Experimental investigation of the serviceability behaviour of a cross laminated timber floor

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ABSTRACT: European timber design standards set out basic serviceability limit design criteria for single span, simply supported floors, but the rotational stiffness of the fixing system and two-way support possible with modern solid timber floors can significantly influence deflection and vibration response. In addition, the added mass due to the use of non-structural floor screeds has an impact on the dynamic behaviour. The objective of this research was to investigate the influence of modern timber fixing systems and added mass on the serviceability behaviour of cross-laminated timber (CLT) floors. This paper outlines experimental research on a laboratory-scale, CLT floor using alternative arrangements of self-tapping screws and brackets, simulating common CLT platform construction details. Both one and two-way span conditions were considered. The influence of added mass was also measured. Non-destructive tests were carried out in accordance with European Standard prEN 16929 guidelines, which included measuring the static serviceability deflection due to a 1kN load applied at midspan and the floors natural frequencies and mode shapes between 0-80Hz. The study found varying degrees of influence on the serviceability response of the floor depending on orientation, imposed load, fixing type and spacing. In the case of single span platform construction using only self-tapping screws, the screw spacing had negligible influence on the fundamental frequency. The addition of support brackets increased the fundamental frequency up to 6%, with 11% reduction in the static point load deflection. Introducing added mass reduced the fundamental frequency by over 25%.

KEY WORDS: Cross-laminated timber, timber floors, serviceability limit design

1 INTRODUCTION

Cross-laminated timber (CLT), first patented in France in 1985, is a result of ongoing developments in timber technology termed mass-timber, where offsite manufacturing expertise is used to create large solid engineered timber products, 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 the mass-timber industry, 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. The use of mass-timber is growing worldwide, especially in central Europe, Scandinavia, and Canada where there is a long tradition of building with wood. Its popularity is increasing also in earthquake-prone regions such as the West coast of the US, Italy, and New-Zealand, due to the reduced seismic loads associated with this lightweight building system. The heights of timber buildings are growing ever taller. Brock Commons, a student accommodation building for the University of British Columbia, is currently the world's tallest timber building. The 18 storey, 53 meter high building is constructed predominately of glulam frame and CLT panels, with concrete stair and lift cores. The timber structure took 8 weeks to erect on site.

In the UK, CLT started as a niche product, but since its introduction in 2000, it has come to be a viable alternative to steel and concrete [1]. Reasons given by designers for choosing mass-timber construction include, its relative speed of construction, versatility where space is restricted, and a lower dead weight in comparison to concrete. In 2012, the London borough of Hackney introduced a 'Timber first' policy, which is a testament in itself to its suitability to high density development.

CLT comprises timber boards aligned in laminae, which are stacked at right angles and glued under high pressure into large solid panels. The panels are manufactured offsite and transported in sequence for assembly in-situ. The panels can be up to 300 mm thick and 16 m in length. CLT projects comprise all building uses including educational, residential, commercial, and civic buildings. Figure 1 shows the erection of a CLT school building in Bishop's Stortford, UK by KLH UK.

Current timber European serviceability design codes (EC5) [2] including regional design criteria outlined in the National Annexes, which are presented by Zhang et al. [3], generally pertain to the vibrational response of traditional timber floor construction. They do not specifically refer to CLT floors. The objective of this study was to investigate the serviceability behaviour of CLT floors. The scope of the research included experimental testing on a laboratory scale CLT floor using alternative arrangements of screws and brackets, spanning one- and two ways in order to characterise the boundary conditions due to the fixing configurations and determine their influence on the vibration response of the floor. In addition, the influence of a non-structural floor screed was also studied, by adding mass. The study was principally concerned with residential and office loading, and footfall induced vibrations within the frequency response range which is perceivable by the building occupants.

Figure 1. CLT construction in Bishop's Stortford, UK

2 FLOOR VIBRATION

2.1 *Frequencies and human perception of floor vibration*

Natural frequencies are inherent characteristics of a structure that depend on its mass and stiffness. Identifying a structure's natural frequencies and their corresponding mode shapes will give a better understanding of how it will respond to exciting forces. The human body too has natural frequencies, distinct for each body member and organ, the fundamental natural frequencies are all typically within the 0-80 Hz range. Exposure to vibrations in this range of frequencies impacts on a person's comfort, perception, and health [4] [5]. 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 [6]. Annoying floor vibration induced by occupants' everyday activity has been a persistent design problem [7]. An extensive study was undertaken by Hamm et al. [8] on in-situ floors to investigate why annoying vibrations continue to be a problem, although EC-5 and German NA: DIN 1052 [9] 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 [8]. However, Hu and Gagnon [10] 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. [11], 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 [12] 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 [13]. Weckendorf and Smiths' [14] 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.

3 TEST ASSEMBLY

The dynamic response of a 162 x 2400 x 4000 mm 5-ply CLT floor panel was supported on different arrangements of 94 x 1200 mm high 3-ply CLT wall panels. The walls were fixed to the concrete laboratory floor using reinforced angle brackets at 500 mm spacing. The brackets were screwed to the wall panels using Ø 5 x 50 mm round-head screws and fixed to the floor using M12 threaded rods secured into Ø 14 mm pre-bored holes with epoxy chemical anchor. Nine variations of the CLT platform construction examined are presented in this paper. Table 1 outlines the various assembly components, with an example juncture illustrated in Figure 2.

3.1 *Bracket and screw assembly*

In the case of one-way span platform construction, eight assembly variations were tested. They compared alternative spacing of partially threaded washer-head screws and the influence of alternative angle brackets at different spacing. An assembly using inclined fully threaded cylindrical-head screws was measured and the influence of added mass and the effect of adding a resilient interlayer was measured also. Assembly P, a two-way platform configuration was tested using partially threaded washer-head screws, shown during erection in Figure 3.

4 DYNAMIC ANALYSIS

The floor was tested using guidelines outlined in prEN 16929 [15] and the more comprehensive guidance on modal testing and analysis, described by Ewins [16] and Maia and Silva [17].

4.1 *Static point load deflection*

Studies have shown that the response parameter provided by a static point load deflection test provide good correlation to the vibrational serviceability of a timber floor [15]. The static point load deflection is determined by applying a concentrated dead load to the position on a floor where the largest deformations are expected and recording the deflection change.

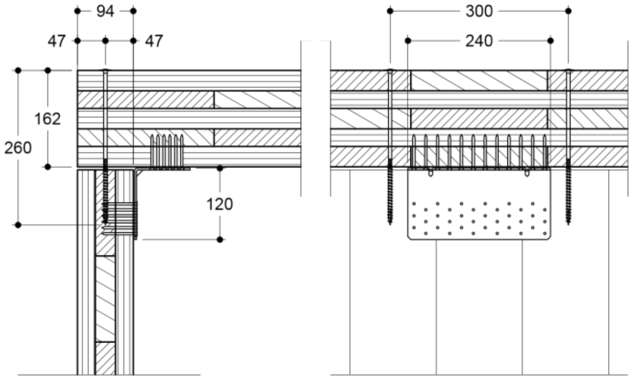

Figure 2. Assembly F, partially threaded vertical screws at 300 mm c/c with 240 x 93 x 120 mm brackets at 800 mm c/c

4.1.1 Applied load

The load was applied at midspan for each floor assembly, using an overhead crane. It consisted of ten 1 kg steel masses mounted on a 100 x 100 mm^2 load pad. The load was weighed to an accuracy of 0.1 %, with results normalized to a load of 1 kN.

Figure 3. Assembly P, erection of two-way span platform construction at NUI Galway

Table 1. One-way long span platform construction: Assemblies A–H and P

Assembly	Screw fixing	Bracket fixing	Added load	Resilient interlayer
A	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 150 mm c/c			
B	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 300 mm c/c			
C	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 300 mm c/c			•
D	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 300 mm c/c		•	
E	Ø 9 x 200 mm fully threaded cylindrical-head inclined screws @ 250 mm c/c			
F	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 300 mm c/c	240 x 93 120 mm angle brackets @ 800 mm c/c Ø 5 x 50 mm round-head screws 2 x 36 no. per bracket		
G	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 300 mm c/c	100 x 100 90 mm reinforced angle brackets @ 800 mm c/c Ø 5 x 50 mm round-head screws 2 x 7 no. per bracket		
H	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 300 mm c/c	100 x 100 90 mm reinforced angle brackets @ 200 mm c/c Ø 5 x 50 mm round-head screws 2 x 7 no. per bracket		
P	Ø 8 x 260 mm partially threaded washer-head vertical screws @ 300 mm c/c			

4.1.2 Deflection measurement

Deflections were measured below the floor at midspan with a Mitutoyo MT2119S-10 dial gauge of range 5 mm, revolution 0.2 mm, and graduation 0.001 mm. The load was applied and the deflection change was recorded. Without changing the position of the load or the measurement device, the test was repeated three times. The differences between successive readings of each floor assembly was less than 5 %, and the time between successive readings was greater than 1 min. Two additional dial gauges of the same type were placed on each supporting wall to record any spread or sway as a result of the applied load. A deflection measurement test is shown in Figure 4.

Figure 4. Static point load deflection measurement, one-way long span platform construction at NUI Galway

4.2 Fundamental frequencies 0 - 80 Hz range

Before beginning the comparative dynamic modal measurement, initial calculations were made to predict the likely frequencies and the number of mode shapes in the range of interest. An estimation of the first natural frequency of the floor simply supported was calculated using the effective bending stiffness from the gamma method, EC-5 [2] and finite element models with pinned and fully fixed support boundary conditions were developed. Additionally, diagnostic impulse measurements were taken to confirm qualitatively the fundamental frequency predictions.

4.2.1 Apparatus

The modal frequencies were measured using the following apparatus:

- Tektronix AFG 1000 signal generator, Sine waveform range: 1 μHz–60 MHz
- Electrodynamic shaker TIRA S 51125-IN, frequency range: 2-2 kHz
- Amplifier TIRA BAA 500
- Cooling blower TIRA TB 0080
- DAQ NI USB-6009
- 1 no. LIVM accelerometer, Dytran model 3055B2, sensitivity 104.34 mV/g
- 2 no. LIVM accelerometers, Dytran model 3100D24, sensitivity's 1002.27 mV/g and 1026.97 mV/g with relative transverse sensitivity less than 3 %, frequency range 0.6-1 kHz, and nonlinearity of ± 1 dB

The signal was recorded and analysed using NI LabVIEW 2014 software.

4.2.2 Modal measurement and analysis

A single excitation was provided by an electrodynamic shaker and roving response transducers measured the response of the floor panel. To characterise the full shape of each of the modes, the transducer locations were predetermined on a grid of 64 measurement points, illustrated in Figure 5.

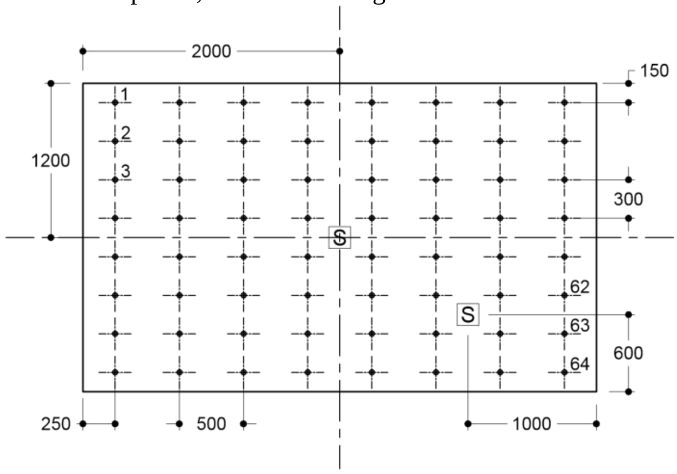

Figure 5. Transducer locations: 500 x 300 mm grid of 64 measurement points. Two alternative shaker locations, midspan and quarter-span

The force input measurement and roving response transducers comprised of three accelerometers. To measure the input force, a LIVM 100mV/g accelerometer was attached to the top of the electrodynamic shaker. A signal generator supplied a burst swept sine signal to the shaker and two single-input, single-output (SISO) measurements were taken simultaneously, with two LIVM 1000 mV/g accelerometers measuring the vibration response. The response transducers measured the response, starting at transverse corners of the floor (points 1 and 64), then moving systematically to the next adjacent points (2 and 63), repeating the test to record two more modal measurements and so on until each response accelerometer had recorded 32 locations on the grid, half the floor panel. An analog-to-digital converter, with a sample rate of 512 Hz, converted the signals to digital which were recorded and processed using NI LabVIEW 2014 software. The discrete Fourier transforms gave the FRF. The final measurements were the result of averaging several samples. The coherence function was monitored as a check on the reliability of the data measured. Measurements were repeated and recorded three times. The maximum deflection of the first and fourth modes were found at the floors midspan, hence the shaker was fixed to the floor panel at this point. However this location coincided with a node of the second, third, and fifth mode, so when the 64 response points were recorded, the shaker was moved and fixed to an alternative location that did not coincide with a modal node and the measurements were repeated. The mode shapes were extracted from the data using the Quadrature Response method. The shaker positions, marked S, are shown in Figure 5.

5 RESULTS AND DISCUSSION

The results for the static point load measurements and dynamic modal analysis are presented in Table 2.

5.1 *Static point load deflection*

Comparing assembly B, which comprised vertical partially-threaded screws at 300 mm spacing with the same configuration adding alternate angle brackets at 800 mm spacing, assemblies G and F, had no sizeable influence on the deflection results, however increasing the number brackets to 200 mm spacing, assembly H, reduced the CLT floor panel deflection by 11%. Increasing the vertical screw spacing two-fold, assembly A, using an alternative configuration of inclined fully threaded cylindrical-head screws, assembly E, or adding mass, assembly D, did not significantly influence the deflection results. Comparing a single spanning floor with a two-way spanning floor, the deflection was reduced by 45%. Introducing a resilient interlayer, assembly C, increased the deflection of the floor panel from 0.178 mm to 0.185 mm. Measurements of sway due to the applied load in either supporting wall were negligible. Figure 6 presents the deflection test results.

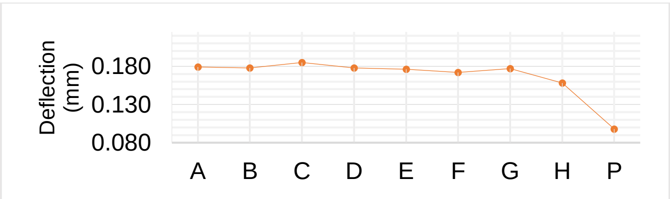

Figure 6. Deflection results Assemblies A-H and P

5.2 *Fundamental frequencies 0 - 80 Hz range*

Four natural modes were found for all single span floor configurations within 0–80 Hz range, with an additional mode for assembly D which had added mass. Modes 1–5 are illustrated in Figure 9. The two-way spanning floor had only one frequency in the range of interest, its corresponding mode shape is shown in Figure 10. A comparison of all frequencies are outlined in Figure 7. Figure 8 compares the influence of adding mass, or a resilient interlayer, assembly C. Added mass reduced the fundamental frequency by over 25%. Two-way support of the floor resulted in an increase of fundamental frequency by over 90%. The spacing of the self-tapping screws had a slight positive influence on the fundamental frequency. Angle support brackets at 200 mm spacing increased the fundamental frequency by over 6%.

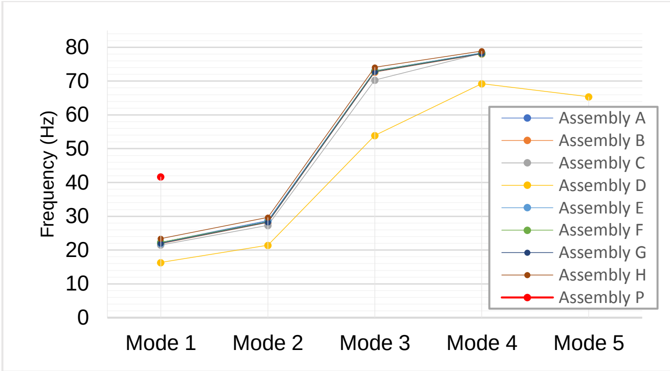

Figure 7. Assemblies A-H and P frequency modes 0-80 Hz

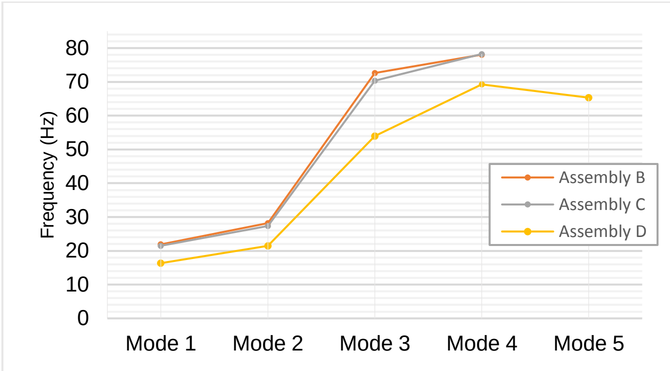

Figure 8. Assemblies B, C, and D frequency modes 0-80 Hz

6 CONCLUSIONS

The addition of support brackets, if closely spaced can have a positive influence on the static point load deflection and fundamental frequencies. Increasing screw fixings improved fundamental frequency results marginally. Adding mass was shown not to influence the deflection of the CLT floor, but reduced the fundamental frequencies to a significant degree. Future work will include alternative floor to wall orientations of CLT construction, considering also the influence of the fixings on damping and acceleration amplification.

Table 2. Fundamental frequencies 0-80 Hz range and static deflection results for floor to wall assemblies A-H and P

Assembly	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Deflection (mm)	Added load	Resilient interlayer
A	22.35	28.75	73.10	78.35	-	0.179		
B	21.90	28.20	72.65	78.05	-	0.178		
C	21.50	27.30	70.35	78.25	-	0.185		•
D	16.35	21.45	54.05	69.25	65.35	0.178	•	
E	22.05	28.55	73.10	78.35	-	0.176		
F	22.30	28.35	72.95	78.20	-	0.172		
G	22.00	28.25	72.75	78.15	-	0.177		
H	23.40	29.70	74.10	78.90	-	0.158		
P	41.65	-	-	-	-	0.098		

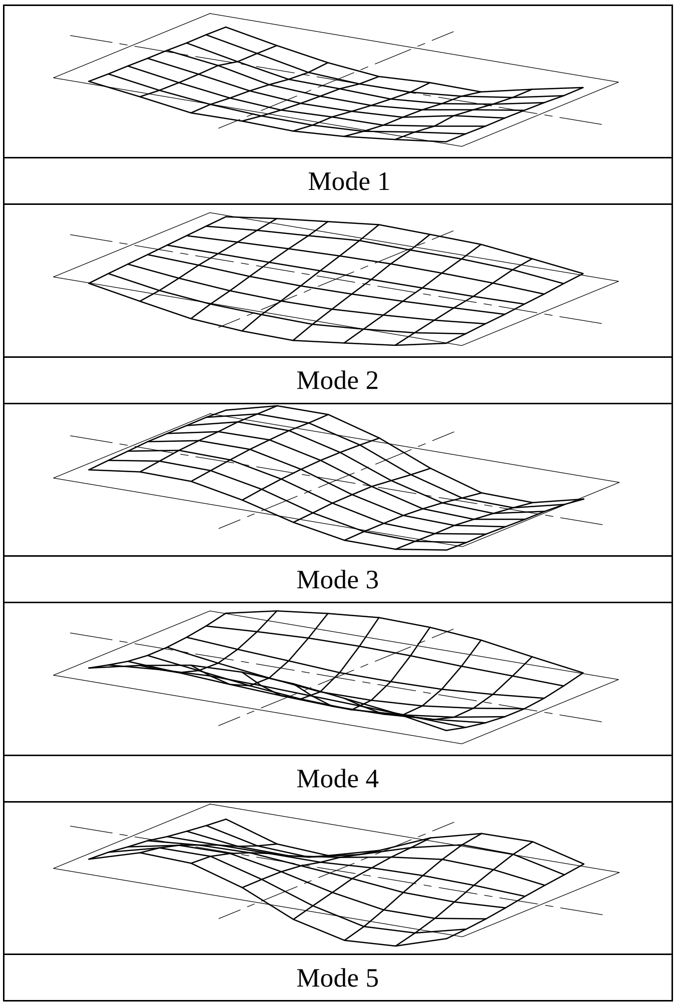

Figure 9. Typical mode shapes for assemblies A-H

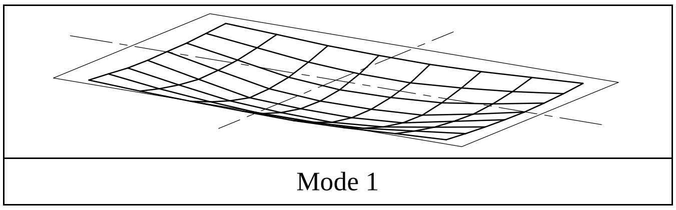

Figure 10. Assembly P mode shape

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