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A comparative study of design standards for assessment of long-span steel-timber composite floors under human-induced vibration

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ABSTRACT: Steel-timber composite (STC) floors are gaining popularity for residential and commercial buildings worldwide. Adding steel joists to wood-based panels is an attractive option for some designers to increase the span of timber floors. However, there is often a serviceability (vibration) concern with timber composite floors. It is well-known from the literature that human comfort due to vibration is subjective, and people's perception of comfort varies. Nevertheless, structural engineers still need to consider vibration in designing composite timber floors according to various standards and guidelines, especially when comparing two alternative designs. This study investigates the vibration behavior of STC floors under footfall force using a numerical model validated by experimental data. Transient finite element (FE) analysis is conducted to simulate human walking on the floor. The study also discusses acceptability of STC floors according to guidelines and building codes (e.g., AISC Design Guide 11, ATC, CLT Handbook, Eurocode 5). Lastly, the effects of various design parameters, such as CLT thickness, damping ratio, and CLT-to-CLT connection, on the vibration behavior of the composite timber floor are assessed.

KEYWORDS: Finite element analysis (FEA), Timber, Steel, Vibration, Standards, Mass timber buildings

1 INTRODUCTION

Over the past 20 years, significant research has been conducted on the vibration behavior of timber and timber-concrete composite (TCC) structures [1–6]. However, limited studies have been done on steel-timber composite (STC) systems [7]. STC flooring systems consist of steel joists and wood-based flooring panels such as cross-laminated timber (CLT) panels and oriented strand boards (OSB). Steel sections provide longer floor spans due to steel's high strength and stiffness. However, human comfort is increasingly considered a vital serviceability requirement for STC floors.

There are different criteria in standards and guidelines to investigate floor vibration based on various parameters, such as frequency, deflection, acceleration and velocity. A finite element (FE) model can accurately determine such parameters. Basaglia et al. [8] employed a numerical model in ANSYS to simulate walking on timber floors. They also used analytical equations in AISC Design Guide 11 [9], CCIP-016 [10], and SCI P354 [11] to find floor responses due to walking. Experimental results showed that the numerical model accurately predicted floor response (RMS acceleration) with an error of less than 3%. Chiniforush et al. [12] and Hassanieh et al. [7] studied the numerical modelling of STC floors under human-induced vibration. Their numerical model was calibrated using 22 variables (i.e., E, G, μ, k) with ABAQUS software [13]. The calibrated model was used for parametric studies to determine influential parameters on the vibration performance of STC floors. Huang et al. [14] generated a numerical model in OPENSEES to simulate running on STC floors. Elastic beam-column elements and springs were used to model CLT panels. All connections were modelled with extremely high stiffness values. Wang et al. [15] used the same numerical model to simulate walking on another steel-timber floor. A review of previous studies suggests more research is needed to create a numerical model for STC floors using characteristic (not calibrated) values of parameters. Moreover, engineers need the ability to model timber composite floors numerically without relying on springs or beam-column members for CLT panels. Further parametric studies are necessary, especially for parameters not studied by researchers, like footfall load functions, damping ratios, CLT panel connections, and loadings.

This study uses numerical modelling to examine the vibration performance of STC floors under footfall forces according to different standards. Similar to Basaglia et al. [8], transient analysis is performed to determine floor velocity and acceleration due to walking. The numerical (FE) model results are compared with estimates from the simplified equation in AISC Design Guide 11 [9] and with limits provided in various standards. Finally, the effect of important design parameters on floor vibration is analyzed.

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2 VIBRATION CRITERA

Generally, guidelines and standards use different approaches to assess floor vibration. The behavior of floors under human-induced force may be examined based on simple parameters such as deflection and frequency [16–18]. More complicated parameters, such as Vibration Dose Value (VDV), peak (or RMS) acceleration, or peak velocity, can be used to assess floor vibration according to ISO [19,20], BS 6472-1 [21], CCIP-016 [10], and the AISC Design Guide 11 [9]. Some standards use a combination of two criteria. For example, Eurocode 5 [22] considers deflection and the limit for maximum impulse velocity. All these standards and guidelines may be used for timber composite floors. However, the different results from various references make it challenging for structural engineers to decide whether a floor has adequate serviceability. To showcase the challenge faced by practitioners, the vibration performance of two STC floors is assessed based on design guides such as the AISC Design Guide 11 [9], ATC [23], as well as timber-specific standards like Eurocode 5 [22] and CSA Standard O86-19 [24].

3 NUMERICAL MODELLING

3.1 Geometry

A finite element (FE) model in ETABS software [25] has been developed to understand floor performance. Under static and dynamic loads, the model was employed to inspect floor response, such as the floor mid-span deflection, velocity, or acceleration. The floor geometry and input properties were selected based on the previous work of Wang et al. [15], as shown in Figure 1. The simply supported floor comprised two steel joists (HN 450×200 mm) and five CLT panels (1.2×6×0.105 m) placed on top of the joists. The properties of CLT layers are provided in Table 1. As Wang et al. provided E1 and E2, other parameters have been taken from Hassanieh et al. [7]. A layered shell and beam elements were used in ETABS software [25] to simulate the three layers of CLT panels (with a thickness of 105 mm) and steel beams, respectively.

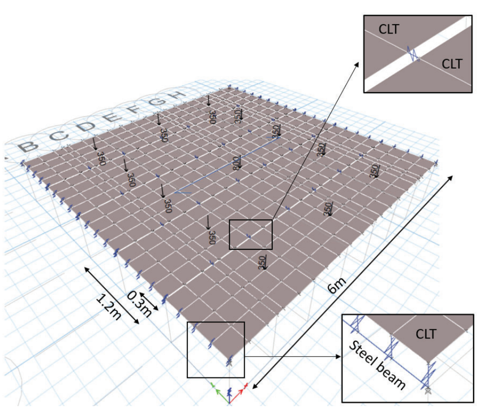

Figure 1: *STC floor considered in Wang et al.* [15] *and selected for this study*

Table 1: *Mechanical properties (MPa) of CLT panels obtained from literature [7, 15]*

Wang et al. [15]		Hassanieh et al. [7]						
E_1	E_2	E_3	G_{12}	G_{13}	G_{23}	υ_{12}	υ_{13}	υ_{23}
10767	979	530	610	860	120	0.59	0.57	0.24

3.2 Connections

As shown in Figure 1, there are six connections between adjacent CLT panels. In the numerical model, the value of 900 N/mm was selected for the shear stiffness of half-lapped connections perpendicular and parallel to CLT panels, according to Ussher et al. [26]. Furthermore, the CLT panels were connected to steel beams at a spacing of 0.3 m. The connection shear stiffness was selected based on the values provided in Hassanieh et al. [7] for Coach Screw 12, Coach Screw 16, and BGP 12 connections. The results varied by less than 3%, and the stiffness of Coach Screw 16 was selected for the results presented in this paper.

3.3 Loading

To define the floor's maximum deflection, a 1 kN static load was applied. For the maximum acceleration of the floor, a walking simulation was conducted according to the experimental study of Wang et al. [15]. In the ETABS software, a 75 kg human walking at 0.789 s/step was considered. Also, concentrated loads (according to the experiment) equal to a constant load of 0.15 kN/m2 were applied on the floor. Figure 2 shows the function employed to model the footfall force according to the experimental data. A transient modal analysis was performed to define the maximum acceleration of the middle point of the floor with a damping ratio of 2% and 3% under the human-induced force.

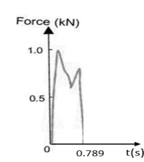

Figure 2: *The single footfall function considered to simulate walking on the floor in Wang et al. [15]*

According to Eurocode 5 [22], an impulsive force of 1 Ns was employed to investigate the velocity of the floor caused by walking. To simulate the impulsive force, the function recommended by Ohlsson [18] and presented in Hassanieh et al. [7] was used, as shown in Figure 3.

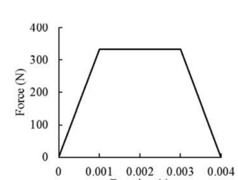

Figure 3: *The force function to simulate the impulsive force of 1 Ns according to Eurocode 5* [22]*, obtained from Hassanieh et al.* [7]

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3.4 Convergence study

Mesh convergence was conducted to determine the suitable mesh size. The acceleration and frequency of the floor remained constant with a finer mesh size of 16 cm. Hence, 16 cm mesh size was used in the study.

4 Validation

The current numerical model was validated using the experimental results of Wang et al. [15] in terms of frequency and acceleration. Table 2 shows the comparison of predicted and measured floor frequencies, with a difference less than 3%. Figure 4 compares the measured acceleration and the current model's predictions of the acceleration at the middle of the STC floor, considering two damping assumptions of 2% and 3%. The results demonstrate that the STC floor is a low-frequency floor (frequency below 9 Hz and 10.5 Hz per AISC Design Guide 11 [9] and CCIP-016 [10], respectively) with a resonant response to walking. The figure depicts a good agreement between the results, displaying a similar trend of changing acceleration over time for all cases.

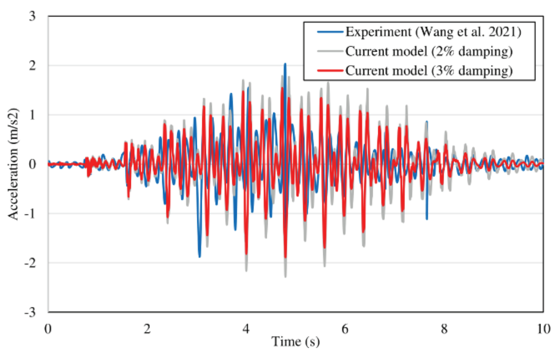

Figure 4: *The predicted acceleration of one point at the middle of the floor (shown in Figure 1) compared to the measured acceleration*

Table 2: *The predicted and measured frequency (Hz) of the STC floor (see Figure 1 for details of the floor)*

Measured frequency (Hz)	Predicted frequency (Hz)	
Wang et al. (2021)	Wang et al. (2021)	Current study (ETABS model)
5.21	5.16	5.15

5 VIBRATION PERFORMANCE

Wang et al. [15] calculated VDV for the floor depicted in Figure 1. The study found that the floor's VDV was about 0.8 $m/s^{1.75}$ with poor vibration performance (likely to receive an adverse comment) as per BS 6472-1 [21] (refer to Table 3). In the current study, the floor vibration is assessed according to other standards and guidelines, such as AISC Design Guide 11 [9], Eurocode 5 [22], ATC [23], and the Canadian CLT Handbook [27].

Table 3: *The VDV values range presented in BS 6472-1* [21]

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 night)	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8

5.1 AISC DESIGN GUIDE 11

According to AISC Design Guide 11 [9], the simplified design criterion based on peak acceleration for low-frequency (< 9 Hz) floors is defined by:

$$\frac{a_p}{g} = \frac{P_o e^{-0.35 f_n}}{\beta W} \leq \frac{a_o}{g} \quad (1)$$

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 5, and a_p is the peak acceleration of the floor.

For high-frequency (>9 Hz) floors, the equivalent sinusoidal peak acceleration (a_{ESPA}) is calculated and compared to the acceleration limit. a_{ESPA} is defined using a calibration factor to adjust the prediction to match the measured data, as:

$$\frac{a_{ESPA}}{g} = \left(\frac{154}{W}\right)\left(\frac{f_{step}^{1.43}}{f_n^{0.3}}\right)\sqrt{\frac{1-e^{-4\pi h\beta}}{h\pi\beta}} \leq \frac{a_o}{g} \quad (2)$$

where W is the effective weight of the floor (lb), f_n is the fundamental natural frequency (Hz), and f_{step} is the step frequency (Hz) while $f_n = hf_{step}$. h is the step frequency harmonic that matches the natural frequency (see Table 4). a_o is the tolerance acceleration limit, according to Figure 5.

Table 4: *Step frequency harmonics matching the natural frequency of high-frequency (>9 Hz) floors adopted from AISC design guide 11* [9]

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

The frequency of the floor presented in Figure 1 was below 9 Hz, making it a low-frequency floor according to AISC design guide 11 [9]. The calculated a_p (from Equation (1)) for the STC floor was around 6.7% g, exceeding the limit shown in Figure 5 for offices and residences.

According to modelling results, the maximum acceleration was 19% g, which exceeds the limit provided in Figure 5 for offices and residences. Therefore, the floor vibration is unacceptable according to AISC Design Guide 11 [9]. It should be noted that there is a considerable discrepancy between the results from Equation (1) and the numerical model for the maximum acceleration of the floor (see the blue and red points in Figure 5). More research is needed to investigate the accuracy of existing design equations for timber composite floors.

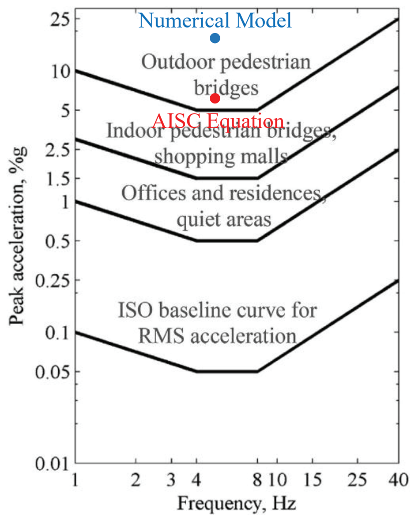

Figure 5: *Vibration performance of the floor showed in Figure 1 according to AISC Design Guide 11* [9]. *Red and blue points highlight the maximum acceleration of the floor estimated from the AISC simplified equation and the numerical model, respectively*

5.2 EUROCODE 5

Eurocode 5 [22] presents simplified equations to evaluate the vibration performance of timber floors with a frequency above 8Hz. This standard limits vertical deflection and unit impulse velocity response (due to an impulsive force of 1Ns) based on the following equations:

$$\frac{w}{F} \leq a \quad (3)$$

$$v \leq b^{(f_1\zeta - 1)} \quad (4)$$

where w is the floor maximum instantaneous deflection (mm) under a point load F (kN), v is the unit impulse velocity response (m/(Ns^2)), and ζ is the modal damping ratio. Two constant floor vibration parameters, a and b, and the relation between them are obtained from a graph in Eurocode 5. Their relationship can be formulated [28] as follows:

$$b = 180 - 60a \qquad a \leq 1\,mm \quad (5.a)$$

$$b = 160 - 40a \qquad a > 1\,mm \quad (5.b)$$

According to the UK National Annex (UKNA) to Eurocode 5 [29], the floor deflection, a (mm), due to 1 kN force, should meet the following requirements [28]:

$$a \leq 1.8 \text{ (mm)} \quad ; \quad L \leq 4000\,mm \quad (6.a)$$

$$a \leq 16{,}500/L^{1.1} \text{ (mm)} \; ; \quad L > 4000\,mm \quad (6.b)$$

where L is the floor span length (mm).
In ETABS software, an impulsive force of 1 Ns was modelled using the function recommended by Ohlsson [18], as presented in Figure 3.

Figure 6 presents the floor velocity diagram due to the impulsive force. Results showed that the maximum velocity of the floor is approximately 5.5 mm/s, which is below the allowable velocity of 18 mm/s. The maximum deflection of the floor under 1kN is 1.5 mm, while the allowable deflection is 1.15 mm. As noted in previous research [30], deflection is a more decisive criterion than velocity. However, the floor does not meet the frequency limit of 8 Hz. Hence, evaluating the floor according to Eurocode 5 may not be appropriate [22].

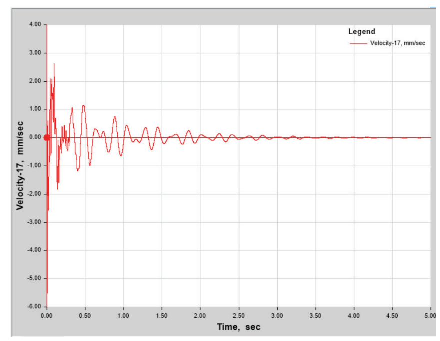

Figure 6: *Floor velocity diagram due to the impulsive force of 1 Ns using the function recommended by Ohlsson [18]*

5.3 ATC DESIGN GUIDE

ATC [23] defines a relation for light-frame floors with a fundamental frequency of more than 8 Hz to limit the maximum floor deflection under a 1 kN load applied at the mid-span. This criterion is defined based on Equation (7):

$$\Delta_p \leq 0.61 + 2.54e^{-0.59(L-1.95)} \leq 2.0\,mm \quad (7)$$

where Δ_p is the maximum floor deflection (mm) and L is the span length (m). Equation (1) is also used by ATC [23] as a resonance criterion. Modelling results showed a maximum floor deflection of 1.5 mm, which is exceeding the allowable deflection of 0.84 mm. Therefore, the vibration performance of the floor is unacceptable according to ATC [23].

5.4 CLT HANDBOOK

The Canadian CLT Handbook [27] presents the following equation to define the deflection of a CLT floor under the uniformly distributed load.

$$\Delta = \frac{5wL^4}{384(EI)_{eff}} + \frac{wL^2}{8(GA)_{eff}} \quad (8)$$

where $(EI)_{eff}$ is the floor's effective bending stiffness (N-mm^2), $(GA)_{eff}$ is the effective shear rigidity (N/mm), L is the span length (mm), and w is the distributed load (N/mm). The FE model predicted the deflection of the floor within 5% of the result of Equation (8). The maximum deflection of the floor under a distributed load of 0.15 kN/m^2 was 2.6 mm, while the result of Equation (8) was around 2.5 mm. According to the Canadian CLT Handbook [27] and the CSA Standard [24], the vibration-

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controlled span (m) for a CLT floor (simply supported) can be obtained from the following equation:

$$L \leq 0.11 \frac{\left(\frac{(EI)_{eff}}{10^6}\right)^{0.29}}{m^{0.12}} \quad (9)$$

here m is the mass of CLT for a 1-meter width (kg/m), and $(EI)_{eff}$ is the floor's effective bending stiffness (N-mm^2). The vibration performance of the considered floor (Figure 1) with a span length below 3 m is satisfactory using Equation (9). Hence, the floor with a span length of 6 m as in (Figure 1) is unacceptable according to the CLT Handbook.

In summary, the floor with the configuration presented in Figure 1 showed unsatisfactory vibration performance per AISC Design Guide 11 [9], ATC [23], and Canadian CLT Handbook [27]. The ratio of floor deflection to allowable deflection in Eurocode 5 [22] seems to be very low. Hence, lowering span length or using thicker CLT panels will increase floor frequency and decrease the deflection. Accordingly, the floor can be acceptable according to Eurocode 5, but still unacceptable according to AISC Design Guide 11 [9], ATC [23], and Canadian CLT Handbook [27]. Hence, it might be helpful to look at another example that illustrates the discrepancy between the results of different standards and guidelines, namely the STC floor studied by Hassanieh et al. [7].

Using the data provided by Hassanieh et al. [7], Table 5 presents the vibration performance of the floor according to different standards and guidelines. The maximum acceleration of the floor exceeded the limit provided in Figure 5 (with a ratio of 1.16). Furthermore, the maximum deflection of the floor (0.72 mm) is more than the allowable deflection according to ATC [23] (0.68 mm) and less than that allowed by Eurocode 5 [22] (0.84 mm). In addition, as a result of Equation (9), the floor (with a span length of less than 10 m) was acceptable according to the CLT Handbook [27]. As mentioned before, AISC Design Guide 11 [9] and ATC [23] were more conservative than others.

Table 5: *Acceptability of STC floors according to different standards and guidelines*

	Vibration performance according to			
Floor	AISC DG 11 [9]	Eurocode 5 [22]	ATC [23]	CLT handbook [27]
[15]	×	×	×	×
[7]	×	✓	×	✓

* see Figure 1 for floor details.
** simply supported STC floor consists of two steel beams (310UB32.0) and 160 mm thick (5-layer) CLT panels on top of the joists with a span of 8m.

6 Parametric studies

Different design parameters can affect the acceleration of the floor due to walking. This study focuses on previously understudied parameters such as force function used to simulate walking. Further research is needed to investigate the effect of various footfall force functions and step frequencies on floor vibrations. Additionally, adding secondary steel beams to CLT panels can change the behavior of the floor from resonant to transient, resulting in a significant reduction of floor acceleration. This study quantifies the impact of CLT thickness, damping ratio, and CLT-to-CLT connections on the acceleration of the floor under footfall force over time, and demonstrates that increasing CLT thickness and damping ratio, as well as improving CLT-to-CLT connections, can effectively decrease floor acceleration.

6.1 CLT thickness

Different thicknesses of CLT panels (105, 160, and 180 mm) with layers at different thicknesses (20, 30, 35, and 40 mm) were used to investigate the effects of the CLT thickness on the acceleration of one point at the middle of the floor. Figure 7 shows that the maximum acceleration of the floor was reduced by almost 65% when the thickness of the CLT panels increased from 105 mm to 180 mm. All models utilized a 3% damping ratio for the floor, with six connections between adjacent CLT panels.

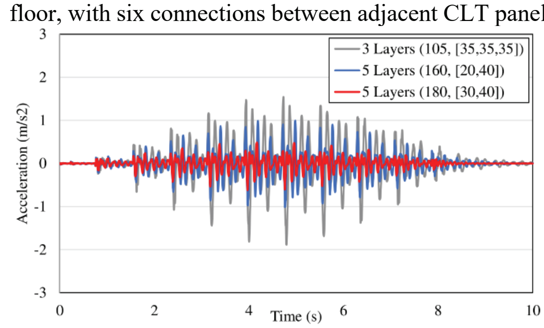

Figure 7: *The predicted acceleration of a point at the middle of the floor (see Figure 1) for different CLT thicknesses*

6.2 Damping ratio

The damping ratio of floors is influenced by multiple factors, such as the floor type and non-structural elements. Figure 8 illustrates that increasing the floor's damping from 1% to 3% reduces the maximum acceleration by approximately 35%. However, further increases in damping have a negligible effect on the floor's maximum acceleration. Despite 3% being suggested as the damping ratio in various sources, further research is needed to assess its impact on the vibration performance of different STC floor types. All models in Figure 8 utilized 105mm thick CLT panels with six connections between them.

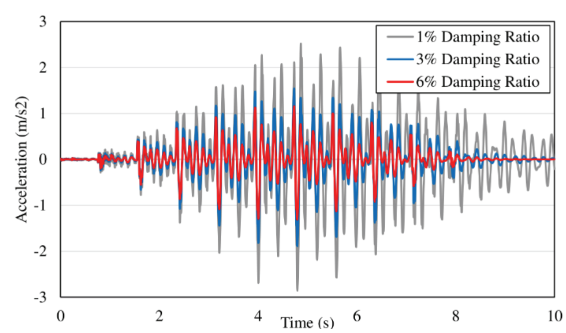

Figure 8: *The predicted acceleration of a point at the middle of the floor (see Figure 1) for different damping ratios*

6.3 CLT-to-CLT connections

Internal spline, single-spline, double-spline, and half-lapped are different methods of connecting adjacent CLT panels. This study used half-lapped connections as described in Section 3.2. To investigate the effect of the number of connections on the acceleration of the floor due to walking, a numerical model was employed using six connections, no connections, and fully bonded connections. The results indicated that increasing the number of connections from 0 to 6 reduced the maximum acceleration by approximately 35% (see Figure 9). However, further increasing connections to fully bond the adjacent CLT panels had little impact on the results. All models utilized a 3% damping ratio for the floor, with 105mm thick CLT panels. The type of CLT-to-CLT connections did not appear to have a significant effect on the floor acceleration under footfall forces. Further research with more detailed information is necessary to validate this finding.

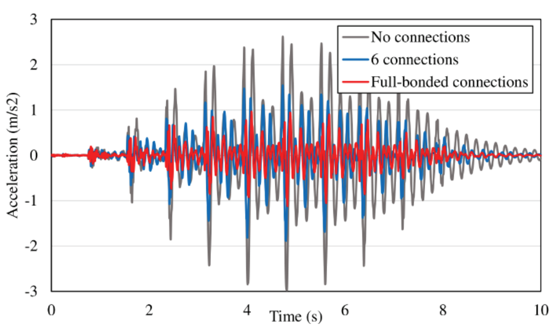

Figure 9: *Predicted acceleration at the mid-floor point (see Figure 1) for different CLT-to-CLT connections*

7 CONCLUSION

The findings of this paper indicate:

- There are various standards and guidelines that may seem applicable to STC floors.
- Different standards may lead to contradictory results based on floor dimensions.
- The AISC Design Guide 11 [9] has an appropriate criterion if the floor's acceleration is predicted accurately.
- The simplified equations in the AISC did not accurately predict the peak acceleration of the floor as compared to the results from the numerical model. Further research is necessary to determine the accuracy of these simplified equations for both high-frequency and low-frequency timber and timber composite floors.
- The deflection limit was found to be a more important criterion than velocity in the Eurocode 5 assessment of floor performance.
- The use of a detailed FE model will enable structural engineers to optimize the design of STC floors according to various standards and assess the impact of different design parameters, such as floor span, damping, and panel-to-beam and panel-to-panel connection systems, on floor vibration.
- Human tests may be necessary to determine the most appropriate standard or guideline for evaluating the vibration performance of composite timber floors.
- Design parameters such as CLT thickness, damping ratio, and CLT-to-CLT connections can affect the maximum acceleration of the floor significantly.

This research suggests the need for further studies to investigate the impact of various single footfall forces with different step frequencies on the acceleration of the composite timber floor. Further research is needed to validate the relevance of the developed numerical model for a real building, taking into account all details including column-to-beam connections, beam-to-beam connections, internal and external walls, and openings.

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