WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

BALANCING FASTENER SPACING, ACOUSTICS, AND SPAN LENGTH IN EXPOSED CLT FLOOR-CEILING ASSEMBLIES

Simon Cleghorn[1], Aedan Callaghan[2]

ABSTRACT: Aside from sustainability, one of the most unique benefits of mass timber as a construction material is its extremely high strength-to-weight ratio. As a result, the weight of a floor slab in a mass timber building is much lighter than in a building constructed with conventional material. This unique benefit of engineered timber also comes with unique challenges. Albeit ironic, the low mass in mass timber assemblies is to blame for two of the most prominent pain points in engineered timber construction: floor vibration and sound transmission. Limits on floor vibration often result in short span lengths and tight structural grid spacing. Timber-concrete composite (TCC) floor systems are one method that can be used to alleviate this restriction. However, connecting a concrete topping to the timber panel underneath with mechanical fasteners harms the acoustic performance of the floor assembly. In this paper, the relationship between fastener spacing, composite slab behaviour, and sound transmission is investigated. Physical testing is carried out to determine the degree of composite action achieved with a timber-concrete composite system in the presence of a resilient acoustic interlayer. The data obtained is used to analyse the resulting span and acoustic performance with various spacing of fasteners.

KEYWORDS: Acoustics, Vibration, Span, Cross Laminated Timber

1 – INTRODUCTION

Due to the lightweight nature of engineered timber, vibration is often a governing aspect of the design of timber floor assemblies. In both the fields of structural engineering and architectural acoustics, mass is understood to have a damping effect on waves as they pass through a building component. With decreased mass, both audible sound waves in high frequency ranges and low frequency vibrational waves face relatively low attenuation in mass timber floor panels.

A common solution to provide adequate acoustics in buildings with exposed cross-laminated timber (CLT) floor-ceiling assemblies is to introduce a resilient interlayer between the timber and mass layer atop. To improve floor stiffness and vibration-controlled span length, engineers can opt to design timber-concrete composite (TCC) floor systems in mass timber buildings. In a TCC floor, the normal weight reinforced concrete topping slab is connected to the structural timber panel beneath with mechanical fasteners, such as self-tapping screws. Unfortunately, the fasteners must pass through the resilient interlayer to achieve this connection. In architectural acoustics, when rigid materials are connected by a path bridging the resilient layer, this is often referred to as a “short-circuit”. Short-circuiting an assembly has been proven to cause significant degradation in acoustic performance [1]. Thus, a contradictory issue arises when designing TCC floor systems, as increasing the number of fasteners simultaneously improves the vibrational response of the floor system and decreases the acoustic performance [2].

To investigate the relationship of fastener spacing, acoustics, and vibration-controlled span length, the methods which are used to quantify performance in each category must be identified. For the context of this paper, vibration-controlled span length will be examined under the FPInnovations (FPI) method for timber-concrete composite floors as shown in the 2019 CLT Handbook [3]. When calculated span lengths are discussed in this paper, it is solely in reference to the FPI method for vibration-controlled span lengths, as full structural designs have not been carried out. It should also be noted that the FPI method only applies to simply supported CLT panels resting on load-bearing walls or beams of adequate stiffness [4]. Acoustic performance is quantified by sound transmission class (STC) per ASTM E90 and impact insulation class (IIC) per ASTM E492, along with the ISO equivalent metrics of R_w and $L_{n,w}$, respectively.

2 – BACKGROUND

2.2 Acoustics in Mass Timber

[1] Cleghorn, Pliteq Inc, Toronto, Canada, scleghorn@pliteq.com

[2] Callaghan, Pliteq Inc, Vancouver, Canada, acallaghan@pliteq.com

https://doi.org/10.52202/080513-0173

While mass timber has many well documented benefits, acoustics are a notorious challenge in designing a mass timber building, particularly for projects with exposed ceilings and/or thin timber floor panels such as a 105mm 3-ply CLT. The table below shows the impact and airborne sound transmission ratings of 105 mm 3-ply and 175 mm 5-ply bare CLT panels.

Table 1: Acoustic Ratings of Bare CLT Panels

Metric	**CLT Panel**		
	3-Ply (105 mm)	***5-ply (175 mm)***	***Multi-Family Residential Code Requirement***
STC	38	40	50 (IBC)
IIC	21	26	50 (IBC)
$R_w + C_{tr}$	35	37	50 (NCC)
$L_{n,w}$	88	86	62 (NCC)

The masses of the 3-ply and 5-ply panels tested were 34.03 kg/m^2 and 89.51 kg/m^2, respectively [5, 6]. As seen from the rightmost column, none of the panels are remotely close to meeting International Building Code (IBC) or National Construction Code of Australia (NCC) requirements. To achieve these acoustic ratings, mass timber floor-ceiling assemblies need either well-designed floating floors on the top side or ceilings on the underside of the structural timber panel. The latter option is undesirable for many designers, as leaving exposed timber ceilings is preferred for aesthetics, monetary returns, and health benefits of building occupants. In many cases, this leaves the topping and acoustic mat largely responsible for improving the acoustic performance of the floor system.

If a TCC system is designed, the acoustic interlayer will be short-circuited causing a reduction in performance [1]. This phenomenon was explored in the 2023 World Conference of Timber Engineering Paper "Influence of Mechanical Fastener Spacing on Acoustic Performance in Timber Composite Panels" by Callaghan and Byrick. Figures 1 and 2 show the test set-up and resulting STC curves from progressively increasing the number of short-circuiting fasteners in a CLT floor assembly.

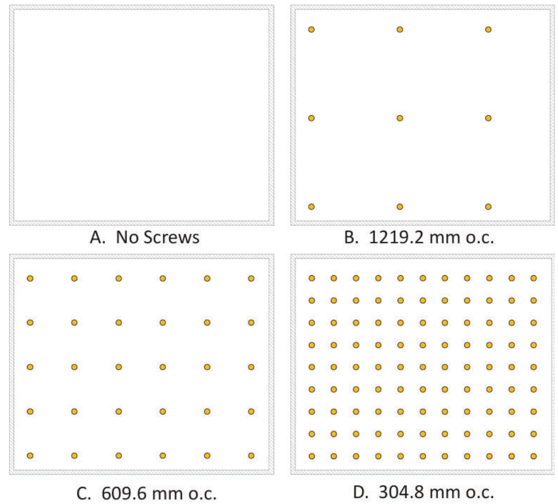


Figure 1: Screw spacing configurations to increasingly short-circuit the CLT floor assembly

The tested assembly which was subjected to short-circuiting shown in Fig. 1 consisted of a 3-ply micro CLT topping, fastened through the GenieMat FF25 acoustic interlayer, to a 3-ply 105 mm structural CLT panel. The fasteners used to short-circuit the assembly were 127 mm long fully threaded self-tapping screws.

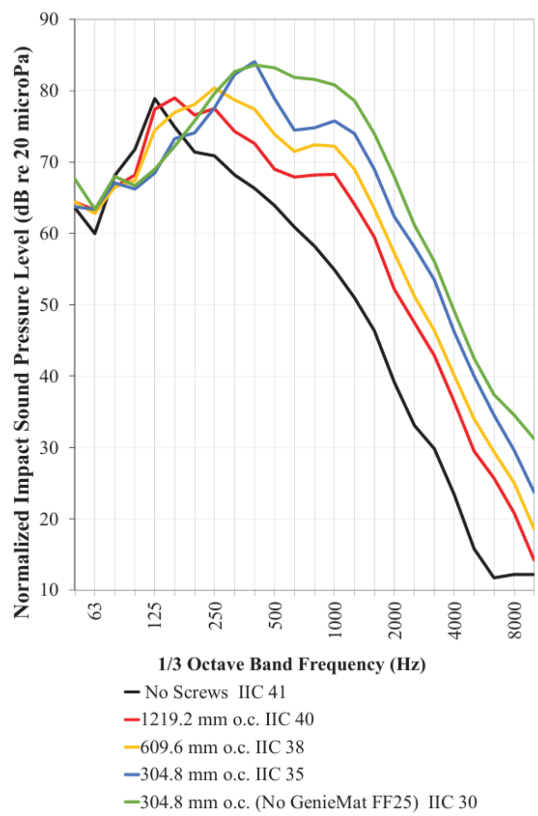


Figure 2: Impact Sound Performance of Progressively Short Circuited CLT Floor

https://doi.org/10.52202/080513-0173

The effect of short-circuiting the resilient interlayer is clear as the impact sound rating consistently decreases with decreased fastener spacing. A reduction of similar nature was found for airborne sound transmission [1].

2.3 Vibration-Controlled Span Lengths in Mass Timber Floor Systems

Floor-vibration is an area of design for which several methods of quantifying targets and limits exist across different texts and jurisdictions. The International Building Code does not explicitly include any requirements that are directly aimed at addressing floor vibration. As a result, the acceptable level of vibration for occupant perception is left to the discretion of designers in areas where the IBC is enforced. Several approaches exist to limit floor vibration to acceptable levels, including deflection limits, floor fundamental frequency requirements, span limits, and more. One common approach in design is the 2019 CLT Handbook method from FPInnovations, which uses a maximum span length limit to control vibration in CLT floors [3]. Two versions of the method exist, one which relies only on the stiffness of the timber panel itself, assuming no stiffness contribution from the topping, and another for TCC systems. Including the stiffness contribution of the concrete slab in TCC systems generally allows for increased span lengths. The equation when adapted for TCC floors is as follows:

$$L \leq 0.329 \, \frac{(EI)_{eff}^{0.264}}{m^{0.206}} \tag{1}$$

Where L denotes the span length, $(EI)_{eff}$ the effective composite bending stiffness, and m the mass per unit length of the floor assembly. The effective composite bending stiffness is calculated with material properties of the timber, concrete, and the gamma-method which accounts for composite action. When Eqn. 1 is applied to a TCC floor system of 100 mm thick (4") normal weight concrete slab cast directly to a 175 mm 5-ply panel of E1 stress grade with self-tapping screws at 300 mm on-centre, a vibration-controlled span length of 8.20 meters is calculated. When the same 5-ply panel is designed as a non-composite system, ignoring the stiffness contribution of the slab, the vibration-governed span length drops to 5.33 meters [3]. Thus, a 53.8% increase in vibration-controlled span length is achieved by designing a timber concrete composite floor system in this scenario. However, an exposed 5-ply floor panel with 100 mm of concrete cast and fastened directly to the CLT does not meet building code for acoustic requirements [7]. Thus, it is necessary to introduce a resilient interlayer if the mass timber ceilings are to remain exposed. When a resilient interlayer is present between the structural timber floor panel and concrete topping, the WoodWorks Mass Timber Floor Vibration Guide implies that the gamma method for composite action can be disregarded, and the effective stiffness taken as the simple sum of the individual stiffness of the timber and concrete layers [8]. Despite this, previous research has shown that some degree of composite action can occur in the presence of a resilient interlayer [8]. For the same 5-ply CLT floor panel as discussed in the previous two examples, if the simple sum approach is used, a span of 5.94 meters is calculated. The results of the comparison of the three calculations for vibration-controlled span length with varying approaches for effective flexural rigidity are summarized below.

Table 2: Comparison of FPI Method Variations for Span Length Calculation

Approach	Effective Flexural Rigidity	Vibration Controlled Span (m)
Non-Composite	$(EI)_1$	5.33
Composite Simple Sum	$(EI)_1 + (EI)_2$	5.94
Composite Gamma Method	$(EI)_1 + (EI)_2 + (\gamma_1)(EA)_1(a_1^2) + (\gamma_2)(EA)_2(a_2^2)$	8.20

If a normal weight reinforced topping with shear connectors is used, the discussion can be simplified to only the composite simple sum and the composite gamma methods. Since the composite simple sum is a derivation of the composite gamma method in which the gamma factor is set to zero, the analysis can again be simplified to focus on just the gamma factor itself. The equation to calculate the gamma factor is as follows:

$$\gamma = \frac{1}{1 + \frac{\pi^2 (EA)}{KL^2}} \tag{2}$$

Where γ is the partial composite action factor, E is the modulus of elasticity, A the cross-sectional area, K the load-slip modulus, and L the design span length [3]. Since variables E, A, and L are accessible material properties of the individual components and have no association to the connection between the two layers, it becomes clear that the load-slip modulus, K, is the defining input in the degree of composite action in TCC floor systems in the FPI method. Load-slip modulus is a function of the fastener spacing and the serviceability stiffness of a singular fastener, k_s, which can be obtained from physical testing in accordance with ASTM D1761.

3 – PROJECT DESCRIPTION

The degree of composite action ultimately relies on the stiffness of the connection between the concrete topping slab and mass timber panel. In addition, there is an established method for experimentally determining this value. Thus, physical testing of the serviceability stiffness with the inclusion of the GenieMat FF25 was carried out to analyse the impact of a resilient interlayer on the partial fixity of a TCC system. Once load-displacement data for the concrete to CLT connection was obtained from testing, the serviceability stiffness was calculated. With the serviceability stiffness of a connection through the acoustic interlayer now known, FPI method vibration-controlled span lengths were calculated for a TCC system of this configuration. Simultaneously, data from Callaghan and Byrick's 2023 paper regarding the degradation of acoustic performance with increased fastener short-circuiting was used to model the STC & IIC ratings as a function of fastener spacing for the same floor assembly. With the relationships for STC, IIC, and vibration-controlled span length defined as functions of fastener spacing, a spacing can be selected that both meets acoustic targets and maximizes span length for the floor assembly in question.

4 – EXPERIMENTAL SETUP

The assembly tested consisted of a 100 mm fibre reinforced concrete topping over the 25 mm GenieMat FF25, on a 175 mm thick 5-ply SPF CLT panel. The concrete topping was fastened through the GenieMat FF25 to the CLT panel with 12 mm diameter, 300 mm long, fully threaded self-tapping screws. The screws were installed at a 45° angle to maximize the likelihood of the desired screw withdrawal failure mode. The screws were fastened into the CLT panel, concrete poured atop and left to cure for 16 days.

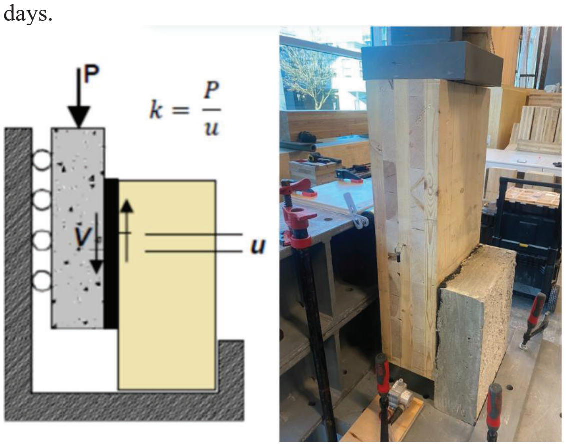


Figure 3: ASTM D1761 Screw Lateral Resistance Test Setup at Concept Lab

In total, four monotonic displacement tests were carried out in accordance with ASTM D1761 at Fast + Epp's Concept Lab. This standard specifies the test methods for screw lateral resistance of mechanical fasteners in wood. Two specimens were tested with concrete cast and fastened directly to CLT, and two specimens were tested with the GenieMat FF25 acoustic mat between the concrete and timber panel. While ASTM D1761 specifies to test screw lateral resistance 1 hour after the mechanical fasteners are installed, in this scenario, the testing had to be carried out 16 days after the concrete pour to allow for adequate curing. String potentiometers were attached to the CLT on each side to track relative movement of the wood element. The load-displacement behaviour of the four assemblies was obtained for analysis.

5 – RESULTS

5.1 Screw Lateral Resistance Test Results

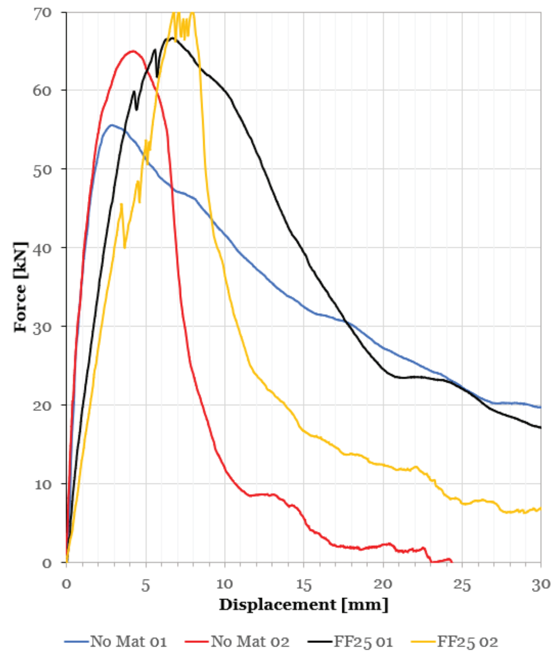


Figure 4: Load-displacement response of all 4 tested assemblies

In both the second iteration of the test with no acoustic mat (No Mat 02) and the second iteration of the test with the mat (FF25 02), the assembly failed by concrete cracking. Since the desired failure mode for the test plan is screw withdrawal, the second tests will not be used in the calculation of fastener serviceability stiffness. Thus, the full response behaviour of the self-tapping screws in both assemblies can be assessed and compared based on the curves labelled NoMat 01 and FF25 01 in Figure 4.

The serviceability stiffness was calculated as specified in ASTM D1761, as the slope of force over displacement measured between 10% and 40% of the maximum load, within 15 mm of slip. Once the serviceability stiffness for an individual fastener is obtained, the load-slip modulus for a given TCC assembly is calculated for the chosen fastener spacing. The maximum loads obtained, 10% values, 40% values, and serviceability stiffnesses for the NoMat 01 and FF25 01 tests are displayed in the table below.

Table 3: Results of ASTM D1761 testing for screw lateral resistance on assemblies with and without acoustic mat

	NoMat 02	FF25 01
Max Load (kN)	55.6	66.7
$V_{40\%}$ (kN)	22.2	26.7
$V_{10\%}$ (kN)	5.56	6.67
$u_{10\%}$ (mm)	0.49	1.48
$u_{40\%}$ (mm)	0.15	0.31

https://doi.org/10.52202/080513-0173

	NoMat 02	FF25 01
k_s (kN/mm)	50.2	17.2

The maximum load reached for the sample with the acoustic mat is 11.1 kN higher than for the sample with concrete cast directly to the CLT panel. Using the data points for shear force and displacement at 10% and 40%, the serviceability stiffness is calculated. For the sample with GenieMat FF25, the serviceability stiffness is 2.91 times lower than the sample with concrete cast directly to CLT. While this reduction in stiffness is significant, the measured serviceability stiffness of 17.2 kN/mm shows that the degree of fixity between the concrete and CLT is not negligible when there is a resilient layer in between. While the limited sample size limits the significance of this result, the outcome remains a promising indication for the concept. When comparing the newly obtained connection stiffness of the sample with GenieMat FF25 to previously measured values for various connector types, the new value is consistent with measured stiffnesses, all of which were direct connections (no interlayer). Listed below are the k_s values for different types of fasteners, with the new result in bold [2].

Table 4: Serviceability stiffness values for several common fastener types

Fastener Type	Serviceability Stiffness (k_s)
Rebar with hook (profiled at 45°)	28.2 – 84.9
Dowel	22.8 – 31.1
2 STS at 45° in CLT	21.2
Tecnaria (Base)	17.9
1 STS at 45° with GenieMat FF25 interlayer	**17.2**
Lag Screws	12.0 – 15.0
2 STS at 45°	14.4
Rebar (profiled)	10.1
Rebar (smooth)	6.6 – 8.6
Nail	5.7

When considering the stiffness of the self-tapping screw connection with GenieMat FF25 interlayer relative to other measured fastener stiffness values, the connection behaves within the range of stiffness that is currently used and relied on in design. This result demonstrates that the fixity between the two mass layers in a TCC system should not be assumed to be non-existent when an acoustic mat is present. Ultimately, the data suggests that designing TCC systems with resilient interlayers is possible if the reduction in individual fastener stiffness is accounted for by increased fastener frequency. However, increasing the frequency of fasteners which penetrate the acoustic mat will result in a degradation in acoustic performance of the assembly.

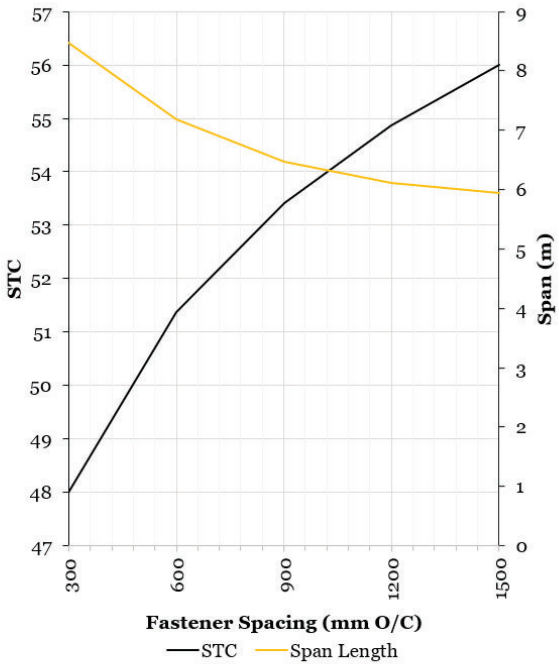
5.2 Simultaneous Span and Acoustic Design Example

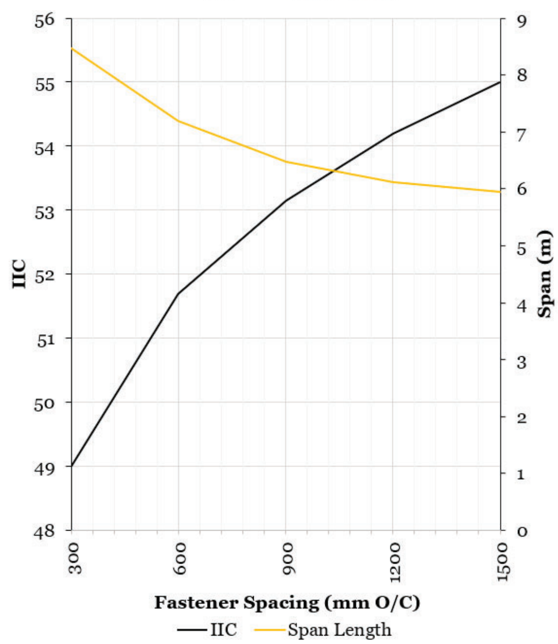
Pairing the newly obtained data for connection stiffness with results from Callaghan and Bryrick's 2023 testing on acoustic performance makes it possible to design for both vibration-controlled span length and acoustic targets simultaneously. The TCC floor assembly investigated in this example consists of 100 mm of normal weight concrete over the GenieMat FF25 over a 5-ply 175 mm CLT panel. The FPI method for vibration-controlled span length is employed on this assembly, including all relevant properties for CLT, concrete and fasteners as inputs. The fastener properties are input with a serviceability stiffness of 17.2 kN / mm, the experimentally determined value from ASTM D1761 testing. The load-slip modulus, *K,* for the system is then calculated with the equation below:

$$K = \frac{k_s n}{s} \tag{3}$$

Where n is the number of fasteners in 1 m of width and s is the spacing of fasteners on-centre lengthwise. For the sake of the following calculations, spacing was assumed to be equal in both orientations, thus n is simply the reciprocal of s. To analyse span length as a function of fastener spacing, several iterations of fastener spacings were input to Eqn. 3 and proceeding calculations carried out. Spacing of the fasteners is set as 0.3 meters, 0.6 meters, 0.9 meters, 1.2 meters, and 1.5 meters. At each spacing, vibration-controlled span length and acoustic performance are estimated. While all material properties for CLT and concrete remain consistent throughout the iterations, the load-slip modulus, K, varies with each spacing, and causes the gamma factor to change. Equation 2 is used to compute γ_2, which is then used in the composite gamma method equation for effective flexural rigidity from Table 2. The effective flexural rigidity, EI_{eff}, is then used in Equation 1 to compute the FPI vibration-controlled span length for the assembly.

Acoustic performance was analysed by using data from two test programs. The baseline test data used is from acoustic testing caried out at Intertek York on an exposed 5-Ply 175 mm CLT assembly with a 100 mm concrete topping on Pliteq's GenieMat FF25 [8]. There is also a wood finished flooring and 2 mm GenieMat RST02 underlayment on top of the concrete pour. With no fastener penetrations, this assembly achieves IIC 55 & STC 56 or $L_{n,w}$ 55 & R_w 50. The second set of test data used to predict the behaviour of this assembly is from the 2023 WCTE Paper "Influence of Mechanical Fastener Spacing on Acoustic Performance in Timber Composite Panels". The data from this paper is used to assess the decrease in airborne and structure borne sound performance of the demising assembly as the fastener spacing is decreased. In this test frame, acoustic testing was carried out at fastener spacings of 0.3 meters, 0.6 meters, 0.9 meters, 1.2 meters, and 1.5 meters. The results of this analysis shown in the Fig. 5 and 6 below.





Figures 5 and 6: Calculated Vibration-Controlled Span Length versus STC and IIC, as a function of fastener spacing

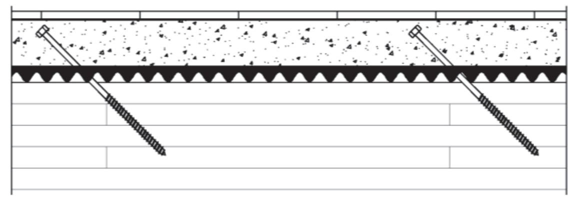


Figure 7: Floor-ceiling assembly analysed (12 mm wood flooring, 2 mm GenieMat RST02, 100 mm concrete topping, 25 mm GenieMat FF25, 175 mm 5-ply CLT, 300-mm screws)

As predicted, the curves for span and acoustic rating vary inversely as a function of fastener spacing. Decreased fastener spacing results in a stiffer connection between the composite system components, also allowing a longer span. Conversely, this causes greater acoustic bridging, reducing the airborne and structure borne ratings.

Plotting vibration-controlled span length and acoustic ratings simultaneously allows engineers to select the fastener spacing based on project requirements and the goals of their design. For instance, if designing an office building with low acoustic sensitivity and open working spaces desired, an engineer could design the assembly assessed in Figs 5 & 6 with a tight fastener spacing of 300 mm on-centre. Doing so would maximize span length for the assembly. With the data in-hand, the STC and IIC are predicted to be 49 and 48, respectively. While the STC & IIC values are not exceedingly high, the client and design team can make an informed decision and balance the priorities on their project. On the contrary, if an engineer is designing a higher-end multi-family residential building with the floor assembly assessed in Figs. 5 and 6, they might choose to place the fasteners at 1.2 meters on-centre. In this scenario, higher-level acoustic performance of STC 55 and IIC 54 is achieved while still benefiting from longer span lengths of the TCC design. Likely the most useful case of these models presented in Figs. 5 & 6 is when a designer needs to balance acoustics and span length. If a TCC system is being implemented on a multi-family residential project in a jurisdiction under the IBC, STC & IIC 50 must be met as per code. In this scenario, the designer could go to the model, look for the minimum fastener spacing which satisfies STC & IIC 50, and choose this spacing as it optimizes span length for the required acoustic targets.

Table 5: STC, IIC, and vibration-controlled span lengths for the assembly shown in Figure 7

Fastener Spacing (mm O/C)	**STC**	**IIC**	**Span (m)**
300	48	49	8.47
600	51	52	7.19
900	53	53	6.47
1200	55	54	6.12
1500	56	55	5.95

https://doi.org/10.52202/080513-0173

6 – CONCLUSION

This study examines the trade-offs between fastener spacing, acoustic performance, and vibration-controlled span length in exposed CLT floor-ceiling assemblies. Results confirm that while tighter fastener spacing enhances structural performance by increasing composite action, it also degrades acoustic performance due to short-circuiting of the resilient interlayer. While a small-scale study, the preliminary results of ASTM D1761 screw lateral resistance tests demonstrated the presence of an acoustic mat reduced fastener stiffness but still allowed for partial composite action. These results challenge the conservative design assumption that such systems behave as fully non-composite.

By combining empirical data on connection stiffness with established acoustic performance trends, this research provides a framework for optimizing TCC floor designs. For high-acoustic-performance applications, wider fastener spacing is recommended to maintain STC and IIC ratings above 50, whereas tighter spacing is preferable in cases where maximizing span length takes priority. These findings enable engineers to tailor fastener placement to project needs, advancing the practical application of mass timber in multi-story construction.

7 – REFERENCES

[1] A. Callaghan, W. Byrick. "Influence of Mechanical Fastener Spacing on Acoustic Performance in Timber Composite Panels". World Conference of Timber Engineering, 2023.

[2] S. Cuerrier-Auclair. "Design Guide for Timber-Concrete Composite Floors in Canada". Special Publication SP-540E. FPinnovations, 2020.

[3] E. Karacabeyli, S. Gagnon. "Canadian CLT Handbook: Volume 1". FPInnovations. 2019.

[4] C. Guo, J. Zhou. "Vibration Serciveability Performance of Mass Timber Floors Under Various Support Conditions". World Conference of Timber Engineering, 2023.

[5] Pliteq Intertek Report #k7453.01-113-11-r1

[6] Pliteq Intertek Report #F2761.06-113-11-R0

[7] Pliteq Intertek Report #k5952.08-113-11-r0

[8] Breneman et al. "U.S. Mass Timber Floor Vibration Design Guide". WoodWorks Wood Products Council, 2023.

[9] Pliteq Intertek Report #F5500.09-113-11-R0

[10] S. Cuerrier-Auclair, L. Hu, R. Ramzi. "Design method for vibration control of timber-concrete composite floor". Final report of projects Nos. 301011242 & 301012202 for the Canadian Forest Service, FPInnovations, 2018.