Review

Review of Vibration Assessment Methods for Steel-Timber Composite Floors

Najmeh Cheraghi-Shirazi [1,2], Keith Crews [3] and Sardar Malek [1,2,*]

1   Department of Civil Engineering, University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada
2   Centre for Advanced Materials and Related Technology (CAMTEC), University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada
3   School of Civil Engineering, Advanced Engineering Building, The University of Queensland, Staff House Road, St. Lucia, QLD 4072, Australia
*   Correspondence: smalek@uvic.ca

Abstract: Human comfort is recognized as an essential serviceability requirement for timber floors. Although several standards and design criteria are available for designing steel and concrete floors, there is no consensus among researchers on the applicability of such design methods to timber composite floors. Adding steel to timber floors is intended to create long spans, however, vibration is still a major challenge in achieving longer spans. To highlight the extent of this issue, a comprehensive search in the literature was conducted. The most common vibration criteria that may be used to assess the performance of steel-timber composite floors under human-induced vibrations were reviewed. For lightweight composite floors, the 1 kN deflection limit was found to be the most suitable vibration limit based on a wide range of subjective evaluation studies. For composite floors comprising steel and heavier timber subfloors, the relevance of 1 kN deflection criterion and other criteria suggested in the literature are questionable due to the lack of subjective evaluation studies. In the advent of advanced computing and data analysis, conducting detailed numerical analysis validated by accurate on-site measurements is recommended. Special attentions should be given to accurate estimation of connection stiffness and damping ratio according to the findings of this study.

Keywords: vibration; finite element analysis; timber; steel; frequency; deflection; standards

1. Introduction

As steel-timber composite floors are emerging as a solution in the construction of mass timber buildings with longer spans, human comfort is becoming an important serviceability concern for the designers of such buildings. In the context of available design standards and code requirements, designing composite floors according to vibration limits can be debatable. There are some general design guides such as the Design Guide for Footfall Induced Vibration of Structures (CCIP-016 [1]) and AISC Design Guide 11 [2] that practitioners commonly use for vibration assessment of concrete, steel, and composite floors. In addition to general design guides, specific standards for timber structures such as Eurocode 5 [3], Canadian Wood Council (CWC) [4], Canadian Standards Association (CSA O86-19) [5], CLT Handbook [6], and the American Engineered Wood Association APA–E710 [7] have specific provisions for the vibration performance of timber floors. Some researchers also recommend SCI P354 [8] for lightweight cold-formed steel floors including those with timber floorboards.

To the authors' knowledge, there is still no consensus among researchers on the applicability of different criteria for the vibration performance of composite flooring systems comprising steel joists and wood-based flooring panels. However, it should be noted that some vibration criteria and assessment methods have gained more attention for timber and composite floors in the literature recently [9–17]. To better understand the discrepancy of such methods, some commonly used vibration criteria are briefly described below. The

validity of such criteria in the context of experimental and numerical studies are explained in Sections 2 and 3. Some future works are highlighted in Section 4.

1.1. Vibration Criteria for Lightweight Timber Floors

The most important criterion for lightweight joisted timber floors was introduced by Onysko et al. [18]. Static deflection of the floor under 1 kN concentrated load was found to be an appropriate parameter to assess the vibration performance of short-span timber floors, including solid timber joists and conventional subfloors [9]. Onysko and co-workers suggested the following limits (Equations (1-a) and (1-b)) for the floor deflection due to 1 kN force:

$$\Delta \leq 2 \text{ mm for } L < 3 \text{ m} \tag{1-a}$$

$$\Delta \leq 8/L^{1.3} \text{ for } L \geq 3 \text{ m} \tag{1-b}$$

where L is span length (m). Equation (1-b) has been modified in Canadian Wood Council (CWC [4]) for the span length of more than 5.5 m as:

$$\Delta \leq 2.55/L^{0.63} \; for \; L \geq 5.5 \text{ m} \tag{2}$$

Applied Technology Council (ATC) Design Guide [19] provides similar equation (Equation (3)) to limit the deflection of lightweight floors with a fundamental frequency of more than 8 Hz:

$$\Delta \leq 0.61 + 2.54e^{-0.59(L-1.95)} \leq 2.0 \text{ mm} \tag{3}$$

It should be highlighted that Swedish [20] and Australian [21] methods use constant values of 1.5 mm and 2 mm to limit the 1 kN deflection of the floors, respectively. According to these standards, the frequency of the floors should be greater than 8 Hz.

Dolan et al. [22] defined the frequency of more than 14 Hz and 15 Hz as the criteria for acceptable floors in occupied and unoccupied buildings, respectively. Combining frequency and 1 kN deflection, Hu and Chui [23] proposed a different vibration criterion for wood-based floors ($f/d^{0.44} \geq 18.7$). Employing a different approach, SCI P354 [8] presented vibration criteria for lightweight cold-formed steel composite floors with wood-based subfloors to limit the frequency, deflection, and response factor (or VDV) of such floors (see Appendix A).

Based on the deflection and unit impulse velocity response of timber floors with a frequency more than 8 Hz, Eurocode 5 [3] considers the following two vibration criteria.

$$\frac{w}{F} \leq \Delta \tag{4}$$

$$v \leq b^{(f_1\zeta - 1)} \tag{5}$$

where w is the floor's vertical deflection (mm) under a concentrated load of F (kN), v is the unit impulse velocity response (m/(Ns^2)), and ζ is the modal damping ratio. Recommended damping ratios for timber floors are 1% in Eurocode 5 [3] and 2% in the UK National Annex (UKNA) [24] to Eurocode 5. More details have been provided in Appendix B. According to UK National Annex (UKNA) to Eurocode 5, the floor deflection due to the 1 kN force, Δ (mm), should satisfy the following requirements [25]:

$$\Delta \leq 1.8 \text{ (mm) for } L < 4 \text{ m} \tag{6-a}$$

$$\Delta \leq 16,500/L^{1.1} \text{ (mm) for } L \geq 4 \text{ m} \tag{6-b}$$

where L is the floor span (mm).

The relationship between Δ and b can be formulated as follows [25]:

$$b = 180 - 60\Delta \quad \Delta \leq 1 \text{ mm} \tag{7-a}$$

$$b = 160 - 40\Delta \quad \Delta > 1 \text{ mm} \tag{7-b}$$

Toratti and Talja [26] defined vibration criteria through a comprehensive study on the lightweight steel and timber floors. Different classes were defined for offices and residences, and limits were assumed for each class in terms of $a_{w,RMS}$, v_{RMS}, v_{max}, u_{max} and deflection. Peak velocity limit of 8 mm/s and 1 kN static deflection limit of 0.5 mm and $a_{w,RMS}$ limit of 0.075 m/s² were defined for a normal apartment. They found for high-frequency floors (f > 10 Hz), peak velocity and static deflection limits are appropriate parameters to limit the floor's vibration.

1.2. General Vibration Criteria for Other Floors

In addition to the criteria described in Section 1.1, the vibration performance of timber floors under human-induced force may also be evaluated by other indicators; Peak (or RMS) acceleration, peak velocity, and Vibration Dose Value (VDV) have been recommended to assess the performance of floors according to ISO [27,28], BS 6472-1 [29], CCIP-016 [1] (see Appendix C), and AISC design guide 11 [2] (see Appendix D). AISC design 11 [2] and CCIP-016 [1] provide two distinct approaches (simplified equations and finite element (FE) analysis method) to address floor vibration. Although simplified equations can be used for rectangular floors, they have been calibrated for concrete and steel floors and may not be applicable to timber composite floors. Furthermore, such equations cannot be used for irregular floors with large openings or cantilevers. Thus, using such simplified equations for long-span timber composite floors is currently not recommended. AISC DG 37 [30] recommends the U.S. mass timber floor vibration design guide [31], including CCIP-016 [1] and AISC design guide 11 [2], for steel frame structures with timber floors. However, the accuracy range of the equations in these design guides has not been investigated experimentally for steel-timber composite floors to the authors' knowledge. For mass timber floors, Canadian CLT Handbook [6] and CSA O86-19 [5] suggest an empirical equation (Equation (8)) for the vibration-controlled span design of CLT floors. This simplified equation has been proposed based on testing several one-span simply supported floors:

$$L \leq 0.11 \frac{\left(\frac{(EI)_{eff}}{10^6}\right)^{0.29}}{m^{0.12}} \tag{8}$$

Here, m is the floor mass per panel width (kg/m) and $(EI)_{eff}$ is its effective bending stiffness (Nmm²).

As will be demonstrated in this paper, there are disparities between various performance indicators and the limits set in existing standards and design guides. Currently, deciding whether an existing composite floor passes a certain analytical serviceability check is quite subjective to structural engineers. Different criteria require calculating the floor response (e.g., the floor's acceleration, velocity, and deflection) due to a dynamic (e.g., walking or running) or static load. As an alternative to simple equations provided in standards, a FE model may be used to carefully investigate the floor response due to walking in terms of deflection, acceleration, or velocity [32].

Based on different vibration design criteria suggested in the literature, a steel-timber composite (STC) floor may be acceptable according to some standards, while it is unacceptable according to a few others. Hence, it is necessary to review all experimental and numerical studies on such floors to better understand the source of disparities between various standards. As construction of mass timber buildings with composite floors comprising steel and engineered wood products is becoming popular, a review of design methods could guide structural engineers in choosing the most relevant vibration design method(s) to a specific project.

2. Experimental Studies on Vibration Performance of Lightweight Steel-Timber Floors

Kraus [33] conducted an experimental study on the vibration performance of cold-formed steel floors with 19 mm OSB subfloors. Static tests, heel drop tests, and walking tests were performed to find the 1 kN deflection, frequency, and time-history acceleration

of floors due to walking on floors with the span length of less than 6 m. Walking tests were conducted by a 240 lb (109 kg) human walking parallel and perpendicular to the steel joists. Measured floor responses were employed to evaluate the floors' vibration according to Canadian [4], American [19], Swedish [20], and Australian [21] standard. Based on human subjective evaluation, the Canadian standard [4] was recommended for the studied STC floors. Further research on floors with longer spans and a wider range of joist spacing were suggested.

To better understand the effect of various parameters on the vibration performance of lightweight steel-timber floors, researchers at the University of Waterloo conducted a multi-phase study on the vibration performance of cold-formed steel floors [34–37]. Lightweight composite floors comprising cold-formed steel C-shape joists with and without web openings were examined; plywood, oriented strand board (OSB), fiber-reinforced cement panels, and cold-formed steel decks were considered as subfloors. The effects of various parameters on the floors' frequency, maximum deflection, and damping were investigated. Additionally, the vibration behavior of in situ and laboratory floors were compared. Subjective evaluation tests were conducted on floors with a span length of around 6 m and the results were presented in the master's thesis of Liu [37]. The experiments and the key findings of the comprehensive study conducted at the University of Waterloo [34–37] are summarized below.

The vibration characteristics of lightweight cold-formed steel-timber residential floors of various span lengths were measured by Xu and Tangorra [34]. The typical plan-view of their floors is presented in Figure 1. Two types of tests, i.e., static and dynamic tests, were performed on each floor. From static tests, each floor's load-sharing capability and its maximum deflection under a static load of 1 kN were determined. In addition to static tests, dynamic tests were conducted to find dynamic responses of the floors, such as their frequency and damping ratio.
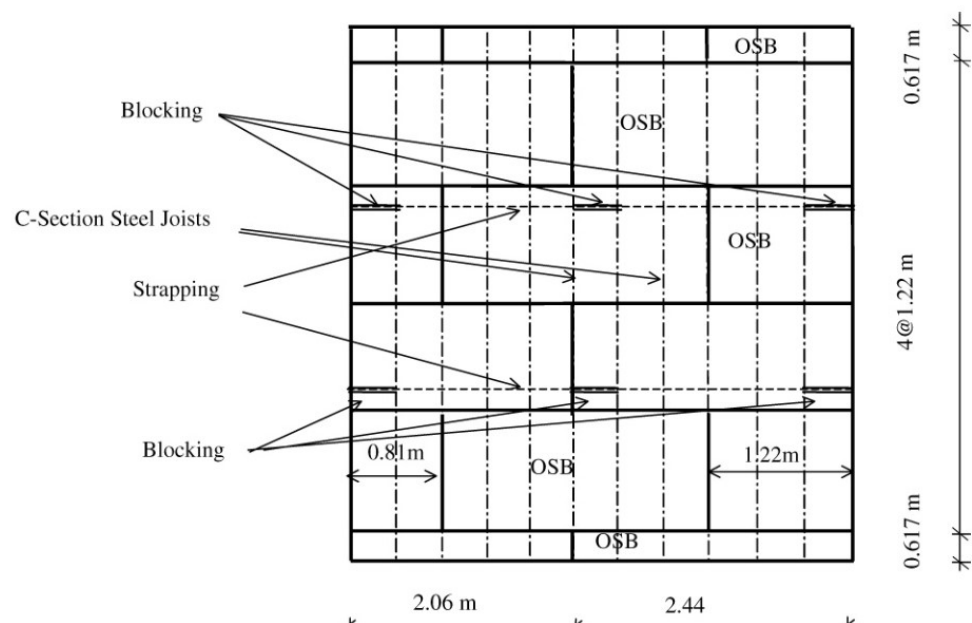
Figure 1. Plan-view of the cold-formed steel-timber composite floors tested by Xu and Tangorra [34]. Tongue-in-groove OSB sheathing was used as the subflooring. Reproduced with permission.

From laboratory testing, the effects of the several construction details such as floor span and support condition at the boundaries (i.e., the effect of the joist ends or all four edges supported), joist end restraints (free or restrained to rotate), blocking, bridging, screw pattern, ceiling, and gluing subfloor on the static and dynamic performance of the floor were quantified and compared in terms of the natural frequencies, maximum deflection, and damping ratio. In addition to laboratory testing, on-site testing was also conducted.

The results of laboratory and on-site tests are summarized in Table 1. Due to different restraints at the joist ends in the laboratory tests, on-site results exhibited generally higher first natural frequencies and smaller maximum deflections. It should be emphasized that the on-site floors had more damping, most probably due to non-structural components. Additionally, less acceleration was measured in the response of a finished floor compared to an unfinished floor. However, as shown in Table 1, the frequency of fully finished floors is less than that of unfinished floors. Hence, it can be concluded that the frequency is not an appropriate indicator to evaluate the vibration of lightweight timber floors.

Table 1. Summary of laboratory and on-site results obtained from static and dynamic tests reported in Xu and Tangorra [34].

	Floorboard Thickness and Type	Cold-Formed Steel Joist Type	Span (m)	Frequency (Hz)	Maximum Deflection (mm)	Damping Ratio (%)
Laboratory floors *	16 mm OSB	C-203 × 41 × 1.22 C-254 × 41 × 1.91	4.12–6.754	10.51–15.98	1.01–1.69	1.29–2.59
On-site unfinished floors *	16 mm plywood	C-254 × 41 × 1.91 C-254 × 41 × 1.52	5.089–5.912	14.9–18.0	0.91–1.20	5–6
On-site fully finished floors	16 mm plywood	C-254 × 41 × 1.52	5.302	12.3–13.6	-	6–6.5

* All floors had two supported edges.

The subjective evaluation tests on floors with span lengths of 6.112 m and 6.754 m were conducted by Liu [37]. The floors were classified as acceptable, non-acceptable, and marginal floors. A person sitting evaluated the floor vibration whilst a 185 lb person was walking in directions parallel, perpendicular, and diagonal to the joists. It is worth mentioning that a simple calculation shows that the examined floors do not satisfy the ATC vibration limit of 1 kN force. Hence, good agreement between subjective evaluation and vibration prediction based on ATC's criterion was expected.

To understand the effect of various subfloor types, Parnell et al. [35] investigated the static and dynamic responses of 43 full-scale floors ranging from 4.4 to 6.5 m long. The details of the floors, including the floor span, joist section, floor system, joist-end restraints, and the type of subfloor, are listed in Table 2. Cold-formed steel deck, OSB, and fiber-reinforced cement (FC) were used as a subfloor. To evaluate the effects of joists' web openings on the modal properties of the floors, two joist types, i.e., Dietrich C-stud joists (CSW) and Dietrich TradeReady joists (TDW), with the same depth but different web openings, were used as illustrated in Figure 2. The plan-view and cross-section of the tested floors are provided in Figure 3.

(a) (b)
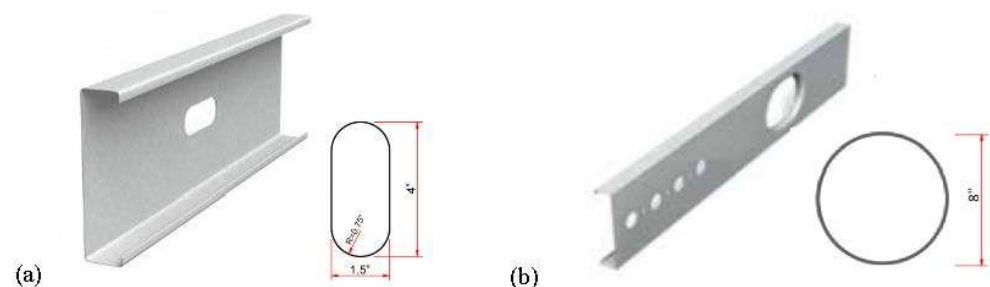
Figure 2. Cold-formed steel joists used in Parnell et al. [35]: (**a**) Dietrich C-stud joists (CSW); (**b**) Dietrich TradeReady joists (TDW). The figures are reproduced from the company website (www.clarkdietrich.com (accessed on 1 January 2022)).

Table 2. Laboratory and in situ construction configuration tested by Parnell et al. [35]. See Figure 3 for a typical cross-section of the floors.

	Span (m)	Joist Section	Subfloor	Floor Support System	Framing
Laboratory floors	4.42	CSW&TDW	OSB, FC, FC with LR	free support	Balloon framing Platform framing
	5.18–5.94	TDW	UFS with LR FC with LR		
In situ floors	4.51–6.46	TDW	FC with LR UFS with LR	supported on all four sides	Balloon framing

Notes:
- Subfloors:
  OSB: 19 mm oriented-strand board
  FC: 19 mm fiber-reinforced cement
  FC with LR: 19 mm FC structural panel topped with a 19 mm lift of LEVELROCK floor underlayment
  UFS with LR: 0.75 mm Dietrich cold-formed steel deck (UFS) topped with a 38.1 mm lift (to bottom flute) of LR floor underlayment.
- The LR floor underlayment was a gypsum-based, self-leveling floor topping.
- All floors were constructed with blocking and strapping.
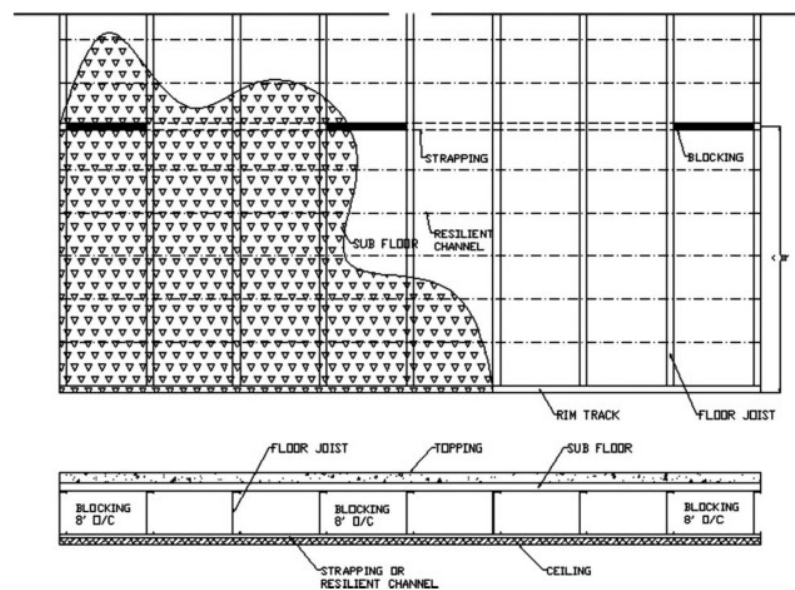
Figure 3. The plan-view and cross-section of the cold-formed steel floor in Parnell et al. [35]. Reproduced with permission.

The maximum static deflection of the floor under a point load of 1 kN was measured at mid-span. Heel drop and sandbag tests were first performed to obtain the natural frequency and damping ratio. Then, a walking test was conducted to evaluate the floor response under footfall force. For this purpose, an 82 kg human walked parallel and perpendicular to joist directions. Additionally, Parnell et al. [35] assessed the effects of construction details such as large lip-reinforced web openings, subfloor material, strongback, and the end framing condition on modal properties and center deflection of the floors. The highest frequency, 26.3 Hz, was reported for a floor with the OSB subfloor, and the lowest frequency, 10.6 Hz, was recorded for the UFS with the LR subfloor. Table 3 summarizes the dynamic and static results of laboratory and in situ tests based on the floor system and span length. The in situ floor systems had a higher first natural frequency and damping ratio than corresponding laboratory floors. The authors noted that the in situ floors had better responses in terms of frequency and damping, most probably due to the presence of

non-structural components and connections between different parts of floors. It is worth mentioning that the recommended damping ratio for timber floors is 1% in Eurocode 5 [3]. However, the measured damping ratio for lightweight steel-timber floors tested by Parnell et al. [35] was more than 2% and 7% in laboratory and in situ tests, respectively (see Table 3).

Table 3. The static and dynamic results for laboratory and in situ floors with various conditions of subfloor, joist type, ceiling, and strongback, evaluated by Parnell et al. [35].

	Span (m)	Frequency, f_1 (Hz)	Damping Ratio, β (%)	Maximum Deflection (mm)
Laboratory floors (Balloon framing)	4.42–5.94	11.4–26.3	2.1–4.7	0.25–0.59
Laboratory floors (Platform framing)	4.42–5.94	11.1–17.9	3.5–7	0.25–0.67
Laboratory floors (Simple support)	4.42–5.94	10.6–19.1	2.3–7.7	0.26–0.71
In situ floors (Balloon framing)	4.51–6.46	14.4–16.6	7.1–8.8	0.28–0.46

All measured static deflections were found to be less than 0.71 mm, which is acceptable according to ATC Design Guide [19]. In addition to deflection, the RMS acceleration response of the tested in situ floors showed satisfactory floor performance according to the ISO [28] criterion; ISO recommends using RMS acceleration as a vibration performance indicator. The RMS acceleration considers changes in vibration amplitude over time and hence could be different from peak values predicted in transient vibration analysis. Figure 4 shows agreement between the results of ATC [19] and ISO for in situ floors. Floors with acceptable vibration performance according to the deflection limit prepared in ATC [19] (Figure 4a) were also acceptable according to the RMS acceleration limit provided in ISO for offices and residences [28] (Figure 4b).

(**a**)　　　　　　　　　　　　　　　　　　　　　　(**b**)
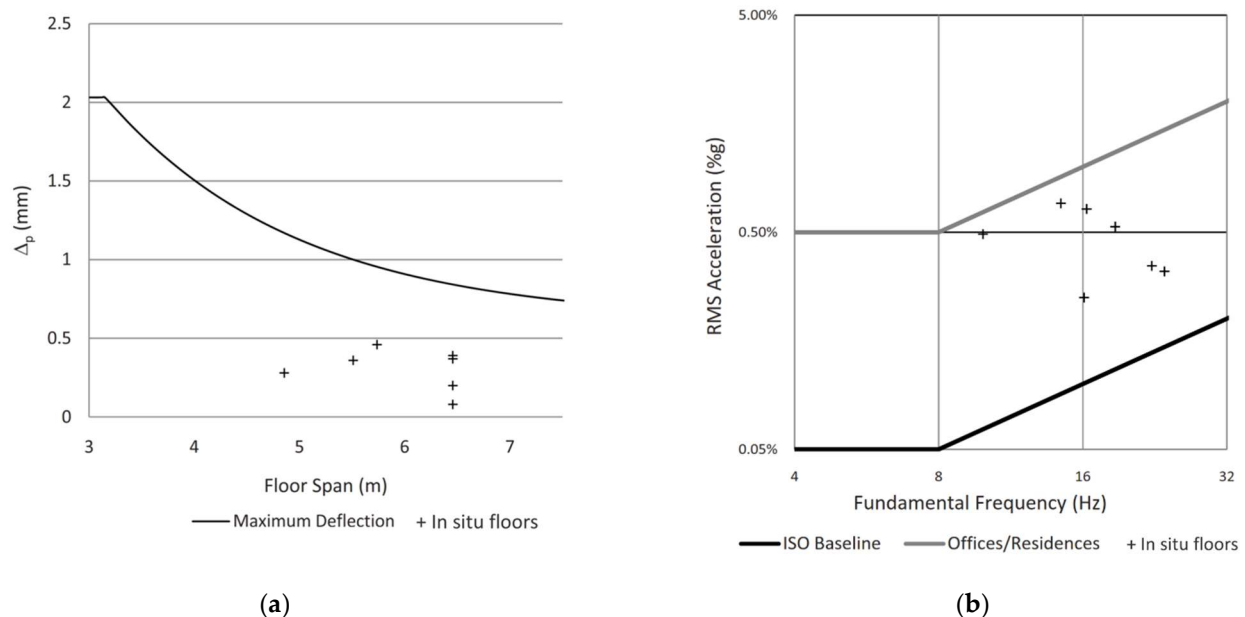
Figure 4. Investigation of floor vibration for in situ floors tested by Parnell et al. [35] according to (**a**) ATC [19] and (**b**) ISO [28]. Reproduced from [35] with permission.

A general discussion comparing the results of all laboratory and in situ tests on cold-formed steel floors conducted at the University of Waterloo has been presented in Xu [36].

The range of measured frequencies and maximum deflections obtained from more than 100 floors tested in the laboratory and 25 in situ floors are included in Table 4. All reported frequencies and deflections were more than 8 Hz and less than 1.9 mm, respectively. In addition to conducting experiments, Xu [36] also examined several design methods for vibration performance of lightweight cold-formed steel floors. The fundamental frequencies and span deflections of the laboratory tests were compared to those estimated using CWC [4], ATC [19], Swedish [20], and Australian [21] method. Except the CWC method [4], all other methods overestimated the floor frequency. Table 5 summarizes the performance of the designed floors in Xu [36]. The results prove that a design based on only the deflection limit of $L/480$ may not be conclusive, as some floors with that limit failed to satisfy the requirements in some standards. On the other hand, floors designed based on the ATC's deflection method showed satisfactory performance according to other three methods. The ATC [19] was found to provide the most restrictive limits compared to other design methods.

Table 4. The results of the frequency and maximum deflection obtained from the multi-phase study on the vibration performance of cold-formed steel floors prepared by Xu [36].

	Fundamental Frequency (Hz)	Maximum Deflection (mm)
Laboratory floors	9.8–26.3	0.17–1.89
In situ floors	9.9–35.7	0.2–1.20

Table 5. Vibration assessment of laboratory floors with span lengths designed based on the ATC method [19] and the deflection limit of $L/480$, according to various design methods considered in Xu [36]. Data reproduced from Xu [36] with permission.

	Criteria Used for Span Design		
	ATC Deflection [19]	$L/480$ with Living Room	$L/480$ with Bedroom
CWC method [4]	satisfactory	unsatisfactory	unsatisfactory
ATC method [19]	satisfactory	unsatisfactory	unsatisfactory
Swedish method [20]	satisfactory	satisfactory	unsatisfactory
Australian method [21]	satisfactory	satisfactory	satisfactory

Subsequently, the measured fundamental frequency and span deflection of the floors tested by Xu and Tangorra [34] with and without lightweight subfloor topping were evaluated based on the ATC [19], AISC Design Guide 11 [38], and Smith, Chui, and Hu's method (SCH) [23,39]. The fundamental frequencies of all laboratory floors with simple support conditions were over-predicted by the three methods. However, the frequency results of in situ floors with simple support conditions were either under- or over-predicted by these methods. It is worth mentioning that the peak acceleration response of the in situ floors due to walking excitation was examined in Xu [36]. A simplified equation from AISC Design Guide 11 [38] was used for this purpose:

$$\frac{a_p}{g} = \frac{P_\text{o} e^{-0.35 f_n}}{\beta W} \tag{9}$$

where P_o is the constant force of 0.29 kN, f_n is the fundamental frequency of the floor, β is the modal damping ratio, and W is the effective weight of the floor. The comparison between the acceleration predictions from Equation (9) and the measured acceleration response showed a significant difference. The authors noted that the underestimated damping and the excitations provided by a person with a weight of 0.8 kN instead of the weight recommended by AISC might contribute to this discrepancy. However, it should be noted

that Equation (9) can only be used for low-frequency floors (<9 Hz) according to the AISC Design Guide 11 [38], while the floors examined in Xu [36] were mainly high-frequency floors, and they required assessment based on equivalent sinusoidal peak acceleration (a_{ESPA}) instead of Equation (9). Accurate estimation of both the fundamental frequency and the peak acceleration is an essential part of using the simple approach provided in AISC Design Guide 11 [38]. For floors with complex boundary conditions, AISC recommends using a FE analysis that identifies various vibration modes.

In summary, researchers at the University of Waterloo have conducted what to date is the most comprehensive study on the vibration performance of lightweight floors comprising cold-formed steel joists and wood-based subfloors. According to their study, in situ floors provided less acceleration due to walking and more damping than laboratory floors and, therefore, demonstrated more acceptable behavior in terms of vibration performance. They also demonstrated that partially constrained laboratory floors represented the beam-to-column connection found in actual building floors. They did a subjective evaluation of the floors with a span length of around 6 m and found ATC 1 kN deflection criterion is appropriate for the evaluation of lightweight floors comprising cold-formed steel joists and OSB subfloors. The results of 1 kN deflection and RMS acceleration of three lightweight in situ floors due to walking showed good agreement between the ATC [19] and ISO limits [28].

Similar to Hu and Chui [23], Zhang and Xu [40] collected all data from [33,37,41–43] to create new criteria for cold-formed steel floors. For this purpose, they used the combination of measured 1 kN deflection and floor frequency of 65 floors, considering the subjective evaluation of the floors. The span of all floors was between 2.16 m to 8.8 m. Their proposed criterion ($f/d^{0.44} \geq 15.9$) against the subjective evaluation of all floors are presented in Figure 5. The accuracy of the proposed criterion ($f/d^{0.44} \geq 15.9$) to predict floor vibration for floors with a span length less than 6 m and between 6 m and 8.8 m was 65% and 80%, respectively. The accuracy of the proposed criterion for all floors was about 72.3%. It should be noted that marginal floors were considered acceptable floors. Although t Zhang and Xu [40] provided a new criterion, according to Section 1.1, the authors of this paper believe that the 1 kN deflection can still be the best indicator for the vibration assessment of wood-based lightweight floors. The new proposed criterion ($f/d^{0.44} \geq 15.9$) and 1 kN deflection limits for evaluating the vibration performance of wood-based lightweight floors will be compared in detail in the discussion section.
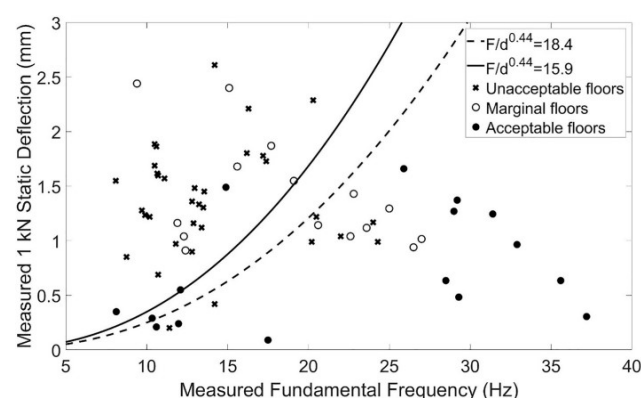

Figure 5. The new vibration criteria proposed by Zhang and Xu [40] for lightweight cold-formed steel floors versus subjective evaluation. Reproduced from [40] with permission.

3. Experimental and Numerical Studies on Mass Timber Composite Floors Comprising Steel Beams and CLT Panels

In addition to lightweight wood-based floorboards, heavier new products such as CLT and NLT can be used as subfloors in timber composite floors. CLT can be used to construct long-span floors because it can be combined with other building materials, such

as steel and concrete [6]. In lightweight, long-span floors, vibration is often a serviceability concern. The vibration performance of mass timber composite floors comprising steel beams and CLT panels has been studied by Huang et al. [44] and Wang et al. [45]. They developed numerical (FE) models to examine the effects of some parameters such as the floor's boundary conditions and multi-person loading on the vibration behavior of CLT floors. In each work, experimental tests were conducted to validate the numerical models. Those numerical studies will be discussed in the following sections. In order to investigate the floor vibration due to running, Huang et al. [44] used the Open Software for Earthquake Engineering Simulation (OPENSEES) framework to simulate a CLT floor system under human-induced force. The finite element (FE) model was based on a real two-story steel framing system comprising CLT panels as subfloors. The plan view of this system is depicted in Figure 6.
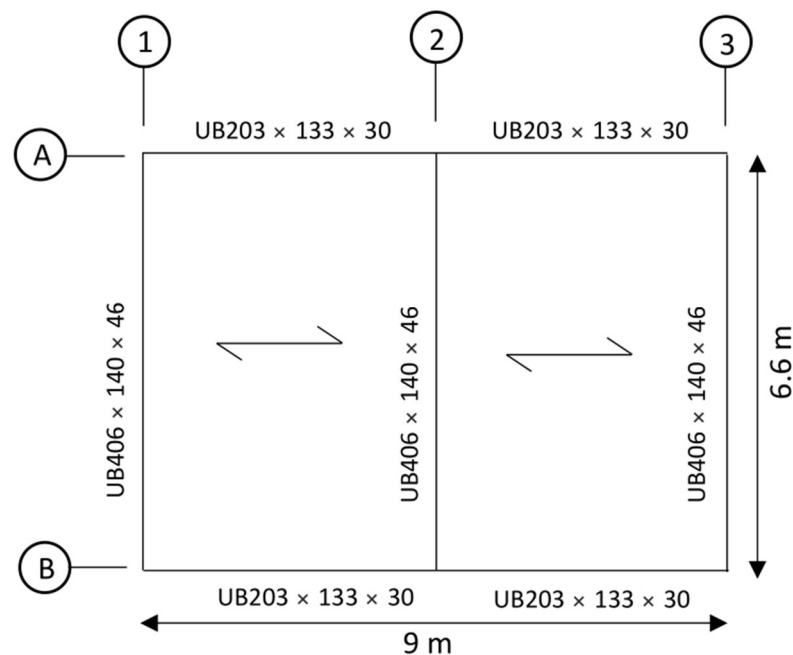
Figure 6. Plan of the CLT floor constructed at the University Centre Farnborough by Huang et al. [44]. Reproduced with permission.

In their study, Huang et al. [44] used beams and springs to model different layers of the CLT panel. Additional springs were employed to model the connection between steel beams and CLT panels. A large value of stiffness was assigned to springs to inhibit any slip between layers and eliminate the effects of the screws. It should be noted that choosing a very high value for spring stiffness and assuming zero slip are not common practices in industry as they could lead to unsafe designs. The location of screws and their spacings in CLT-to-CLT and CLT-to-steel beams connections were not specified. The beam-to-column connection was considered by defining restrains at two ends of the beam in three directions. However, the effect of this assumption on the vibration behavior of the floor was not investigated. The FE model was used to simulate a person's running with a weight of 1 kN in a straight path of the floor through 15 points; the load was applied to every point, step-by-step, using a force function. The weight of the non-structural components and the measured damping ratio of 3% were considered in the numerical model. Validation of numerical model against experiment was conducted in terms of the floor frequency (see Table 6) and time history acceleration of a point at the center of CLT floor due to running.

Table 6. The floor details and frequency results investigated by Huang et al. [44] (see Figure 6 for plan view of the floor).

Floorboard Type	Hot-Rolled Steel I-Beams	Floor Dimension	First Natural Frequency (Hz)	
			Numerical	Experimental
3-Ply CLT floor (t = 120 mm)	UB 406 × 140 × 46 UB 203 × 133 × 30	9.0 m × 6.6 m	7.6	7.5

The developed FE model in [44] was employed to investigate the effects of some parameters, such as the size and number of steel beams as well as the beam supporting condition (in one-way or two-way), on the CLT floors vibration. According to FE simulations, removing the middle beam (the beam on axis (2) in Figure 6) significantly decreased the natural frequency to 2 Hz while increasing the steel beam size increased the natural frequency to 9 Hz from about 7.5 Hz as expected. An analytical model was employed based on Equation (10) to obtain the natural frequency of CLT floors. The analytical results were claimed to agree with the results of the FE model. However, some errors (less than 20%) were reported. The authors employed VDV method in ISO 10137 [27] and BS 6472-1 [29] to assess the vibration performance of their floors. The VDV was calculated based on Equation (11).

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m}}$$ (10)

$$\text{VDV} = \left[\int_0^T a_w^4(t)dt\right]^{0.25}$$ (11)

where $a_w(t)$ is the weighted acceleration according to the frequency-weighting curve presented in BS 6472-1 [29]. All tests were assessed for probabilities of adverse comments for people. Removing the middle beam (on axis (2) in Figure 6) made the floor discomforting to residents, as expected. Quantitatively, removing the middle beam changed VDV from 0.6 m/s$^{-1.75}$ to 1.9 m/s$^{-1.75}$ and made the floor discomforting to residents according to BS 6472-1. The acceptable ranges of the VDV values in BS 6472-1 [29] are given in Table 7. It should be noted that the effects of some important parameters such as the type of screws and spacing between them, CLT-to-CLT connections, thickness of CLT panel as well as different beam to column connections were not considered in the numerical model. The results of frequency, RMS acceleration, and VDV for each specimen due to running are listed in Table 8. Interestingly, some specimens with different frequencies (e.g., No.3 and No.11) had similar RMS accelerations while different VDVs were noted. Hence, different standards and indicators for vibration performance can lead to contradictory results and subjective evaluation is still needed.

Table 7. The ranges of the VDV values presented in BS 6472-1 [29].

Place and Time	Low Probability of Adverse Comment (m/s$^{-1.75}$)	Adverse Comment Possible (m/s$^{-1.75}$)	Adverse Comment Probable (m/s$^{-1.75}$)
Residential buildings (16 h daytime)	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Residential buildings (8 h nighttime)	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8

Table 8. Floor responses in terms of frequency, RMS acceleration and VDV due to running as described in Huang et al. [44].

| Floor	Frequency (Hz)	a_{RMS} (m/s^2)	VDV (m/s$^{-1.75}$)
No.1	7.6	0.321	0.613
No.2	7.9	0.318	0.602
No.3	2	0.615	1.9
No.4	9.7	0.306	0.513
No.5	9.8	0.321	0.528
No.6	9.8	0.32	0.527
No.7	9.7	0.309	0.514
No.8	7.2	0.585	1.149
No.9	7.7	0.339	0.667
No.10	7.1	0.608	1.205
No.11	7.2	0.614	1.212

Employing the FE model developed by Huang et al. [44], Wang et al. [45] investigated the vibration behavior of the one-way CLT floor under multi-person loading. The floor was excited by defining a footfall force; the schematic of human-induced force applied to the floor has been shown in Figure 7. The location of CLT-to-CLT panel and CLT-to-steel beam connections, and the walking path along 9 points have been provided. However, some details regarding the spacing between spring elements and stiffness of spring/connection were not reported in Wang et al. [45]. General details of the experimental specimen comprising five 1.2 × 6.0 × 0.105 m CLT panels have been provided in Table 9. The authors considered the weight of the furniture as a constant load applied to the floor. The natural frequency of the floor was obtained using the heel drop test. The numerical and experimental results for the first natural frequency (see Table 9) and time history acceleration of point A (see Figure 7) due to the slow walking of one person showed good agreement.
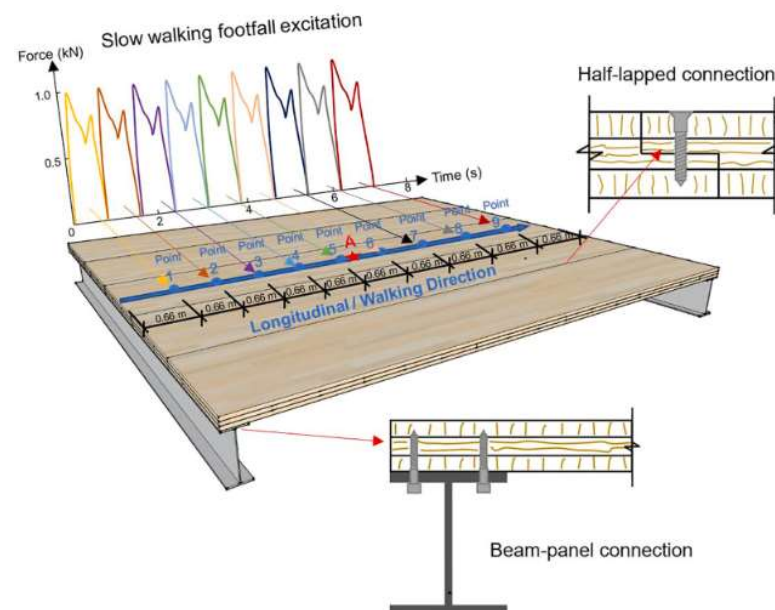
Figure 7. The scheme of human-loading used by Wang et al. [45]. Reproduced with permission.

Table 9. The floor details and frequency results of STC floors studied by Wang et al. [45]. A mass of 0.5 ton was applied to represent the presence of the furniture.

CLT Panels	Hot-Rolled Steel Beams	Span (m)	First Natural Frequency (Hz)	
			FE Model	Experiments
3-Ply CLT with the thickness of 105 mm	HN 450 × 200 mm	6.0	5.16	5.21

In addition to frequency, Wang et al. [45] examined their numerical results under the one-person excitation based on the Vibration Dose Value (VDV) method. The different types of motion of 1 to 5 persons were considered to investigate the accuracy of the numerical model under multi-person loading. Slow walking, fast walking, and running were simulated using different step frequencies of 1.3 Hz, 1.8 Hz, and 2.2 Hz. The VDV results from numerical models and experimental tests are shown in Figure 8. The most significant difference was related to the running of 5 persons. In almost all fast walking and running models, the measured VDVs were higher than the numerical ones. In other words, the numerical model was unconservative in predicting VDV of the floor for fast walking and running.
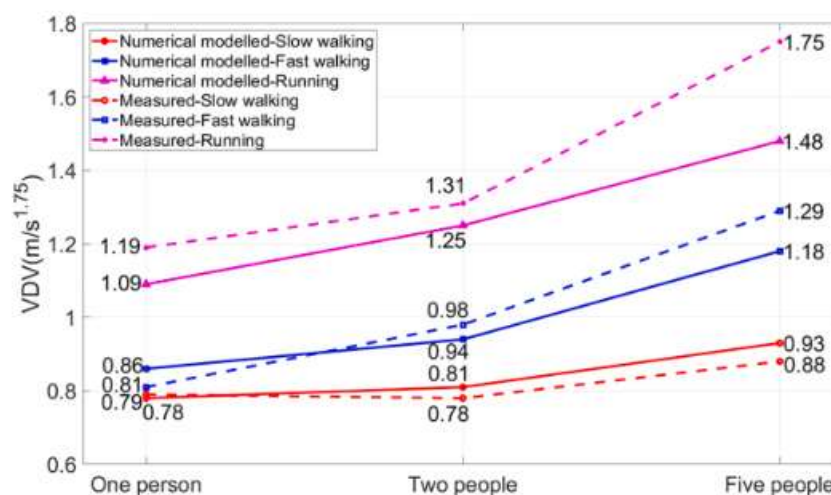
Figure 8. VDVs of the one-way CLT floor in experimental testing and numerical modelling prepared by Wang et al. [45]. Reproduced with permission.

It should be noted that the above FE models were developed based on certain assumptions and simplifications, validated against the experimental test of a specific floor. More studies are required to quantify the effects of simplification on the dynamic response of the floor [46]. The main simplification in [44] and [45] was to consider isolated substructures, including one span or panel, regardless of the effect of spring stiffness and distances, real connections of beams to columns, and partitions on the floor vibration. Thus, the acceptability or unacceptability of vibration behavior of a simple one-span floor according to available standards may not be applicable for a whole floor in a real building. On the other hand, underpredicted acceleration and VDV values highlight the need for more detailed FE models and further combined numerical-experimental campaigns. Furthermore, subjective evaluation of long-span STC floors under multi-person loading is needed to prove the relevance of VDV limits to such floors.

In a comprehensive research similar to Wang et al. [45], Chiniforush et al. [47] evaluated the behavior of steel-timber composite (STC) beams through a combined experimental-numerical campaign. Six simply supported STC beams with a span of 5.8 m were constructed using steel girders (310UB32 grade) and CLT panels. The details of experimental

specimens are summarized and provided in Table 10. The specimens had different shear connectors and two CLT panel orientations. An impact hammer was employed to excite the bending and torsional modes of the floors. The modal characteristics such as mode shape, frequency, and damping ratio were obtained using the Enhanced Frequency Domain Decomposition (EFDD) technique. The frequencies of the flexural mode of specimens with different CLT configurations, i.e., parallel and perpendicular, are given in Table 11. Due to discrete CLT panels in STC floor with perpendicular configuration (see Figure 9), the natural frequency of such specimen was smaller than that of floors with parallel CLT panels.

Table 10. The details of the six STC floors constructed and tested by Chiniforush et al. [47].

| Floor Panel | Panel Dimension (m) | | Shear Connector * | | CLT-to-CLT Connection |
	Parallel Configuration	Perpendicular Configuration	Type	Spacing (mm)	
CLT	2 pcs 3.0 × 1.0 × 0.12	6 pcs 1.0 × 1.0 × 0.12	bolt/screw	250/300	-

* The laminated timber panels are connected to the top flange of the steel through shear connectors.

Table 11. Natural frequency (flexural mode) and damping ratio of various STC floors measured by Chiniforush et al. [47]. CLT panels with different shear connectors and configurations were tested.

Floor Panel	Span (m)	Steel Joist	Parallel CLT Configuration	Perpendicular CLT Configuration	Damping Ratio
CLT	5.8	310UB32	21.40–24.73 Hz	17.19 Hz	less than 2%
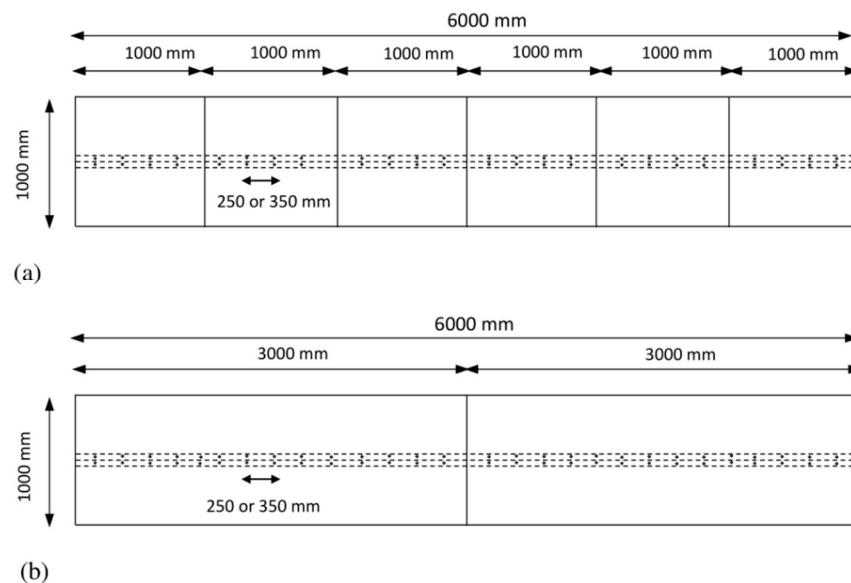
Figure 9. Schematic plan of steel-timber floors in (**a**) perpendicular and (**b**) parallel configuration by Chiniforush et al. [47].

Panel orientation and continuity of panels were reported to have the most significant effect on the frequency of the STC floors, while the effect of the shear connector type was found to be negligible. This is consistent with the findings of other researchers who analyzed long-span timber composite and TCC floors [48–50]. To better understand the dynamic behavior of floors, a FE model was created in ABAQUS©. Twenty-two unknown variables of one floor (E, G, μ, k) were determined using an updating procedure. After calibration, the model was used to predict the frequency of other models. The results of the first bending mode obtained from the numerical model agreed well with the experimental results. In other words, the numerical model was well-calibrated using experimental data.

In addition to numerical and experimental results, the accuracy of some available analytical equations was also investigated by Chiniforush et al. [47]. The first natural frequency of STC beams was estimated analytically using different equations and compared with experimental and numerical results. Wyatt [51] and Murray [38] equations are identical to the equation provided in Eurocode 5 [3]. Hence, only two different analytical equations (Allen [52] and Eurocode 5 [3]) were considered. The comparison between the frequency obtained from experimental tests and analytical equations showed that the Eurocode 5 [3] equation was more accurate in estimating the natural frequencies of STC floors, with a mean error of 9.5%. In Chiniforush et al. [47], the high frequency of 24 Hz and the lower weight compared to conventional steel-concrete beams were reported to be among the main benefits of utilizing steel and timber for floors. Hassanieh et al. [53] employed the calibrated FE model of Chiniforush et al. [47] to assess the effect of different parameters on the dynamic response of STC floors. The effect of different parameters/conditions on the frequency of STC floors was examined numerically (see Table 12). The steel joists' span length significantly affected the natural frequencies of the STC floors whilst the aspect ratio of the floor and CLT-to-CLT connection effect was found to be negligible. More importantly, the CLT slab thickness had a negligible effect (less than 3%) on the first natural frequency of the STC floor. Their numerical results also showed that the orientation of CLT slab panels could impact the frequency up to 20%.

Table 12. Effect of various parameters on STC floor frequency studied numerically by Hassanieh et al. [53].

Parameter	Support	Span (m)	Steel Joist	Aspect Ratio	CLT-to-CLT Connection	CLT Thickness (mm)	Slab Orientation	Connection Spacing (mm) *	Connection Type *
Type/ Value	Pined, Continuous, Discontinuous	6, 8, 10	360UB44.7, 310UB32.0, 250UB25.7	1, 2, 3	Continuous, Double screws, Without connection	140, 160, 180	Parallel, Perp.	125, 250, 500	Screw 16, Screw 12, BGP12
Frequency (Hz)	9.8–12.4	6.8–15.7	8.6–11.9	9.8	9.8	9.6–9.9	7.5–9.8	8.8–10.8	9.5–10.4

* The laminated timber panels are connected to the top flange of the steel through shear connectors.

Hassanieh et al. [53] employed their model to assess the vibration performance of STC floors based on AISC design guide 11 [2], Eurocode 5 [3], and the ECCS report [54]. The fundamental frequency, deflection under a 1 kN point load, and maximum impulse velocity were calculated and compared to the Eurocode 5 criteria. FE results showed that almost all specimens met the requirements of maximum deflection and velocity according to Eurocode 5 [3]. However, specimens with a perpendicular configuration or span length of 10 m had a natural frequency of less than 8 Hz. Eurocode 5 does not have any provisions for floors with a frequency of less than 8 Hz. It should be noted that the velocity limit did not govern the design of STC floors. It means that the deflection criterion is more critical than the velocity criterion. This finding is consistent with those of [11,55,56] regarding the applicability of Eurocode 5 to timber floors. There was good agreement between Eurocode 5 and ECCS for the vibration performance of the STC floors. The acceleration of STC floors was obtained from the numerical model and compared with peak acceleration limits provided in AISC design guide 11 [2]. Results demonstrated that some of the STC floors considered in the parametric study were unacceptable according to the AISC design guide 11 [2] and acceptable according to Eurocode 5 [3]. Hence, the AISC design guide 11 [2] criteria for the vibration assessment of the STC floors were reported to be a more restrictive one compared to other guides. As no human walking test or subjective evaluation was conducted in Hassanieh et al. [53], further research to check the relevance of AISC design guide 11 [2] to STC floors is recommended.

As a final note on the experimental and numerical works on mass timber floors and joisted timber floors, including steel joists/beams, it is crucial to investigate the procedure and equations in standards and design guides to predict the floor response due to walking.

For long-span timber-timber composite floors, Basaglia et al. [32] evaluated the floor response due to walking according to different standards. They investigated the procedure and equations presented in AISC design guide 11 [2], CCIP-016 [1], and SCI P354 [8] to define the response of timber floors due to walking. RMS acceleration and velocity obtained from different standards were compared to the measured responses. It was found that CCIP-016 [1] was the most accurate of all three and underestimated the RMS velocity with an error of approximately 8%. The AISC design guide 11 [2] underestimated the RMS acceleration of the floor by an error of around 25%. A similar approach is recommended to evaluate the human-induced vibration response of steel-timber composite floors and the relevance of different standards in this area. It should be noted that Basaglia et al. [32] employed numerical models to simulate walking on the floor using a single trace footfall. The simulation of walking on the floor using a single trace footfall function overestimated the floor response (RMS acceleration) with an error of less than 3%. Hence, it can be concluded that as an alternative to the approach presented in each standard or guideline, a finite element (FE) model may be used as a powerful tool to determine the floor response due to a specific footfall force more accurately.

4. Discussion

The literature reports that 1 kN deflection is the best vibration indicator for lightweight timber floors; however, some researchers have attempted to develop new criteria. In fact, studies in [18] and [26] showed that for lightweight joisted flooring systems, the 1 kN deflection limit is able to control the floor vibration accurately. By reviewing several studies, Figure 10 has been created in this paper to demonstrate that 1 kN deflection is still the best vibration indicator for the lightweight timber floors studied in [33,37,41–43] and a new criterion may be redundant. Figure 10 compares the subjective evaluation of lightweight cold-formed steel-timber floors tested in [33,37,41–43] with the limits provided in the CWC [4], ATC [19], Swedish [20], and Australian standards [21]. The CWC method [4] is found to be the most accurate of all four in predicting the vibration performance of lightweight cold-formed steel-timber composite floors.
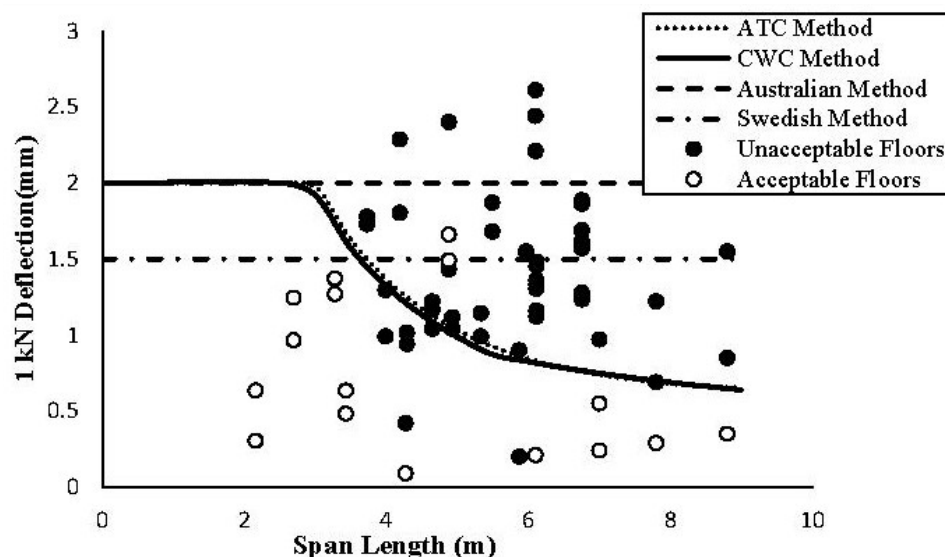
Figure 10. Evaluation of the floor vibration based on 1 kN deflection criteria for lightweight cold-formed steel floors according to reported data in [33,37,41–43].

According to Table 13, the accuracy of the CWC method [4] in predicting the vibration performance of such floors is about 89%. Figure 10 shows that constant values of 1.5 mm and 2 mm proposed in Swedish and Australian standards to limit the floor deflection are too conservative. The new criterion presented in Zhang and Xu [40] predicted the floor vibration with an accuracy of about 74%, while the CWC [4] criterion seems more

accurate with an accuracy of around 89%. It is worth mentioning that marginal floors were considered as acceptable floors in [40] while unacceptable in Figure 10. Although the 1 kN deflection has been identified as the best vibration limit for wood-based joisted lightweight floors, for heavier composite floors comprising steel and thick timber subfloors, this simple criterion may not be sufficient as noted in [56]. For long-span STC floors with mass timber products such as CLT, there is still no reference to suggest which standard may be the most relevant one to floor vibration.

Table 13. The accuracy of CWC [4] (Equation (2) in predicting the vibration performance of lightweight cold-formed steel-timber floors.

Span Length	2.16 < L < 8.8 m
Number of tested floors	65
Correctly predicted by CWC method *	58
Method's accuracy	89%

* Marginal floors considered as unacceptable floors.

Vibration performance of STC floors comprising hot-rolled steel beams and CLT panels based on different standards and guidelines has been investigated through some experimental and numerical studies. The UNSW team in [47,53], worked on STC floors and reported relatively good agreement between the Eurocode 5 and ECCS guide predictions. For such floors, the AISC Design Guide 11 [2] provides the most restrictive limits compared to the other guides. Subjective evaluation is still required to define which standard or guideline is suitable to evaluate the vibration performance of STC floors, e.g., those studied in [47,53]. Similar to the UNSW team [47,53], Huang and co-workers [44,45] evaluated the vibration behavior of the STC floors with CLT panels based on a numerical model validated against the experimental results. Huang and co-workers [44,45] examined the vibration performance based on different vibration indicators such as RMS acceleration and VDV (Eq. (11)). It should be noted that RMS acceleration is the square-root of the sum of accelerations over footstep period while VDV considers the combined effect of the magnitude and duration of the vibration. The results showed that the conclusion based on RMS acceleration might differ from VDV. In addition to prior research [47,53], the authors evaluated the probabilities of adverse comments from people using VDV analysis based on the BS 6472 [29] and ISO 10137 [27]. They also evaluated the vibration behavior of the STC floors under multi-person loading through a numerical model, experimental test, and analytical approach. Multi-person loading increased the VDV by about 30% compared to one person walking on the floor. Similar to the UNSW team [47,53], the subjective evaluation was not conducted to evaluate the prediction of floor vibration under multi-person loading based on VDV.

Due to the similar CLT properties and floor span in [45] and [47], a frequency comparison can be made between the above two studies. The frequency comparison reveals a significant difference between the floor frequency of experimental studies conducted by Chiniforush et al. [47] and Wang et al. [45]. For a typical floor, the results are provided in Table 14 where the predicted frequency by Eurocode 5 is also shown for comparison. The frequency differences in Chiniforush et al. [47] and Wang et al. [45] can be attributed to different boundary conditions and the addition of steel beams which increase the floor's flexural stiffness, and its frequency, consequently.

Table 14. The details and frequency results of the STC floors studied in Chiniforush et al. [47] and Wang et al. [45].

Work	CLT Panel Size (m) Length × Width × Thickness	Span (m)	Flexural Stiffness (N·m^2)	Predicted Frequency * (Hz)	Measured Frequency ** (Hz)	Support
Chiniforush et al. [47]	2 pcs 3.0 × 1.0 × 0.12 (S1CS∥), Figure 9	5.8	1.97×10^7	21.7	24.16	simply support
Wang et al. [45]	6.6 × 5.6 × 0.105, Figure 6	6.0	6.02×10^6	6.24	6.68	partial simply support

* Estimated from the Eurocode 5 [2] equation based on floor's geometry. ** Measured for floors without any additional mass.

In addition to all standards and guidelines used in literature for vibration design of STC floors comprising steel beams and CLT panels, it would be interesting to investigate the accuracy of the vibration controlled-span equation for STC floors according to the CLT handbook [6] and CSA O86-19 [5]. It is worth mentioning that calculation of EI_{eff} (needed for the controlled-span equation) for STC floors with different connection types between steel and timber parts needs more assessment. This study reviewed several experimental and numerical studies on the vibration behavior of STC floors. Various standards and guidelines were used in the literature to investigate floor vibrations. It was demonstrated that researchers have yet to reach a consensus on the applicability of such design methods to timber composite floors. Therefore, before the practical implementation of vibration design methods, the accuracy of those methods for STC should be specified. In future research, two main areas can be explored:

First, it should be highlighted that for STC floors comprising steel beams and CLT panels, subjective evaluation is necessary to prove the appropriate criteria based on available standards and guidelines. In fact, in this review, only the comparison between different standards were conducted and some standards were found to be more conservative. However, without consideration of subjective responses of occupants, it cannot be determined which standard is more appropriate for STC floors. Several studies have focused on the subjective evaluation of timber-timber composite floors comprising engineered wood products such as Glulam, LVL, and CLT to find which available criteria are appropriate to predict the vibration performance of such floors [10,57–60]. The requirements according to Dolan et al. [22], Hu and Chui [23], Onysko et al. [18], CCIP-016 [1], and ISO 10137 [27] were evaluated in those studies. Recently, Shahnewaz et al. [59] found that although the RMS acceleration for CLT—glulam composite floors with different span lengths met the requirement of ISO 10137 [27], some of them were unacceptable according to subjective evaluation. Interestingly, the floors' vibration control span obtained from CSA O86-19 [5] agrees well with the subjective evaluation of such TTC floors, most probably due to conservative nature of span equation in CSA O86-19 [5]. Similar studies on STC floors and further research on composite floors in mass timber buildings are needed.

Second, as different criteria are based on the floor response due to walking, more accurate assessment of acceleration, velocity, deflection of STC floor under walking is required. Basaglia et al. [32] evaluated the prediction of timber floor response due to walking using different standards and guidelines such as AISC design guide 11 [2], CCIP-016 [1], and SCI P354 [8]. Comparison between RMS acceleration and velocity obtained from different standards and those measured responses showed that in some cases, the methods in the standards could not correctly predict the floor's response due to footfall force. However, a numerical model using a single trace footfall function predicted the acceleration of the floor very accurately (less than 3% error). Based on the findings of Basaglia et al. [32], a similar detailed numerical model can be insightful for understanding the STC floor response due to footfall force.

5. Conclusions

The following conclusions for evaluation of the vibration performance of steel-timber floors can be drawn from the literature:

- ATC [19] and CWC [4] standard evaluate the vibration of lightweight timber floors due to walking based on very simple deflection limits. Although these limits can be employed in the design of conventional wood-frame floors with high frequencies (i.e., more than 8 Hz), they may be sufficient for STC floors with heavier subfloors such as CLT, NLT, or LVL.

- Very limited studies have examined the validity of Eurocode 5 equations in designing STC floors. According to Eurocode 5, floors with a frequency less than 8 Hz need a special investigation, while floors with a frequency of more than 8 Hz can be designed based on the vibration limit provided in this standard.

- CCIP-016 [1] was originally proposed for concrete structures and is currently being used in the vibration design of floors in mass timber buildings. Although using CCIP-016 [1] for the vibration assessment of timber floors is recommended by some experts in industry (e.g., see [31]), its accuracy for STC floors has not been clearly investigated within the research community.

- Both AISC design 11 [2] and CCIP-016 [1] provide two different approaches (simplified equations and FE analysis methods) to address floor vibration. To the authors' knowledge, the simplified equations in these guides have been calibrated for concrete and steel floors and may not be applicable to all timber composite floors. Furthermore, such equations cannot be used for irregular floors with large openings or cantilevers. Thus, using such simplified equations for long-span timber floors is currently not recommended. As an alternative to general equations, FE analysis is suggested for such systems. FE models enable the structural analyst to consider more details in their vibration assessment of composite floors. For this purpose, it is vital to conduct a proper modal analysis and capture higher modes of vibration correctly to evaluate the behavior of such floors with confidence.

- SCI P354 [8] presented vibration criteria for cold-formed steel framing floors. Such criteria are based on frequency, 1 kN deflection, and response factor (or VDV). However, in the case of using hot-rolled steel joists or heavy subfloors such as CLT, LVL, or NLT, there is no recommendation or criterion in SCI P354 [8]. Hence, SCI P354 [8] may not be applicable to STC floors.

- Canadian CLT Handbook [6] and CSA O86-19 [5] use an analytical equation for the vibration-controlled span design of CLT floors. This simplified equation is intended for only a one-span simply supported floor. The applicability of this equation for STC has not been examined. It is believed that this equation is too conservative for STC floors with CLT subfloors.

To the best of the authors' knowledge, AISC Design 11 [2] and CCIP-016 [1] currently provide the most comprehensive approach to evaluate the vibration performance of timber composite floors. However, such approaches still need to be validated using more subjective evaluation studies on STC floors. Developing parameterized 3D finite element models that include several key parameters (e.g., boundary conditions, discontinuity of panels, slip modulus, and damping ratio) and conducting sensitivity analyses will enable researchers to investigate the validity range of these approaches. Special attentions should be given to accurate estimation of connection stiffness and damping ratio according to the findings of this research.

Author Contributions: Conceptualization, N.C.-S. and S.M.; methodology, N.C.-S. and S.M.; validation, N.C.-S. and S.M.; formal analysis, N.C.-S. and S.M.; investigation, N.C.-S., K.C. and S.M.; resources, S.M.; data curation, N.C.-S.; writing—original draft preparation, N.C.-S. and S.M.; writing—review and editing, N.C.-S., K.C. and S.M.; visualization, N.C.-S.; supervision, S.M. and K.C.; project administration, S.M.; funding acquisition, S.M. All authors have read and agreed to the published version of the manuscript.

Appendix A. Analytical Equations for the Floor Vibration according to SCI P354

SCI P354 provides vibration criteria for lightweight cold-formed steel composite floors to limit the frequency and deflection. According to this design guide, the frequency of floors without and with linking corridors should be more than 8 Hz and 10 Hz, respectively. Additionally, the second moment of area criterion limiting 1kN deflection for each joist can be defined as follows:

$$I_b \geq \frac{L_y^3 \times 10.16}{N_{eff} \times \delta_j} \tag{A1}$$

where L_y is the span of joists (m), N_{eff} is the number of effective joists, and δ_j is the deflection limit according to Table A1.

Table A1. 1 kN deflection limit of lightweight cold-formed steel composite floors based on SCI P354.

Span length (m)	3.5	3.8	4.2	4.6	5.3	6.2
Deflection (mm)	1.7	1.6	1.5	1.4	1.3	1.2

SCI P354 also provides an equation to predict $a_{w,RMS}$ of floors. The floor's response factor can be calculated by $a_{w,RMS}$ divided by a base value of 0.005 m/s^2. There is a limit of 16 for the floor's response factor.

This design guide suggests using the VDV method based on the limits in Table A2 for floors with a response factor greater than 16.

Table A2. VDV values to control the vibration performance of lightweight cold-formed steel floors according to SCI P354.

Place	VDV Value for Low Probability of Adverse Comment
Buildings: 16 h day	1.6
Buildings: 8 h night	0.51

Appendix B. Analytical Equations for the Floor Vibration according to Eurocode 5

Based on Eurocode 5, residential floors fall into two categories: floors with a fundamental frequency of less than 8 Hz and those with a fundamental frequency of more than 8 Hz. According to this standard, the former floors require special investigation and are not covered in this standard. For floors with a fundamental frequency greater than 8 Hz, Eurocode 5 presents the following equations to limit the vertical deflection and unit impulse velocity response.

$$\frac{w}{F} \leq a \tag{A2}$$

$$v \leq b^{(f_1 \zeta - 1)} \tag{A3}$$

where w is the floor maximum instantaneous deflection (mm) under a point load of F (kN), v is the unit impulse velocity response (m/(Ns^2)), and ζ is the modal damping ratio.

Eurocode 5 recommends damping ratio of 1% for timber floors, while the UK National Annex (UKNA) to Eurocode 5 recommends 2%.

Two constant floor vibration parameters, *a* and *b*, and the relation between them are obtained from the graph in Figure A1.
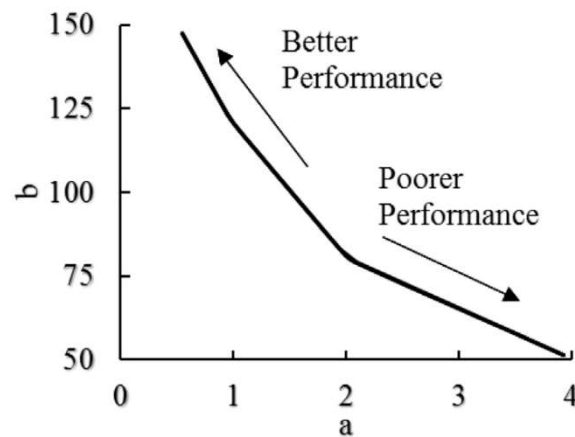
Figure A1. The relation between two recommended floor vibration parameters, *a* and *b*, according to Eurocode 5. Reproduced from [53] with permission.

The relationship between *a* and *b* in Figure A1 can also be formulated [25] as follows:

$$b = 150 - (30(a - 0.5)/0.5) = 180 - 60a \qquad a \leq 1\text{mm} \tag{A4}$$

$$b = 120 - (40(a - 1)) = 160 - 40a \qquad a > 1\text{mm} \tag{A5}$$

According to UK National Annex (UKNA) to Eurocode 5, the floor deflection due to 1 kN force, *a* (mm), should satisfy the following requirements [25]:

For floors with a span length of less than 4000 mm:

$$a \leq 1.8 \text{ (mm)} \tag{A6}$$

Otherwise:

$$a \leq 16{,}500/l^{1.1} \text{ (mm)} \tag{A7}$$

where *l* is the floor span length (mm).

Appendix C. Analytical Equations for the Floor Vibration according to CCIP-016

CCIP-016 categorizes the vibration behavior of structures based on the response factor (*R*). The response factor is the ratio of the peak acceleration to the ISO baseline limit on the peak acceleration. There are different criteria for commercial buildings, residential buildings, hospitals, bridges, ramps, and walkways. As shown in Table A3, the response factor derived from BS 6472 is used to specify the vibration behavior of buildings. CCIP-016 recommends twice the value shown in Table A3 for residences under footfall-induced forces.

Table A3. Critical vibration levels at which the probability of adverse comments is low, presented in CCIP-016 and BS 6472 (1992).

Environment	Response Factor
Critical working areas	1
Residence-day	2–4
Residence-night	1.4
Office	4
Workshop	8

CCIP-016 presents a procedure to determine the response factor (*R*) which can be used for steel, concrete, timber, and composite structures. According to this standard, floors are divided into high-frequency floors (floors with lowest natural frequency more than 10.5 Hz) and low-frequency floors (floors with lowest natural frequency less than 10 Hz).

First, the following procedure is used for floors with a natural frequency of less than 10 Hz. This procedure is applied only for structures with a vertical natural frequency of less than 4.2 times the maximum footfall rate. The maximum footfall rate is defined according to Table A4. It should be noted that all modes with a frequency of less than 15 Hz need to be included in calculations.

Table A4. The maximum footfall rates related to different environments according to CCIP-016.

Environment	Maximum Footfall Rates footfalls/s
Footbridges	2.5
Corridor and circulation zones in any building	2.5
Within office bays and residential rooms (i.e., not corridor zones)	2.0
Within laboratories, operating theatres, and the like	1.8

R factor for each of four harmonics is introduced as:

$$R_h = \frac{|a_h|}{a_{R=1,h}} \tag{A8}$$

where *h* is the harmonic number, $|a_h|$ is the magnitude of the acceleration and $a_{R=1,h}$ is calculated by following relations:

$$If\ f_h < 4 Hz,\ a_{R=1,h} = \frac{0.0141}{\sqrt{f_h}}\ m/s^2 \tag{A9}$$

$$If\ 4\ Hz < f_h < 8\ Hz,\ a_{R=1,h} = 0.0071\ m/s^2 \tag{A10}$$

$$If\ f_h > 8\ Hz,\ a_{R=1,h} = 2.82\pi f_h \times 10^{-4}\ m/s^2 \tag{A11}$$

Finally, *R* factor related to all four harmonics is expressed by:

$$R = \sqrt{R_1^2 + R_2^2 + R_3^2 + R_4^2} \tag{A12}$$

For structures with a lowest natural frequency of more than 10.5 Hz, the following procedure should be followed. All modes with a frequency of less than twice fundamental frequency should be included in calculations.

The total velocity response at time *t*, for all *N* modes can be defined by

$$V(t) = \sum_{m=1}^{N} V_m(t) \tag{A13}$$

Over a period of one footfall, *T*, the total RMS velocity response would be

$$V_{RMS} = \sqrt{\frac{1}{T} \int_0^T V(t)^2 dt} \tag{A14}$$

So, the response factor is presented as

$$R = \frac{V_{RMS}}{V_{R=1}} \tag{A15}$$

where, for a fundamental frequency, f_1, the baseline RMS velocity for $R = 1$, $V_{R=1}$, can be obtained by

$$If \ f_1 < 8\text{Hz} \ V_{R=1} = \frac{5 \times 10^{-3}}{2\pi f_1} \ \text{m/s} \tag{A16}$$

$$If \ f_1 > 8\text{Hz} \ V_{R=1} = 1.0 \times 10^{-4} \ \text{m/s} \tag{A17}$$

Appendix D. Analytical Equations for the Floor Vibration according to AISC Design Guide 11

AISC design guide 11 categorizes all floors to Low-Frequency (<9 Hz) and High-Frequency (>9 Hz). Floors under walking excitation are designed based on two methods: simplified design criteria, which is not applicable to irregular framing or cantilevers, and finite element analysis method, which is used for all floors. The vibration tolerance acceleration limit for all floors is presented in Figure A2.
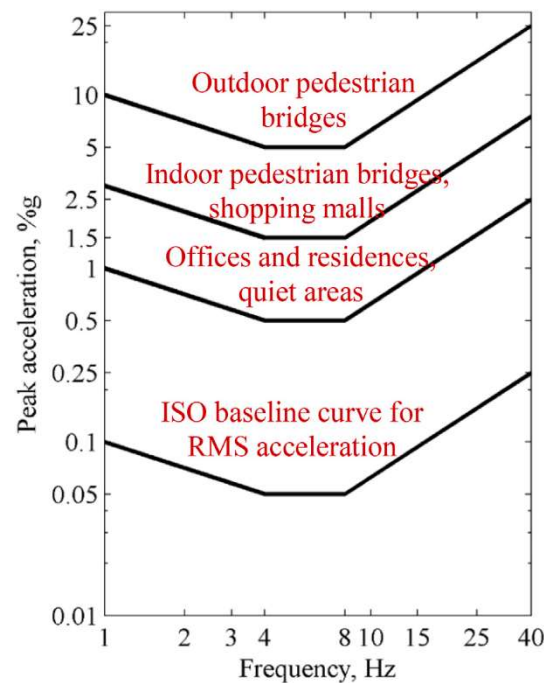
Figure A2. Recommended tolerance limits for human comfort as published in AISC design guide 11. Reproduced from [53] with permission.

For Low-Frequency (<9 Hz) floors, the simplified design criterion based on the peak acceleration is defined by

$$\frac{a_p}{g} = \frac{P_o e^{-0.35 f_n}}{\beta W} \leq \frac{a_o}{g} \tag{A18}$$

where P_o is the constant force (65 lb), W is the effective weight of the floor (lb), β is the damping ratio, a_o is the vibration tolerance acceleration limit according to Figure A2, and a_p is the peak acceleration of the floor.

For High-Frequency (>9 Hz) Floors, the equivalent sinusoidal peak acceleration (a_{ESPA}) is defined by

$$\frac{a_{ESPA}}{g} = \left(\frac{154}{W}\right)\left(\frac{f_{step}^{1.43}}{f_n^{0.3}}\right)\sqrt{\frac{1 - e^{-4\pi h\beta}}{h\pi\beta}} \leq \frac{a_o}{g} \tag{A19}$$

where W is the effective weight of the floor (lb), f_n is the fundamental natural frequency (Hz), and f_{step} is step frequency (Hz) while $f_n = h f_{step}$. h is the step frequency harmonic

matching the natural frequency (See Table A5). a_o is the acceleration limit, according to Figure A2.

Table A5. Harmonic matching the natural frequency of high-frequency (>9 Hz) floors adopted from AISC design guide 11.

f_n (Hz)	h
9–11	5
11–13.2	6
13.2–15.4	7

h is step frequency harmonic matching the natural frequency.

References

1. Willford, M.R.; Young, P.; CEng, M. *A Design Guide for Footfall Induced Vibration of Structures*; Concrete Society for The Concrete Centre: London, UK, 2006.
2. Murray, T.M.; Allen, D.E.; Ungar, E.E.; Davis, D.B. *Vibrations of Steel-Framed Structural Systems Due to Human Activity: AISC Design Guide 11*; American Institute of Steel Construction: Chicago, LI, USA, 2016.
3. *EN 1995-1-1*; Eurocode 5: Design of Timber Structures-Part 1-1: General-Common Rules and Rules for Buildings. CEN: Brussels, Belgium, 2004.
4. Canadian Wood Council. *Development of Design Procedures for Vibration Controlled Spans Using Engineered Wood Members*; Canadian Wood Council: Ottawa, ON, Canada, 1997.
5. *CSA O86-19*; Engineering design in wood. Canadian Standards Association: Toronto, ON, Canada, 2019.
6. Karacabeyli, E.; Gagnon, S. *Canadian CLT Handbook*; FPinnovation: Vancouver, BC, Canada, 2019.
7. *E710-Minimizing Floor Vibration by Design And Retrofit*; APA—The Engineered Wood Association: Tacoma, DC, USA, 2004.
8. Smith, A.L.; Hicks, S.J.; Devine, P.J. *Design of Floors for Vibration: A New Approach*; Steel Construction Institute Ascot: Berkshire, UK, 2007.
9. Hu, L.J.; Chui, Y.H.; Onysko, D.M. Vibration serviceability of timber floors in residential construction. *Prog. Struct. Eng. Mater.* **2001**, *3*, 228–237. [CrossRef]
10. Negreira, J.; Trollé, A.; Jarnerö, K.; Sjökvist, L.-G.; Bard, D. Psycho-vibratory evaluation of timber floors—Towards the determination of design indicators of vibration acceptability and vibration annoyance. *J. Sound Vib.* **2015**, *340*, 383–408. [CrossRef]
11. Weckendorf, J.; Toratti, T.; Smith, I.; Tannert, T. Vibration serviceability performance of timber floors. *Eur. J. Wood Prod.* **2016**, *74*, 353–367. [CrossRef]
12. Basaglia, B.M. Dynamic Behaviour of Long-Span Timber Ribbed-Deck Floors. Ph.D. Thesis, University of Technology Sydney, Sydney, Australia, 2019.
13. Movaffaghi, H.; Pyykkö, J. Vibration performance of timber-concrete composite floor section—Verification and validation of analytical and numerical results based on experimental data. *Civ. Eng. Environ. Syst.* **2022**, *39*, 165–184. [CrossRef]
14. Zhang, L.; Zhou, J.; Chui, Y.H.; Li, G. Vibration Performance and Stiffness Properties of Mass Timber Panel–Concrete Composite Floors with Notched Connections. *J. Struct. Eng.* **2022**, *148*, 04022136. [CrossRef]
15. Ussher, E.; Arjomandi, K.; Smith, I. Status of vibration serviceability design methods for lightweight timber floors. *J. Build. Eng.* **2022**, *50*, 104111. [CrossRef]
16. Thai, M.-V.; Elachachi, S.M.; Ménard, S.; Galimard, P. Vibrational behavior of cross-laminated timber-concrete composite beams using notched connectors. *Eng. Struct.* **2021**, *249*, 113309. [CrossRef]
17. Zhao, X.; Huang, Y.; Fu, H.; Wang, Y.; Wang, Z.; Sayed, U. Deflection test and modal analysis of lightweight timber floors. *J. Bioresour. Bioprod.* **2021**, *6*, 266–278. [CrossRef]
18. Onysko, D.M.; Hu, L.J.; Jones, E.D.; Di Lenardo, B. Serviceability design of residential wood framed floors in Canada. In Proceedings of the World Conference on Timber Engineering, Vancouver, BC, Canada, 31 July–3 August 2000.
19. ATC. *Design Guide 1: Minimizing Floor Vibration*; Applied Technology Council: Redwood City, CA, USA, 1999.
20. Ohlsson, S. *Springiness and Human-Induced Floor Vibrations: A Design Guide*; Swedish Council for Building Research: Stockholm, Sweden, 1988.
21. *AS 3623*; Domestic Metal Framing. Standards Association of Australia: Sydney, Australia, 1993.
22. Dolan, J.D.; Murray, T.M.; Johnson, J.R.; Runte, D.; Shue, B.C. Preventing annoying wood floor vibrations. *J. Struct. Eng.* **1999**, *125*, 19–24. [CrossRef]
23. Hu, L.J.; Chui, Y.H. Development of a design method to control vibrations induced by normal walking action in wood-based floors. In Proceedings of the 8th World Conference on Timber Engineering, Lahti, Finland, 14–17 June 2004; Volume 2, pp. 217–222.
24. *BSI. NA to BS EN 1991-1-1:2002*; NA: UK National Annex to Eurocode 1: Actions on Structures—Part 1-1: General Actions—Densities, Self-Weight, Imposed Loads for Buildings. British Standards Institution: London, UK, 2002.
25. Porteous, J.; Kermani, A. *Structural Timber Design to Eurocode 5*; Wiley-Blackwell: Oxford, UK, 2007.
26. Toratti, T.; Talja, A. Classification of Human Induced Floor Vibrations. *Build. Acoust.* **2006**, *13*, 211–221. [CrossRef]

27. *ISO 10137*; Bases for design of structures Serviceability of buildings and walkways against vibrations. International Standards Organization: Geneva, Switzerland, 2007.
28. *ISO 2631-2*; Evaluation of Human Exposure to Whole Body Vibration—Part 2: Human Exposure to Continuous Shock-Induced Vibrations in Builidngs (1 to 80 Hz). British Standards Institution: London, UK, 1989.
29. *BS 6472-1:2008*; Guide to evaluation of human exposure to vibration in buildings–Part 1: Vibration sources other than blasting. British Standards Institution: London, UK, 2008.
30. Barber, D.; Blount, D.; Hand, J.J.; Roelofs, M.; Wingo, L.; Woodson, J.; Yang, F. *Design Guide 37: Hybrid Steel Frames with Wood Floors*; American Institute of Steel Construction: Chicago, IL, USA, 2022.
31. *U.S. Mass Timber Floor Vibration Design Guide*, 1st ed.; WoodWorks—Wood Products Council: Washington, DC, USA, 2021.
32. Basaglia, B.M.; Li, J.; Shrestha, R.; Crews, K. Response Prediction to Walking-Induced Vibrations of a Long-Span Timber Floor. *J. Struct. Eng.* **2021**, *147*, 04020326. [CrossRef]
33. Kraus, C.A. Floor Vibration Design Criterion for Cold-Formed C-Shaped Supported Residential Floor Systems. Ph.D. Thesis, Virginia Tech, Blacksburg, VA, USA, 1997.
34. Xu, L.; Tangorra, F. Experimental investigation of lightweight residential floors supported by cold-formed steel C-shape joists. *J. Constr. Steel Res.* **2007**, *63*, 422–435. [CrossRef]
35. Parnell, R.; Davis, B.W.; Xu, L. Vibration Performance of Lightweight Cold-Formed Steel Floors. *J. Struct. Eng.* **2010**, *136*, 645–653. [CrossRef]
36. Xu, L. Floor Vibration in Lightweight Cold-Formed Steel Framing. *Adv. Struct. Eng.* **2011**, *14*, 659–672. [CrossRef]
37. Liu, W. *Vibration of Floors Supported by Cold-Formed Steel Joists*; University of Waterloo: Waterloo, ON, Canada, 2001.
38. Murray, T.M.; Allen, D.E.; Ungar, E.E. *Floor Vibrations Due to Human Activity*; American Institue of Steel Construction: Chicago, IL, USA, 1997.
39. Smith, I.; Chui, Y.H. Design of lightweight wooden floors to avoid human discomfort. *Can. J. Civ. Eng.* **1988**, *15*, 254–262. [CrossRef]
40. Zhang, S.; Xu, L. Vibration serviceability evaluation of lightweight cold-formed steel floor systems. *Structures* **2022**, *38*, 1368–1379. [CrossRef]
41. Wiss, J.F.; Linehan, P.W.; Kudder, R.J. *Report of Laboratory Tests and Analytical Sudies of Structural Characteristics of Cold-Formed Steel-Joist Floor Systems*; Janney, Elstner & Associates, Inc.: Rolla, MO, USA, 1977.
42. Kullaa, J.; Talja, A. Vibration tests for lightweight steel joist floors–subjective perceptions of vibrations and comparisons with design criteria. In Proceedings of the Finnish R&D Conference on Steel Structure (Teräsrakenteiden tutkimus-ja kehityspäivät), Lappeenranta, Finland, August 1998.
43. Samuelsson, M.; Sandberg, J. *Vibrations in Lightweight Steel Floors*; Swedish Institute of Steel Construction: Stockholm, Sweden, 1998; p. 190.
44. Huang, H.; Gao, Y.; Chang, W.-S. Human-induced vibration of cross-laminated timber (CLT) floor under different boundary conditions. *Eng. Struct.* **2019**, *204*, 110016. [CrossRef]
45. Wang, C.; Chang, W.-S.; Yan, W.; Huang, H. Predicting the human-induced vibration of cross laminated timber floor under multi-person loadings. *Structures* **2020**, *29*, 65–78. [CrossRef]
46. Cai, Y.; Gong, G.; Xia, J.; He, J.; Hao, J. Simulations of human-induced floor vibrations considering walking overlap. *SN Appl. Sci.* **2020**, *2*, 19. [CrossRef]
47. Chiniforush, A.A.; Alamdari, M.M.; Dackermann, U.; Valipour, H.; Akbarnezhad, A. Vibration behaviour of steel-timber composite floors, part (1): Experimental & numerical investigation. *J. Constr. Steel Res.* **2019**, *161*, 244–257. [CrossRef]
48. Khorsandnia, N.; Valipour, H.; Bradford, M. Deconstructable timber-concrete composite beams with panelised slabs: Finite element analysis. *Constr. Build. Mater.* **2018**, *163*, 798–811. [CrossRef]
49. Bernard, E.S. Dynamic Serviceability in Lightweight Engineered Timber Floors. *J. Struct. Eng.* **2008**, *134*, 258–268. [CrossRef]
50. Labonnote, N.; Rønnquist, A.; Malo, K.A. Prediction of material damping in timber floors, and subsequent evaluation of structural damping. *Mater. Struct.* **2014**, *48*, 1965–1975. [CrossRef]
51. Wyatt, T.A. *Design Guide on the Vibration of Floors*; SCI Publication: London, UK, 1989.
52. Allen, D.E. Building vibrations from human activities. *Concr. Int.* **1990**, *12*, 66–73.
53. Hassanieh, A.; Chiniforush, A.; Valipour, H.; Bradford, M. Vibration behaviour of steel-timber composite floors, part (2): Evaluation of human-induced vibrations. *J. Constr. Steel Res.* **2019**, *158*, 156–170. [CrossRef]
54. Feldmann, M.; Heinemeyer, C.; Butz, C.; Caetano, E.; Cunha, A.; Galanti, F.; Goldack, A.; Hechler, O.; Hicks, S.; Keil, A.; et al. *Design of Floor Structures for Human Induced Vibrations*; JRC–ECCS joint report; Publications Office of the European Union: Brussels, Belgium, 2009.
55. Zhang, B.; Rasmussen, B.; Jorissen, A.; Harte, A. Comparison of vibrational comfort assessment criteria for design of timber floors among the European countries. *Eng. Struct.* **2013**, *52*, 592–607. [CrossRef]
56. Hu, L.J. *Serviceability Design Criteria for Commercial and Multi-Family Floors*; Canadian Forestry Service: Canada; Australia, 2000.
57. Ebadi, M.M. *Vibration Behaviour of Glulam Beam-and-Deck Floors*; Université d'Ottawa/University of Ottawa: Ottawa, ON, Canada, 2017.
58. Ebadi, M.M.; Doudak, G.; Smith, I. Evaluation of floor vibration caused by human walking in a large glulam beam and deck floor. *Eng. Struct.* **2019**, *196*, 109349. [CrossRef]

59. Shahnewaz, M.; Dickof, C.; Zhou, J.; Tannert, T. Vibration and flexural performance of cross-laminated timber—Glulam composite floors. *Compos. Struct.* **2022**, *292*, 115682. [CrossRef]

60. Christian, S.; Carla, D.; Fast, T. Evaluation of a long span mass timber floor under footfall vibration loads. In Proceedings of the CSCE 2022—CSCE Annual Conference, Las Vegas, NV, USA, 25–28 July 2022.