research needs? Mass Timber Constr J 6:1
11. Stenson J, Ishaq SL, Laguerre A, Loia A, MacCrone G, Mugabo I, Wymelenberg KVD (2019) Monitored indoor environmental quality of a mass timber office building: a case study. Buildings. https://doi.org/10.3390/buildings9060142
12. Homb A, Guigo-Carter C, Hagberg K, Schmid H (2016) Impact sound insulation of wooden joist constructions: collection of laboratory measurements and trend analysis. Build Acoust 23:73–91
13. Caniato M, Bettarello F, Ferluga A, Marsich L, Schmid C, Fausti P (2017) Acoustic of lightweight timber buildings: a review. Renew Sustain Energy Rev 80:585–596. https://doi.org/10.1016/j.rser.2017.05.110

14. Jayalath A, Navaratnam S, Gunawardena T, Mendis P, Aye L (2021) Airborne and impact sound performance of modern lightweight timber buildings in the Australian construction industry. Case Stud Constr Mater. https://doi.org/10.1016/j.cscm.2021.e00632
15. Karampour H, Piran F, Faircloth A, Talebian N, Miller D (2023) Vibration of timber and hybrid floors: a review of methods of measurement, analysis, and design. MDPI (Buildings) 13:49
16. Ljunggren F, Simmons C (2023) Sound insulation in multi-family houses: proposal of single number limits for acoustical protection and comfort. Build Acoust 30:387–407. https://doi.org/10.1177/1351010X2312060
17. Gibson B, Nguyen T, Sinaie S, Heath D, Ngo T (2022) The low frequency structure-borne sound problem in multi-storey timber buildings and potential of acoustic metamaterials: a review. Build Environ. https://doi.org/10.1016/j.buildenv.2022.109531
18. Ding Y, Zhang Y, Wang Z, Gao Z, Zhang T (2020) Vibration test and comfort analysis of environmental and impact excitation for wooden floor structure. BioResources 15:8212–8234
19. Marfella G, Winson-Geideman K (2021) Timber and multi-storey buildings: industry perceptions of adoption in Australia. Buildings. https://doi.org/10.3390/buildings11120653
20. Aloisio A, Pasca DP, Santis YD, Hillberger T, Giordano PF, Rosso MM, Bedon C (2023) Vibration issues in timber structures: a state-of-the-art review. J Build Eng. https://doi.org/10.1016/j.jobe.2023.107098
21. Leyder C, Chatzi E, Frangi A (2021) House of natural resources - modal vibration tests and long-term monitoring. Retrieved from ETH Zurich
22. Araujo VD, Christoforo A (2023) The global cross-laminated timber (CLT) industry: a systematic review and a sectoral survey of its main developers. Sustainability. https://doi.org/10.3390/su15107827
23. Pei S, Rammer D, Popovski M, Williamson T, Line P, Lindt JW (2016) An overview of CLT research and implementation in North America. Paper presented at the WCTE 2016, Vienna, Austria
24. ISO 21136 (2017) Timber Structures - Vibration Performance Criteria for Timber Floors. In International Standards Organisation/ Technical Report. Geneva, Switzerland
25. CSA-086:19 (2019) Engineering Design in Wood. In National Standard of Canada. Ottawa, ON, Canada
26. Lewis K, Basaglia B, Stirling R, Crews K (2016) The use of Cross Laminated Timber for Long Span Flooring in Commerical Buildings. WCTE 2016 - World Conference on Timber Engineering. 4813–4821
27. Wood Solutions (2020) Long-span Timber Floor Solutions. Technical Design Guide, 49
28. Basaglia B, Li J, Shrestha R, Crews K (2021) Response prediction to walking-induced vibrations of a long-span timber floor. J Struct Eng. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002888
29. Hughes WO, McNelis AM, Nottoli C, Wolfram E (2015) Examination of the measurement of absorption using the Reverberant Room Method for highly absorptive acoustic foam. Paper presented at the Aerospace Testing Seminar, Los Angeles, CA, USA
30. Ljunggren F (2019) Sound insulation prediction of single and double CLT panels. 23rd international congress on acoustics. 242–248
31. Müller T, Borschewski D, Albrecht S, Leistner P, Spah M (2021) The dilemma of balancing design for impact sound with environmental perforamnce in wood ceiling systems - a building physics perspective. Sustainability. https://doi.org/10.3390/su13168715
32. Müller T, Leistner P (2023) Ecologically motivated approaches for improving low-frequency sound and vibration performance in multistory timber buildings. Paper presented at the Forum Acousticum, September 11–15, Torino, Italy
33. ISO 12354-1 (2017) Building acoustics - estimation of acoustic performance of buildings from the performance of elements Part 1: Airborne sound insulation between rooms. In International Standards Organisation. Geneva, Switzerland
34. ISO 12354-2 (2017) Building acoustics - Estimation of acoustic performance of buildings from the performance of elements Part 2: Impact sound insulation between rooms. In International Standards Organisation. Geneva, Switzerland
35. Willford MR, Young P (2006) A design guide for footfall induced vibration of structures. In Concrete Centre. Concrete Society, London
36. AS/ISO 2631-2 (2014) Mechanical Vibration and Shock - Evaluation of Human Exposure to Wholebody Vibration, Part 2: Vibration in Buildings (1 Hz to 80 Hz). In Standards Australia. Sydney, Australia
37. Pavic A (2019) Results of IStructE 2015 Survey of Practitioners on Vibration Serviceability. Paper presented at the SECED 2019, Greenwich, London, UK
38. Hamm P, Knopfle V, Ruf J, Bacher P, Gotz T (2023) Full scale vibration tests on a long span timber floor. Paper presented at the World Conference on Timber Engineering Oslo 2023, Olso, Norway
39. Steiger R, Gulzow D, Gsell A (2010) Non-destructive evaluation of elastic materail properties of cross-lamianted timber (CLT). World Conference on Timber Engineering 2010
40. Faircloth A, Brancheriau L, Karampour H, Kumar C (2023) Evaluation of full-sized and thick CLT panels using in-line non-destructive techniques. Wood Sci Mater Eng. https://doi.org/10.1080/17480272.2023.2286622
41. Vallely S, Schoenwald S (2023) An efficient analytical method to obtain the homogenised frequency-independent elastic material properties of cross-laminated timber elements. J Sound Vib. https://doi.org/10.1016/j.jsv.2022.117424
42. Bos F, Casagrande SB (2003) On-line non-destructive evaluation and control of wood-based panels by vibration analsysis. J Sound Vib 268:403–412
43. Opazo-Vega A, Benedetti F, Nunez-Decap M, Maureia-Carsalade N, Oyarzo-Vera C (2021) Non-destructive assessment of the elastic properties of low-grade CLT panels. MDPI 12:1734
44. Huang H, Gao Y, Chang WS (2020) Human-induced vibrations of cross-laminated timber (CLT) floor under different boundary conditions. Eng Struct. https://doi.org/10.1016/j.engstruct.2019.110016
45. Kawrza M, Furtmuller T, Adam C (2022) Experimental and numerical modal analysis of a cross laminated timber floor system in different construction states. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2022.128032
46. Nilsson E, Menard S, Bard D, Hagberg K (2023) Effects of building height on the sound transmission in cross-laminated timber buildings - airborne sound insulation. Build Environ. https://doi.org/10.1016/j.buildenv.2023.109985
47. Goncalves MS, Pavic A (2024) Vibration serviceability and environmental impact of steel-concrete composite floors featuring openings and partitions. Pract Period Struct Des Constr. https://doi.org/10.1061/PPSCFX.SCENG-1430
48. Moons S, Lanoye R, Reynders PB (2025) Prediction of flanking sound transmission through cross-laminated timber junctions with resilient interlayers. Appl Acoust. https://doi.org/10.1016/j.apacoust.2024.110317
49. Labonnote N (2012) Damping in Timber Structures (PhD). Norwegian University of Science and Technology, Trondheim, Norway
50. Zhang J, Zhang C, Chang WS, Huang H (2023) Cross-laminated timber (CLT) floor serviceability under multi-person loading: impact of beam–panel connections. Eng Struct. https://doi.org/10.1016/j.engstruct.2023.116941
51. Aloisio A, Pasca DP, Owolabi D, Loss C (2024) Vibration serviceability of hybrid CLT-steel composite floors based on experimental and numerical investigations using random walk models. Eng Struct. https://doi.org/10.1016/j.engstruct.2024.117600
52. Blake RE (1961) Basic vibration theory. In: Harris CM, Crede CE (eds) Shock and vibration handbook. The McGraw-Hill Companies, Inc., New York, pp 1–32
53. Safarik D, Elbrecht J, Miranda W (2022) CTBUH: State of Tall Timber 2022. CTBUH J. 1. Accessed 06/05/2024. https://www.ctbuh.org/mass-timber-data
54. Casagrande D, Giongo I, Pederzolli F, Franciosi A, Piazza M (2018) Analytical, numerical and experimental assessment of vibration performance in timber floors. Eng Struct 168:748–758. https://doi.org/10.1016/j.engstruct.2018.05.020
55. Cheraghi-Shirazi N, Crews K, Malek S (2022) Review of vibration assessment methods for steel-timber composite floors. Buildings 12:26. https://doi.org/10.3390/buildings12122061
56. Sagerud JB, Stamatopoulos H, Malo KA, Ronnquist A (2023) Dynamic tests on a long span, stressed-skin, timber floor. Wood Mat Sci Eng 18:1868–1877. https://doi.org/10.1080/17480272.2023.2197857
57. Skinner J, Martins C, Bregulla J, Harris R, Paine K, Walker P, Dias AMPG (2014) Concrete upgrade to improve the vibration response of timber floors. Proc Inst Civ Eng 167:559–568. https://doi.org/10.1680/stbu.13.00057

58. Mushina J, Ghafar NA, Yeoh D, Mushina W, Boon KH (2020) Vibration behaviour of natural timber and timber concrete composite deck system. Paper presented at the IOP Conference Series: Materials Science and Engineering
59. Thai MV, Elachachi SM, Menard S, Galimardi P (2021) Vibration behavior of cross-laminated timber-concrete composite beams using notched connnectors. Eng Struct. https://doi.org/10.1016/j.engstruct.2021.113309
60. Zhou J, Chui YH, Zhang L, Li G (2022) Vibration performance and stiffness properties of mass timber panel-concrete composite floors with notched connections. J Struct Eng. https://doi.org/10.1061/(ASCE)ST.1943-541X.0003450
61. Bettarello F, Gasparella A, Caniato M (2021) The influence of floor layering on airborne sound insulation and impact noise reduction: a study on cross laminated timber (CLT) structures. Appl Sci (MDPI). https://doi.org/10.3390/app11135938
62. Schoenwald S, Kumer N, Wiederin S, Bleicher N, Furrer B (2019) Application of elastic interlayers at junctions in massive timber buildings. Paper presented at the Proceedings of the 23rd International Congress on Acoustics, Aacheen, Germany, 9–13 September
63. Vardaxis NG, Hagberg DB, Dahlstrom J (2022) Evaluating laboratory measurements for sound insulation of cross-laminated timber (CLT) floors: configurations in lightweight buildings. Appl Sci (MDPI). https://doi.org/10.3390/app12157642
64. Huang H, Lin X, Zhang J, Wu Z, Wang C, Wang BJ (2021) Performance of the hollow-core cross-laminated timber (HC-CLT) floor under human-induced vibration. Structures 32:1481–1491. https://doi.org/10.1016/j.istruc.2021.03.101
65. Krtschil A, Orozco L, Bechert S, Wagner HJ, Amtsberg F, Chen T, Y, Knippers, J, (2022) Structural development of a novel punctually supported timber building system for multi-storey construction. J Build Eng. https://doi.org/10.1016/j.jobe.2022.104972
66. Jarnero K, Brandt A, Olsson A (2015) Vibration properties of a timber floor assessed in laboratory and during construction. Eng Struct 82:44–54. https://doi.org/10.1016/j.engstruct.2014.10.019
67. Hamm P, Richter A, Winter S (2010) Floor Vibration - new results. Paper presented at the 11th World Conference on Timber Engineering 2010, Riva del Garda
68. Hu L, Chui YH, Hamm P, Toratti T, Orskaug T (2018) Development of ISO baseline vibration design method for timber floors. Paper presented at the World Conference on Timber Engineering (WCTE 2018), Seoul, Republic of Korea
69. Mindlin RD (1951) Influence of rotary inertia and shear on flexural motions of isotropic, elastic plates. J Appl Mech 18:31–38
70. Reissner E (1976) On the theory of transverse bending of elastic plates. Int J Solids Struct 12:545–554
71. Deobald LR, Gibson RF (1988) Determination of elastic constants of orthotropic plates by a modal analysis/ Rayleigh-Ritz technique. J Sound Vib 124:269–283
72. Shahnewaz M, Dickof C, Zhou J, Tannert T (2022) Vibration and flexural performance of cross-laminated timber - glulam composite floors. Compos Struct. https://doi.org/10.1016/j.compstruct.2022.115682
73. Opazo-Vega A, Munoz-Valdebenito F, Oyarzo-Vera C (2019) Damping assessment of lightweight timber floors under human walking excitations. MPDI. https://doi.org/10.3390/app9183759
74. Zhang J, Huang H, Wang BJ (2024) Long-term loading effect on vibration performance of CLT floors: an 896-day monitoring study. Eng Struct. https://doi.org/10.1016/j.engstruct.2024.118562
75. Zhang Y, Miao C, Wang Z, Xu Z (2024) Study on vibration performance and comfort of glulam beam and deck floor. Eur J Wood Wood Prod. https://doi.org/10.1007/s00107-024-02067-1
76. Chang WS, Goldsmith T, Harris R (2018). A new design method for timber floors - peak acceleration approach. Paper presented at the INTER 2018 Conference Proceedings, Tallinn, Estonia, 13–16 August 2018
77. Smith AL, Hicks SJ, Devine PJ (2007) Design of floors for vibration: a new approach. Steel Construction Institute, Berkshire
78. FprEN 1995-1-1 (202X (E)) Eurocode 5: Design of Timber Structures - Part 1–1: General - Common rules and rules for buildings. In European Committee for Standardisation. Brussels, Belgium
79. ISO 2631-1, AS 2670.1 (2001) Evaluation of Human Exposure to Whole-body Vibration, Part 1: General requirements. In Standards Australia. Sydney, Australia
80. AS/NZS 1170.0 (2002) Structural Design Actions, Part 0: General Principles. In Standards Australia/Standards New Zealand. Sydney, Australia
81. Waarts, P (2005) Vibrations from floors due to walking - Guidelines for predicting, measuring, and assessing. Rottendam, Netherlands
82. ISO 10137 (2007) Basis for design of structures-serviceability of buildings and walkways against vibrations. In International Standards Organisation. Geneva, Switzerland
83. BS 6472-1 (2008) Guide to Evaluation of Human Exposure to Vibration in Buildings. In British Standards Institute. London, UK
84. RFS2-CT-2007-00033 (2009) Design of footbridges guideline. Human induced vibrations of steel structures. In HIVOSS. Luxembourg
85. Galanti F, Heinemeyer C, Feldmann M, Lentzen S (2011) Assessment of floor vibration using the OS-RMS90 method. Paper presented at the Proceedings of the 8th international conference on structural dynamics, EURODYN2011, Leuven, Belgium
86. ISO18324 (2016) Timber Structure - Test Methods - Floor Vibration Performance. In International Standards Organisation. Geneva, Switzerland
87. Murray T, Allen D, Ungar E, Davis DB (2016) Steel design guide series 11: vibrations of steel-framed structural systems due to human activity. American Institute of Steel Construction, Chicago
88. Karacabeyli E, Gagnon S (2019) Canadian CLT handbook: cross-laminated timber. FPInnovations, Pointe-Claire
89. Barber D, Blount D, Hand JJ, Roelofs M, Wingo L, Woodson J, Yang F (2022) Design guide 37: hybrid steel frames with wood floors. The American Institute of Steel Construction, Chicago
90. Hamm P (2022) *Vibrations, Deflections*. Paper presented at the 4th International conference on timber bridges (ICTB 2021), Biel/Bienne, Switzerland.
91. Muhammad ZO, Reynolds P (2019) Vibration serviceability of building floors: performance evaluation of contemporary design guidelines. J Perform Contrusted Facil. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001280
92. Shahabpoor E, Pavic A (2024) Human-structure dynamic interactions: identification of two-degrees-of-freedom walking human model. J Sound Vib. https://doi.org/10.1016/j.jsv.2023.117974
93. Wang C, Chang WS, Yan W, Huang H (2021) Predicting the human-induced vibration of cross-laminated timber floor under multi-person loadings. Structures 29:65–78. https://doi.org/10.1016/j.istruc.2020.10.074
94. Wood Works (2023) U.S. Mass Timber Floor Vibration Design Guide. Retrieved from Maine, USA.
95. Xie H, Li H, Liu C, Li M, Zou J (2016) Noise exposure of residential areas along LRT lines in a mountainous city. Sci Total Environ 568:1283–1294. https://doi.org/10.1016/j.scitotenv.2016.03.097
96. Huang H, Zhang J, Uttley J, Chang WS, Wang BJ (2022) The effect of the environment on the serviceability of the cross-laminated timber (CLT) floor: virtual reality as a research tool. Adv Civ Eng. https://doi.org/10.1155/2022/7562656
97. Wei X, Zivanovic S (2018) Frequency response function-based explicit framework for dynamic identification in human-structure systems. J Sound Vib 422:453–470. https://doi.org/10.1016/j.jsv.2018.02.015
98. Rikard, O (2017) Measurement and perception of sound insulation from 20 Hz between dwellings (Doctoral thesis). Lulea University of Technology, Lulea tekniska universitet. (ISSN 1402-1544)
99. Kraler A, Brugnara P (2022) Acoustic behaviour of CLT structures: influence of decoupling bearing stripes, floor assembly and connectors under storey-like loads. Paper presented at the InterNoise22, Glasgow, Scotland
100. Pavic A, Mohamad A, Walker I, Margnelli A, Pelekis I (2024) Investigating the impact of vertical floor vibration on cognitive performance. Paper presented at the 2024 AHFE International Conference on Human Factors in Design, Engineering, and Computing (AHFE 2024 Hawaii Edition), Hawaii, USA, 24–27 July
101. IHBE (2022) Research Tools - Microacoustic Test Chamber. Accessed 14/10/2024. https://buildhealth.uoregon.edu/microacoustic-test-chamber/
102. Schoenwald S, Vallely S (2023) Cross laminated timber elements with functional grading and localised ballast to improve airborne and

impact sound insulation. Paper presented at the 10th Convention of the European Acoustics Association, Turin, Italy.
103. Division UNP (2022) United Nations Population Division. World Population Prospects: 2022 Revision. The World Bank - Population Total. Accessed 06/05/2024. https://data.worldbank.org/indicator/SP.POP.TOTL?end=2022&locations=CN&start=2022&view=map
104. WoodWorks (2024) Mapping Mass Timber. Mass Timber Projects Constructed in The US. Accessed 02/12/2024. https://www.woodworks.org/resources/mapping-mass-timber/
105. Evison CD, Kremer P, Guiver J (2018) Mass timber construction in Australia & New Zealand - status, and economic and environmental influences on adoption. Wood Fiber Sci 50:128–138
106. Anderson R (2020) Mass Timber Outlook - Mass Timber Price Index. The Beck Group - Softwood Lumber Board (XXIV/2022 International Mass Timber Report). Accessed 06/05/2024. https://www.masstimberreport.com/performance-index
107. Sandoli A, D'Ambra C, Ceraldi C, Calderoni B, Prota A (2021) Sustainable cross-laminated timber structures in a seismic area: overview and future trends. Appl Sci (MDPI) 11:23. https://doi.org/10.3390/app1105207
108. Aurecon (2018) 25 King Street. Sustainable timber building design putting people at the heart. Accessed 14/10/2024. https://www.aurecongroup.com/projects/property/25-king
109. Hines (2023) T3 Collingwood. Timber, Transition and Technology. Accessed 14/10/2024. https://www.hines.com/properties/t3-collingwood-melbourne
110. ARUP (2022) WS2 Building Design. Designing Western Australia's first timber-hybrid office tower. Accessed 14/10/2024. https://www.arup.com/projects/ws2-building-design/
111. Brugnara P, Scheibmair F, Speranza A (2022) Resilient interlayers and connectors: acoustic-structure interaction in timber buildings. Paper presented at the Conference of the Acoustical Society of New Zealand, Wellington, New Zealand
112. Sahnaci C, Meinhardt C, Krampe T (2017) Performance of MTMD systems based on realistic load contributions due to walking. Paper presented at the Footbridge 2017 - Tell a Story, Berlin, Germany
113. Huang H, Chang WS (2020) Re-tuning an off-tuned mass damper by adjusting temperature of shape memory alloy: exposed to wind action. Structures 25:180–189. https://doi.org/10.1016/j.istruc.2020.02.025
114. Huang H, Wang C, Chang WS (2020) Reducing human-induced vibration of cross-laminated timber floor - application of multi-tuned mass damper system. Struct Control Health Monit. https://doi.org/10.1002/stc.2656
115. Felicita M, Roijakkers R, Cojocaru R, Ravenshorst G (2024) Comfort assessment of timber floor vibrations. Paper presented at the INTER 11, Padova, Italy
116. Gibson BT (2022) Nonlinear acoustic metamaterial for attenuation of low-frequency structure-borne sound in multi-storey timber buildings (Doctor of Philosophy). The University of Melbourne

Publisher's Note