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INFLUENCE OF CONNECTION SYSTEMS ON SERVICEABILITY RESPONSE OF CLT TIMBER FLOORING

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ABSTRACT: In this paper finite element analysis of a five layer cross-laminated timber (CLT) rectangular floor is presented. The model was developed using 3D shell elements with linear elastic orthotropic material properties. Support conditions analysed included fully fixed, semi-rigid and simply supported, and both one and two-way span conditions were considered. For each case, the serviceability deflection was determined from a static small displacement analysis and the first three natural frequencies bending and torsional mode shapes, within a 0-80 Hz range, from mode frequency analysis. The analysis shows that the maximum displacement and frequency response are significantly impacted by the support stiffness and the number of edges supported. These results will contribute to determining the optimum fixing configuration with regard to serviceability limit design (SLD) for various CLT floor geometries.

KEYWORDS: Timber floors, mass-timber, cross-laminated timber, serviceability limit design, finite element analysis

1 INTRODUCTION

Mass-timber is the collective term for large solid timber construction materials, which are suitable for mid- to high-rise buildings. Mass-timber products include cross-laminated timber (CLT or X-lam), nail laminated timber (NLT), and glued laminated timber (glulam). Due to advances in mass-timber technology, wood is increasingly seen by designers as a solution to improving the environmental impact of the built environment while still meeting the demands of modern design along with safety and performance considerations. Although glulam beams are now commonly considered for selection in beam design, CLT is emerging as the preferred structural floor and wall element in multi-storey development, competing with concrete and steel, as it incorporates flexibility, a reduced dead weight in comparison with concrete and relatively fast on-site construction time [1]. However, the general benefit of timber's low dead weight, is a disadvantage when it comes to floor design. The potential of uncomfortable static deflections and vibrations in timber floors, particularly due to footfall, continues to be a limiting factor in the selection of timber generally for floors by designers.

The objective of this study is to investigate current practise in relation to vibration design of a timber floor and to evaluate its relevance to CLT floor design. The type of connection system used in CLT construction can affect the structural response. In this paper, the influence of the connection configuration on the vibration response of CLT floors is investigated using finite element modelling.

2 VIBRATION DESIGN

2.1 VIBRATIONS, FREQUENCIES AND MODES

Vibrations are mechanical oscillations that occur about an equilibrium point. Their rate per unit time, is their frequency. A fundamental frequency is the rate a system will vibrate freely if set in motion by one input. All objects have inherent fundamental frequencies, with corresponding mode shapes. The fundamental frequencies of a structural system depends on its material properties, damping, and boundary conditions. If any parameter of the system changes, its geometry, density, or support configuration, for instance, so do the fundamental frequencies and modes. An exciting force applied at the same rate as a fundamental frequency will cause resonance, which will amplify vibrations and cause deflections greater than as a result of static loading.

2.2 HUMAN RESPONSE TO BUILDING VIBRATIONS

The human body has its own fundamental frequencies, distinct for each body member and organ, but all typically within the 0-80 Hz range. Exposure to

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vibrations in this range of frequencies, particularly within the 4-8 Hz range, impacts on a person's comfort, perception, and health [2] [3]. Although tolerance to vibration depends on proximity and awareness of the source, and the person's own activity level, studies have shown that the longer the duration the greater the discomfort [4-5].

Research has shown that the components of force due to a person walking dominate at 0-6 Hz, and the force intensity falls away almost linearly until 50 Hz, dissipating rapidly after 50 Hz [4].

As the frequency of everyday footfall and the resonant frequency range which is most uncomfortable coincide, construction standards give guidelines on serviceability limit design (SLD) to ensure that footfall does not resonate with the floor.

2.3 EUROCODE 5 CRITERIA FOR VIBRATIONS DESIGN

Eurocode 5 (EC-5) [6] requires that, actions which can reasonably be anticipated on a structure, do not cause vibrations that can impair the function of the structure or cause unacceptable discomfort to the users.

Vibration should be estimated by measurements or by calculation taking into account the expected stiffness of the structure and the modal damping ratio. A modal damping ratio ξ of 1% should be assumed, unless other values are proven more appropriate.

The code then sets out design guidelines for residential floors with fundamental frequency (f_1) below and above 8Hz. If the floor f_1 is less than 8 Hz, a special investigation should be made. Where f_1 is greater than 8 Hz, two main conditions must be satisfied: the static deflection due to a unit point load and the unit impulse velocity response must be lower than prescribed limits.

In addition to the main EC-5 provisions, additional regional design criteria, outlined in National Annexes (NA) are applicable. A study, which investigated the vibration design criteria of thirteen countries for traditional timber floor types by Zhang et al. [7], presents the alternative equations and parameters for each country.

2.3.1 Fundamental frequency

The first fundamental frequency f_1 for a rectangular floor, simply supported on four sides, is found using Equation 1.

$$f_1 = \frac{\pi}{2l^2}\sqrt{\frac{(EI)_l}{m}} \qquad \text{(Hz)} \qquad (1)$$

where

m - mass per unit area in kg/m^2 of unloaded floor

l - floor span in m

$(EI)_l$ - equivalent plate bending stiffness of the floor about an axis perpendicular to the beam direction in Nm^2/m.

Austria and Finland NA include a quasi-permanent load to represent partitions and furniture and account for the lateral stiffness contributed by strutting, floor deck, and ceiling. [7].

2.3.2 Unit point load deflection

The maximum instantaneous vertical deflection w in mm, caused by a vertical concentrated static force F in kN, should satisfy Equation 2.

$$\frac{w}{F} \leq a \qquad \text{(mm/kN)} \qquad (2)$$

where a is the permissible deflection limit.

The values of a range from 0.5–4.0 mm depending on NA criteria. The Irish and UK NA define a as

$$\begin{aligned} a &= 16500/l^{1.1} \qquad l \geq 4000mm \qquad \text{(mm)} \qquad (3)\\ &= 1.8 \qquad\qquad\quad l < 4000\,mm \end{aligned}$$

Zhang et al. [7] found that the unit point load deflection criterion was the most critical when considering traditional timber floor design.

In determining the floor deflection, only four countries, namely, Austria, Finland, Ireland, and the UK, include additional stiffening from transverse floor members, while only Finland, Ireland, and UK include the effect of joist spacing. Only Ireland and UK incorporate the added deflection due to shear.

The Irish and UK NA calculate the deflection due to a 1 kN load using Equation 4.

$$w = \frac{1000\,k_{dist}\,L_{eq}^3 k_{amp}}{48(EI)_{joist}} \qquad \text{(m/m)} \qquad (4)$$

where

L_{eq} - equivalent floor span in m,

k_{dist} - additional stiffening factor from transverse floor members; $k_{dist} \geq 0.30$

k_{amp} - shear deflection factor ranging from 1.05–1.45

$(EI)_{joist}$ - the bending stiffness of the floor joist in Nm^2/m.Unit impulse velocity response.

The maximum initial value of the vertical floor vibration velocity response caused by an ideal unit impulse is found using Equations 5 and 6. The impulse is applied at the point of the floor giving maximum response. Components above 40 Hz can be disregarded.

$$v = \frac{4(0.4+0.6\,n_{40})}{mxl+200} \qquad \text{(m/Nm}^2\text{)} \qquad (5)$$

$$n_{40} = \left\{\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\left(\frac{x}{l}\right)^4 \frac{(EI)_l}{(EI)_x}\right\}^{0.25} \qquad (6)$$

where

v - unit impulse velocity response in m/Nm^2

x - floor width in m

n_{40} - number of first-order modes with natural frequencies below 40 Hz

$(EI)_x$ - equivalent plate bending stiffness of the floor about an axis parallel to the beam direction in Nm^2/m.

The limit defining the unit impulse velocity is found using Equation 6.

$$\nu \leq b^{(f_1(\xi-1))} \qquad (\mathrm{m/Ns^2}) \qquad (6)$$

The parameter b is determined using Figure 1 where a is the permissible deflection limit. The modal damping ratio ξ is generally 1%, but is taken as 2% in Ireland and the UK, due to different construction norms.

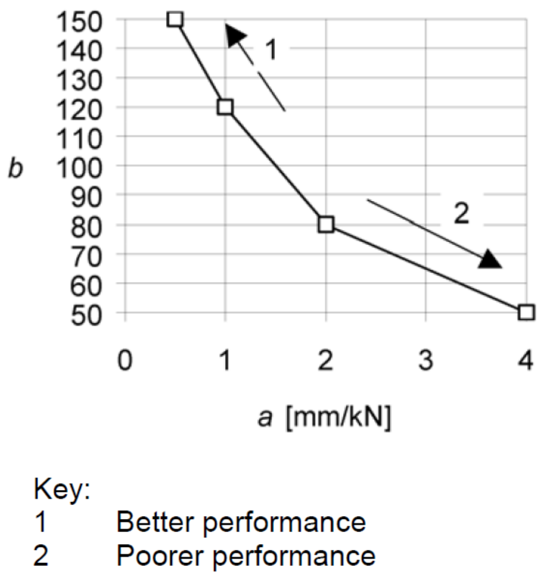


Figure 1: *Recommended range of and relationship between a and b from EC-5* [6].

Zhang et al. [7] found that the unit impulse velocity response is very difficult to determine. Finland, Germany, Netherlands, and Spain, disregard the criteria totally.

2.4 SERVICEABILITY LIMIT DESIGN IN PRACTICE

Annoying floor vibration induced by occupants' everyday activity has been a persistent design problem [8]. An extensive study was undertaken by Hamm et al. [9] on in-situ floors to investigate why annoying vibrations continue to be a problem, although EC-5 and German NA: DIN 1052 [10] are generally adhered to. Measurements were taken from in-situ timber floors, including traditional and CLT floors, with and without screed topping. It found that in-situ frequency measurements and calculated values did not sufficiently correlate. The study attributed the difference to the assumed boundary conditions, which did not include the torsional spring influence of the walls above. Non-bearing partitions positively influenced vibration behaviour in all cases, and the static deflection criterion was determined to be equally as important as the frequency parameter. It found no significant correlation between frequency measurements and perceived vibration annoyance [9]. However, Hu and Gagnon [11] conducted subjective and dynamic tests of a laboratory floor, and found human perception to correlate well with the dynamic load results. The damping ratio of a bare CLT test floor consistently measured 1%. A study assessing the vibrations of a timber floor in the laboratory and during construction by Jarnerö et al. [12], found that the dynamic response of the floor, improved considerably when incorporated into the building, the damping ratio improving the most. Maldonado and Chui's [13] study of one-way and two-way spanning floors, found that introducing screws at floor supports, improved the frequency results. Maldonado and Chui's investigation on the rotational stiffness of floor supports showed an improved fundamental frequency and static deflection response, with increased rotational support stiffness [14]. Weckendorf and Smiths' [15] study of the dynamic response of shallow floors with CLT structural spines, asserted that it is the flexibility of the supporting structure, not the movement within the structure of the floor itself that influenced vibration serviceability of a CLT floor. They concluded that floor vibration serviceability design criteria applied to traditional timber floors was probably not appropriate for CLT floor design.

2.5 CROSS-LAMINATED TIMBER FLOORS AND SERVICEABILITY LIMIT DESIGN

Current serviceability design codes in Europe essentially pertain to the design of traditional timber floor construction, where annoying vibration is attributed to movement in the floor structure alone. The design parameters generally relate to the geometry and stiffness of the floor, or in some cases, one-way spanning floor joists only. As CLT floors are solid plates, discernible movement within the floor structure from serviceability loading is not expected, however annoying vibrations may still occur. Due to the orthotropic nature of CLT, the floor stiffness is not equal in perpendicular directions, but continuous support can be provided to all edges. Supports in EC-5 are assumed to be simply supported.

Mid- to high-rise CLT buildings are generally platform construction, where each successive storey is built from the floor below, hence the floor and walls are interlocked. A degree of semi-rigidity is therefore expected in all CLT floor-to-wall fixing configurations, which combined with the stiffness of the walls above and below, will influence the dynamic response of the floor. The number of storeys above or below along with adjacent building components will also have an influence.

Current industry standards recommend connecting CLT floor and wall panels with different combinations of steel brackets, plates, screws, and anchors. Figure 2 shows a typical floor to wall junction. By establishing the rotational stiffness of different connection configurations, using proprietary components, optimum set-ups with regard to SLD can be determined. All bearing in mind the construction industry's requirement for economical standardised components and simple assembly.

analysis using an 8-noded element (SR8) was made without a significant effect on the results. Initial checking of the modelling approach was undertaken by modelling isotropic square floors, fully fixed and simply supported and comparing results with analytical classic plate theory.

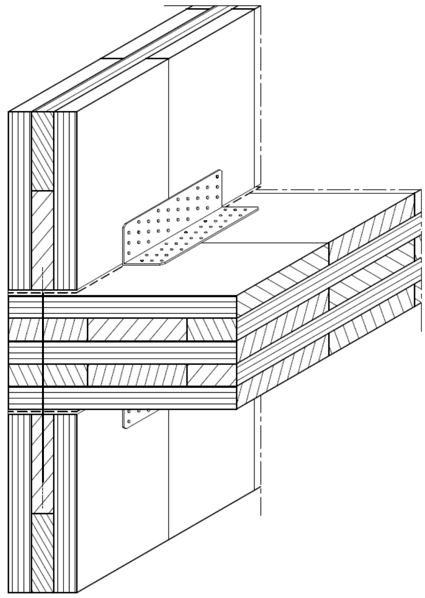


Figure 2: *Typical CLT shear angle bracket*

3 FINITE ELEMENT MODELLING

Finite element analysis (FEA) is a convenient way of appraising engineering problems virtually, before implementing expensive experimental testing. In order to determine the key characteristics of CLT floor-wall connections that influence the vibration characteristics, FEA models were developed using the ABAQUS finite element package, which use the classical pinned and fully fixed support models, corresponding to the extreme rotational support stiffnesses of zero and infinity. As real connections exhibit semi-rigid behaviour, FEA models of CLT floors having supports with intermediate rotational stiffness are also investigated. The influence of the different support conditions on the unit load deflection and natural frequencies in the 0 – 80 Hz range are examined.

3.1.1 Geometry

A 6960 x 2400 mm rectangular 5-ply CLT floor with a total thickness of 200 mm was modelled. The maximum dimension was based on a reasonable floor span for a residential room or school. Category C1 [16] design load criteria for a classroom and proprietary CLT manufacturers design guidelines determined the floor depth. The floor edges are supported either along the two short sides or alternatively along all four sides. Figure 3 shows the one- and two-way spanning fully fixed floor geometry, with a static load applied at mid-span.

3.1.2 Finite element mesh

The model was meshed with 3D shell elements with a five layer composite layup. Each layer was 40 mm thick. Four-noded, reduced-integration curved shell elements with hourglass control (SR4) were used, with six degrees of freedom at each node. Following a mesh convergence study a global element size 0.1 m was found to be suitable. The floor model comprises a total of 1775 nodes and 1680 elements. For comparison,

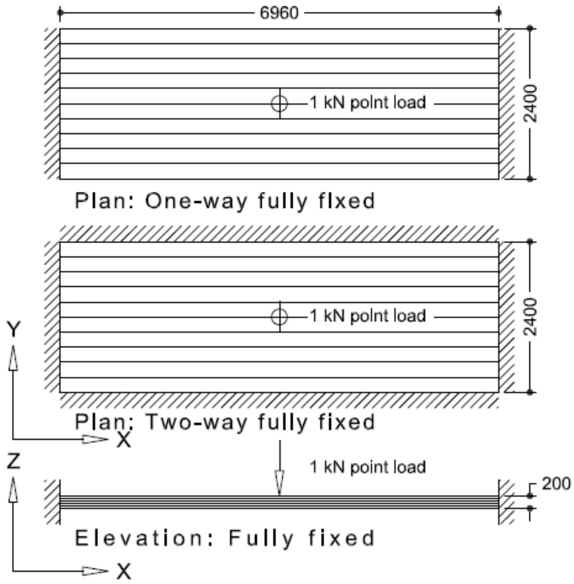


Figure 3: *Fully fixed geometry with static point load*

3.1.3 Boundary Conditions

The supported edges of the floors were modelled as fully fixed, semi-rigid and simply supported. One and two-way spanning conditions were considered. In simulating the fully fixed support conditions, all six degrees of freedom at each edge node were constrained. The three translational degrees of freedom at each edge node were constrained to simulate the simply supported condition.
The semi-rigid support condition was simulated by using a combination of springs and ties. In order to account for the influence of the supporting walls, vertical and horizontal springs, with a stiffness of 10 E+06 N/m, were deployed at 350 mm spacing. Multi-point constraint (MPC) ties were introduced diagonally from floor to wall, at 350 mm spacing to simulate rigid brackets.

3.1.4 Material properties

Using FEA to analyse CLT floors, Weckendorf et al. [17] contended that reliable results could only be achieved with orthotropic material analysis, including good characterisation and semi-rigidity of the supports and joints.
In the current model, the floor material was assumed to be orthotropic and linear elastic. The material properties used for each ply are given in Table 2. These properties represent a consistent orthotropic set that have been used by Bejtka and Blaβ [18] in numerical modelling of the bearing capacity and the stiffness of connections with dowel type fasteners in spruce. The orientation of each

successive ply was rotated 90° to simulate cross-laminated characteristics of CLT.

Table 1: *Linear elastic material properties from Bejtka and Blaβ* [18]

Bulk density	435	kg/m^3
E_1 (Longitudinal)	12.80E +09	N/m^2
E_2 (Rotational)	0.275E +09	N/m^2
E_3 (Tangential)	0.275E +09	N/m^2
ν_{12}	0.511	
ν_{13}	0.511	
ν_{23}	0.203	
G_{12}	0.550E +09	N/m^2
G_{13}	0.550E +09	N/m^2
G_{23}	0.055E +09	N/m^2

3.2 ANALYSIS

Two types of analysis were performed to investigate structural response. To determine the maximum static unit point deflection on any point on the floor, a 1 kN static load was applied at mid-span for each support condition and a small-displacement analysis was undertaken. The maximum deflection in each case was recorded. To find the natural frequencies, a mode-frequency analysis of the floor was performed for each of the six support conditions. The first natural frequencies and modes were found for each floor within the 0-80 Hz range of interest.

4 RESULTS AND DISCUSSION

4.1.1 One-way span - unit point load deflection

The static analysis of the one-way spanning fully fixed, semi-rigid and simply supported floors, carrying a central point load, showed that the deflection reduced with the rigidity of support conditions, as seen in Table 2. Increased rigidity improved deflection performance, decreasing the maximum deflection from 0.53 mm for the simply supported floor by 60 % to 0.21 mm for the fully fixed support conditions. For the semi-rigid case, the maximum deflection was found to be 0.38 mm, which represents a 28 % improvement from the simply supported condition. The deflection analysis contour plot for the one-way fully fixed support condition is shown in Figure 4.

Table 2: *One-way unit point load deflection*

Support conditions	Deflection (w)	
Fully fixed	0.21	mm/kN
Semi-rigid	0.38	mm/kN
Simply supported	0.53	mm/kN

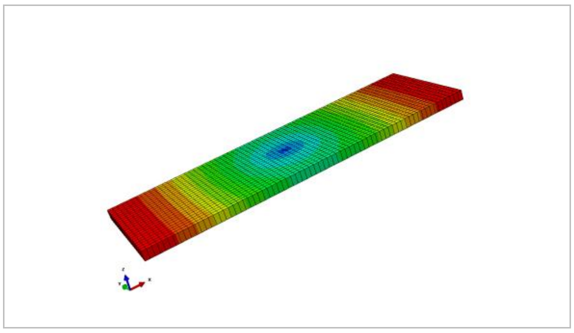


Figure 4: *One-way fully fixed w = 0.21 mm / 1kN*

4.1.2 Two-way span - unit point load deflection

Deflection results for the two-way spanning floor with different support conditions are outlined in Table 3, with a contour plot for the two-way fully fixed support condition shown in Figure 5. The maximum deflection was found to be 0.11 mm for the simply supported condition. The deflection reduced with rigidity of support, 0.10 mm and 0.09 mm for semi-rigid and fully fixed supports, respectively.

Comparing these results with the one-way spanning cases, the maximum floor deflection was seen to be reduced by 79 %, 74% and 57 % for the simply supported, semi-rigid and fully fixed supports, respectively.

Table 3: *Two-way unit point load deflection*

Support conditions	Deflection (w)	
Fully fixed	0.09	mm/kN
Semi-rigid	0.10	mm/kN
Simply supported	0.11	mm/kN

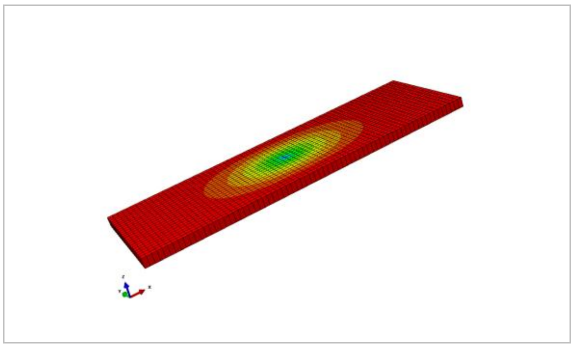
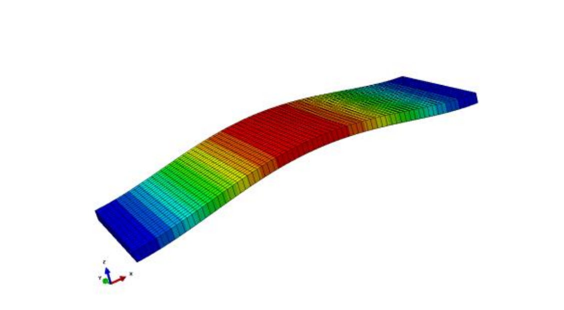


Figure 5: *Two-way fully fixed w = 0.09 mm / 1kN*

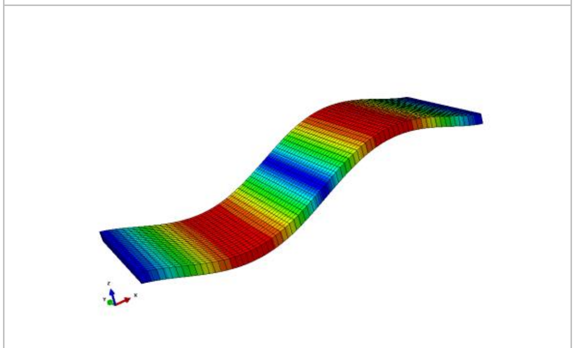
Based on the Irish NA to Eurocode 5 criterion for unit point load deflection, the limiting deflection for a 6.960 m is 0.98 mm. All FE analysis showed the deflection from a static unit point load well within this limit.

4.1.3 One-way span – modal analysis

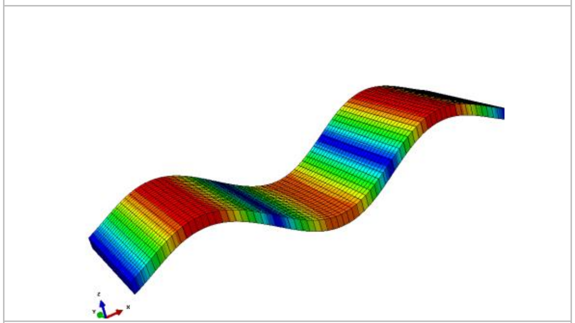
For all support conditions, the modal analysis showed three bending and three torsional modes within the 0-80 Hz range. Figure 6 shows the contour plots of the first three bending modes with fully fixed supports. The mode shapes were similar for all support conditions. Table 4 sets out the frequencies for the first three bending modes for each support condition. The frequencies increased with increased support rigidity, from 8.74 Hz for simply supported floor, just above the EC-5 criterion, to 10.74 Hz for semi-rigid supports, and 17.35 Hz when supports were fully fixed. Therefore, a 99 % increase in f_1 is found for a fully fixed floor, and 23 % for the semi-rigid condition. The influence of the support rigidity reduced for higher mode shapes, to a minimum 13 % in the third modes. The fully fixed support condition brought the second bending mode outside the EC-5 impulse velocity 40 Hz limit for first order frequency modes.



1st bending mode shape f_1 = 17.35 Hz



2nd bending mode shape 41.17 Hz



3rd bending mode shape 70.15 Hz

***Figure 6**:Contour plots of one-way fully fixed bending modes*

***Table 4:** One-way spanning bending frequencies*

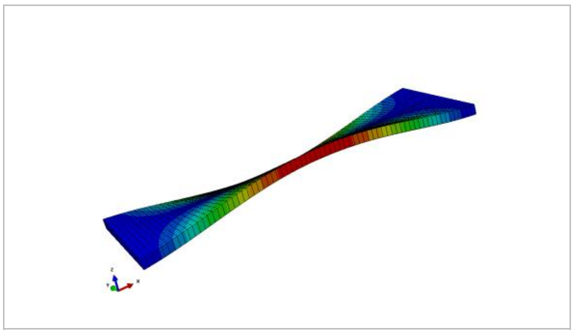
Support conditions	1st	2nd	3rd	
	Bending frequencies			
Fully fixed	17.35	41.17	70.15	Hz
Semi-rigid	10.74	33.68	62.66	Hz
Simply supported	8.74	31.57	62.18	Hz

The frequencies corresponding to the first three torsional modes for the each of the support conditions are outlined in Table 5. The lowest torsional frequency was 14.35 Hz and was found for the simply supported case. Again, the frequency values were found to increase with support rigidity. The influence is greatest for first mode where it increased by 44 % to 20.72 Hz for the fully fixed condition and by 9 % to 15.71 Hz for the semi-rigid case. The influence of the support conditions on frequencies is significantly less with the higher modes shapes.

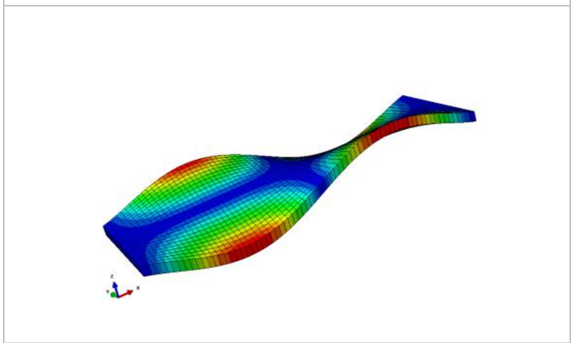
***Table 5**: One-way spanning torsional frequencies*

Support conditions	1st	2nd	3rd	
	Torsional frequencies			
Fully fixed	20.72	45.81	75.04	Hz
Semi-rigid	15.71	39.37	69.65	Hz
Simply supported	14.35	37.68	67.83	Hz

Figures 7 and 8 show the first three torsional contour plots for the fully fixed support condition. The mode shapes were similar for all support conditions.

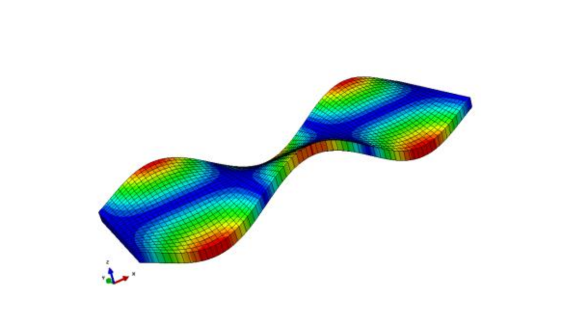


1st torsional mode shape 20.72 Hz



2nd torsional mode shape 45.81 Hz

***Figure 7**:Contour plots of one-way fully fixed torsional modes*



3rd torsional mode shape 75.04 Hz

Figure 8: *Contour plots of the third one-way fully fixed torsional mode*

Only the first simply supported fundamental frequency is calculated in EC-5 guidelines. Higher bending and torsional mode shapes are ignored, however it can be seen from the FE results that there are several natural frequency modes still within the 0-80 Hz range that may disrupt comfort levels.

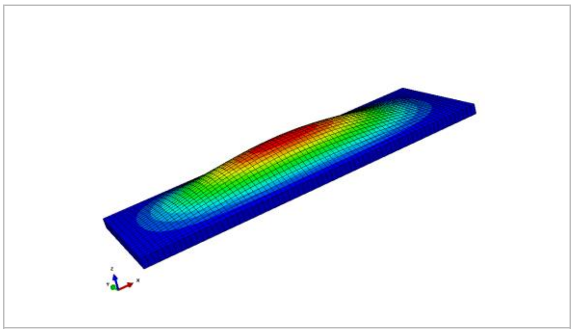
4.1.4 Two-way span – modal analysis

The modal analysis of the two-way spanning floors resulted in three bending modes within the 0-80 Hz range for simply supported and two for semi-rigid and fully fixed support conditions. There were no torsional mode shapes in this range. Table 6 outlines the frequency results for all support conditions, the third mode for semi-rigid and fully fixed, was above the relevant range, but is included for completion.

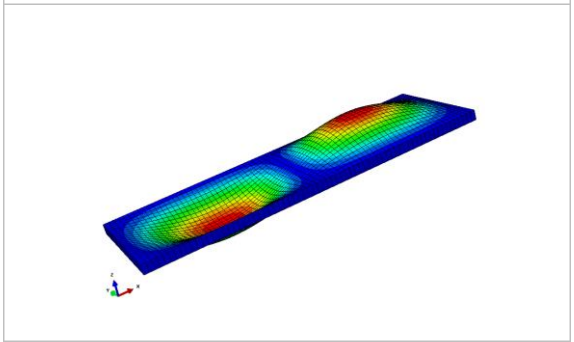
Table 6: *Two-way spanning frequency modes*

Support conditions	1^{st}	2^{nd}	3^{rd}	
	Bending frequencies			
Fully fixed	59.69	71.17	91.60	Hz
Semi-rigid	57.11	66.10	85.51	Hz
Simply supported	37.49	50.14	74.72	Hz

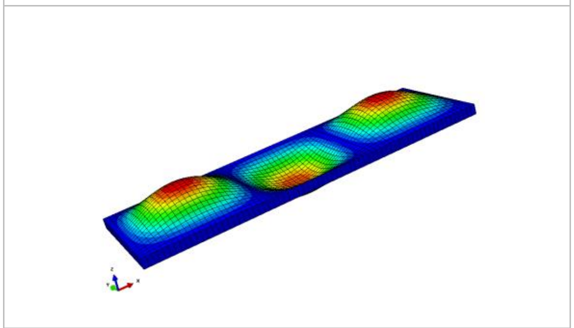
The modal analysis results for two-way spanning floors show fewer natural frequency modes within the 0-80 Hz range than for the one-way spanning floors. Of these, only one lies within the 0-50 Hz range that may resonate with footfall. The rigidity of the support conditions again influenced the frequency results. The fundamental frequency varied from 37.49 Hz for a simply supported floor, to 57.11 Hz for semi-rigid supports, and 59.69 Hz for the fully fixed case. This corresponds to a 59 % improvement in frequency values for the first modes, when changing from simply supported to fully fixed support conditions. The influence of the support rigidity was less for higher modes. With the exception of the simply supported floor, frequencies were above the EC-5 40 Hz unit impulse velocity response limit. Figure 9 shows the contour plots of the bending frequencies and modes with fully fixed supports. The mode shapes were similar for all support conditions.



1st two-way mode shape 59.69 Hz



2nd two-way mode shape 71.17 Hz



3rd two-way mode shape 91.60 Hz

Figure 9*:Contour plots of two-way fully fixed modes*

5 CONCLUSIONS

The timber SLD criteria and design guidelines for floor vibrations from EC-5, including the Irish NA, have been described. The parameters that were identified in literature as the critical criteria were examined for a sample CLT floor, namely, the first fundamental frequency and the unit point static load deflection. Finite element models of the CLT floor were developed and three different types of support conditions were investigated: simply supported, semi-rigid and fully fixed. In each case, both one and two way spanning situations were considered.

The study found that, by increasing rigidity in the support conditions, the serviceability response in accordance with EC-5 Irish NA parameters was improved. The finite element static analysis for a unit point load showed that the increased support rigidity improved the deflection performance by up to 60 %. The influence of spanning the floors both-ways reduced the deflection of up to 79 % compared to the one-way spanning floors. All results for static deflection were below the EC-5 Irish NA limit for a floor of this span.

Modal analysis of the one-way spanning CLT floor showed that, for semi-rigid and fully fixed support conditions, the first bending frequencies were increased by 23 % and 99%, respectively, compared to a simply supported floor. The difference is reduced to 13 % in the case of higher modes. By changing the support conditions to two-way spanning from one-way spanning, the fundamental frequencies increased by a factor of between three and five times.

These results demonstrate that the vibration behaviour of CLT floors is strongly influenced by the assumed support conditions. Assuming simply supported conditions may be overly conservative and may result in an overdesign of the floor. Assessing the rotational rigidity of CLT support configurations, would allow more realistic assumptions of the static deflections and the frequency of vibrations in CLT floors.

Future work will include experimental investigation to establish the rotational stiffness of proprietary support systems. These will then be incorporated in future FE models.

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REFERENCES

[1] P. Zumbrunnen and J. Fovargue, "Mid rise CLT Buildings - The Uk's experience and Potential for Australia and New Zealand," 2012, vol. 6, no. July, pp. 91–98.

[2] (International Organization for Standardization) ISO, *Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements*. 1997.

[3] ISO (International Organization for Standardization), *ISO 2631-2:2003(E): Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole Body Vibration Part 2: Vibration in buildings (1Hz to 80 Hz)*. 2003.

[4] S. Ohlsson, *Springiness and human induced floor vibrations*. Stockholm, Sweden: Swedish Council for Building Research, 1988.

[5] T. M. Murray, D. E. Allen, and E. E. Ungar, *Floor Vibrations due to Human Activity*, Steel Desi. American Institute of Steel Construction, INC., 1997.

[6] Eurocode CEN, *Eurocode 5 : Design of timber structures - Part 1-1 : General - Common rules and rules for buildings*, vol. 44, no. 0. Ireland: NSAI, 2014.

[7] B. Zhang, B. Rasmussen, A. Jorissen, and A. Harte, "Comparison of vibrational comfort assessment criteria for design of timber floors among the European countries," *Eng. Struct.*, vol. 52, no. 52, pp. 592–607, 2013.

[8] A. Pavic and P. Reynolds, "Vibration serviceability of long-span concrete building floors. Part 1: Review of background information," *Shock Vib. Dig.*, vol. 34, no. 3, pp. 191–211, 2002.

[9] P. Hamm, A. Richter, and S. Winter, "Floor vibrations – new results 2 EXISTING DESIGN RULES IN CODES," in *World Conference on Timber Engineering - WCTE 2010*, 2010, no. 1.

[10] D. D. I. für Normung, *DIN EN 1995-1-1/NA:2010-12 German National Annex – Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings*. 2010, pp. 1–99.

[11] L. Hu and S. Gagnon, "Controlling cross-laminated timber (CLT) floor vibrations: Fundamentals and method," in *World Conference on Timber Engineering 2012, WCTE 2012*, 2012, vol. 2, pp. 269–275.

[12] K. Jarnerö, A. Brandt, and A. Olsson, "Vibration properties of a timber floor assessed in laboratory and during construction," *Eng. Struct.*, vol. 82, pp. 44–54, Jan. 2015.

[13] S. A. H. Maldonado and Y. H. Chui, "Vibrational performance of cross laminated timber floors," in *World Conference on Timber Engineering 2012, WCTE 2012*, 2012, vol. 1, pp. 370–377.

[14] S. A. H. Maldonado and Y. H. Chui, "Effect of End Support Conditions on the Vibrational Performance of Cross-Laminated Timber Floors," in *WCTE Quebec*, 2014, pp. 3–4.

[15] J. Weckendorf and I. Smith, "Dynamic characteristics of shallow floors with Cross-Laminated-Timber Spines," 2012.

[16] E. CEN, *Eurocode 1: Actions on structures - Part 1 -1: General actions - Densities, self-weight, imposed loads for buildings*, vol. 44, no. 0. 2000, pp. 0–9.

[17] J. Weckendorf, T. Toratti, I. Smith, and T. Tannert, "Vibration serviceability performance of timber floors," *Eur. J. Wood Wood Prod.*, 2015.

[18] H. J. Blaß and I. Bejtka, "Numerische Berechnung der Tragfähigkeit und der Steifigkeit von querzugverstärkten Verbindungen mit stiftförmigen Verbindungsmitteln. Karlsruher," Karlsruhe, Germany, 2008.