Vibration serviceability assessment of complex-shaped CLT floor

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Abstract. Cross-laminated timber (CLT) floors are typically an assembly of prefabricated panels connected together on the site. CLT offers a wide range of configuration possibilities, as it can be easily pre-cut into various shapes and sizes, making it suitable for use in different architectural design requirements. However, available CLT design guidelines do not apply to complex-shaped CLT floors, i.e. unconventional geometry of floor plans including concave polygons, arches and openings. This paper presents a numerical vibration analysis of such a floor with openings, which represents a standard floor structure for residential and commercial buildings. Influence of panel orientation and inter-panel connections on modal properties and vibration response induced by a single pedestrian walking is analysed and discussed.

1. Introduction

In line with the urgent need for sustainable civil engineering structures and controlled carbon emission from construction industry, there is a growing pressure on structural designers to use energy-efficient and eco-friendly materials. The emergence of cross-laminated timber (CLT) has a great potential to bring to an end decades-long dominance of concrete and composite floors, which significantly contribute globally to the embedded carbon footprint [1-3].

CLT is a multilayer composite made of solid thin wood boards glued together in a cross-wise manner. Besides being eco-friendly, CLT has remarkable stiffness, fire resistance and thermal and acoustic insulation properties [4-5]. The high stiffness-to-mass ratio makes CLT floors flexible, thus prone to vibrations induced by people walking. Consequently, vibration serviceability assessment often governs their design [6-9]. Currently, the design of CLT floors follows the guidelines provided by national annexes of Eurocode 5 [10], their improvements [11], as well as various handbooks [12-13]. Their common objective is to avoid resonant vibrations induced by a pedestrian walking by increasing the fundamental frequency of a floor above 8Hz. This frequency limit results from an outdated and false assumption that walking excitation does not possess enough energy to cause resonant response above 8Hz [14]. Consequently, thicker slabs are designed, leading to wastage of material, which goes against sustainable civil engineering principles.

Typically, CLT panels are manufactured in a rectangular shape, while CLT floors are constructed by assembling prefabricated panels on-site using connections that transfer in-plane shear forces and bending moments. As the panels can easily be cut into various shapes and sizes, the assembled floors can meet well more or less complex architectural layouts [15]. In the case of simple floor geometry, establishing the layouts of CLT panels is straightforward. The panel's outer layers' direction defines the panel orientation and is usually placed to cross the shorter span. When faced with a complex floor

geometry, evaluating several different panel configurations and connection locations may be necessary to identify an optimal layout.

The guidelines mentioned address only rectangular plates featuring common boundary conditions, such as simply supported at two opposite edges (SFSF) or simply supported at all four edges (SSSS). In addition, neither of them takes into account the inter-panel connections in vibration serviceability assessment. A multi-panel floor is treated either as a monolith slab or without any inter-panel connections, leading to an error in estimating both floor's modal properties and vibration response [16].

This paper presents a numerical study on the influence of the connections and panel orientation on vibration modes of a complex-shape CLT floor and its response induced by a single pedestrian walking. The analysis was carried out for the corresponding monolith floors, i.e. as if composed of a single panel, for comparison. As different connection types yield similar modal properties and vibration response [16], only single surface spline connection is presented in this study.

2. Numerical analysis

Analysed complex-shaped floor with openings (Figure 1a) is an example of a CLT floor in residential and commercial buildings [17]. The floor's cross-section is composed of five layers of timber class C24, with a total thickness of 160mm (Figure 1b).

With a similar span length in both *x* and *y* directions, the floor can be assembled with panels in either *x* or *y* direction. This creates two distinct configurations. If oriented in *x* direction (*x*-oriented floor), the floor comprises of two connected panels (Figure 1c). If oriented in *y* direction (*y*-oriented floor), the floor is composed of three interconnected panels (Figure 1d).

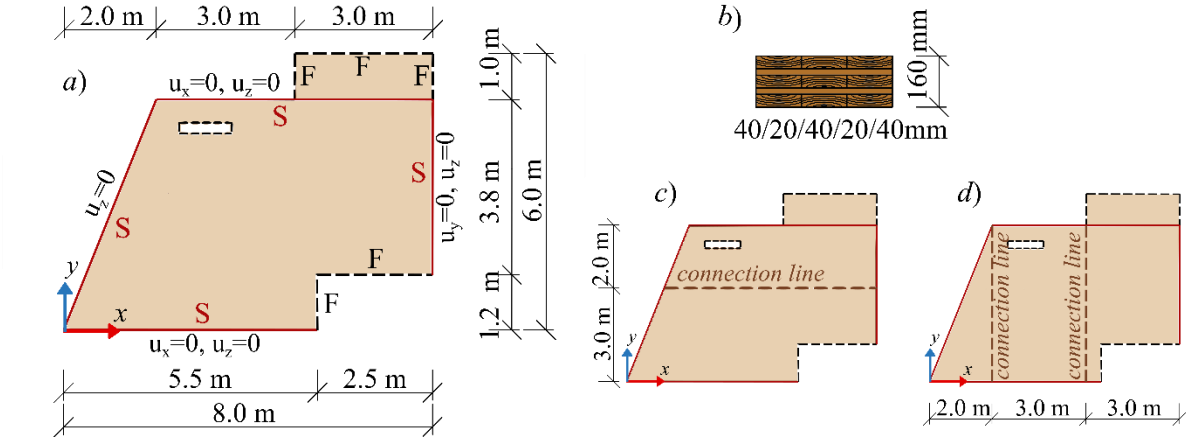

Figure 1. Analysed complex-shape CLT floor structure (a) floor layout with boundary conditions, (b) floor cross-section, (c) floor configuration with panels oriented in *x*, and (d) *y* direction.

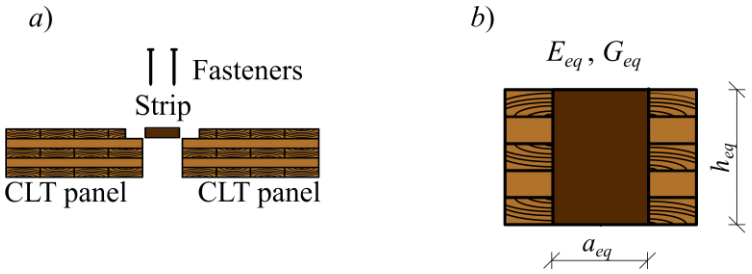

Figure 2. a) Single surface spline connection; b) equivalent elastic strip.

Single surface spline connection (Figure 2a) was simplified and modelled using a 2D homogeneous elastic strip that is connected rigidly to the adjacent panels, as illustrated in Figure 2b. The elastic strip's mechanical and geometric properties were adjusted to match the actual connection's shear and rotational

stiffness [18]. The elastic strip's height h_{eq} was set equal to the height of the CLT panels, while the strip's width a_{eq} was fixed at 100mm. Consequently, the resulting elastic strip properties were E_{eq} = 2.96 MPa and G_{eq} = 10 MPa. For more information about the connection modelling and their influence on the vibration levels of CLT floors, a reader is directed to the recent publication by Milojevic et al. [16].

The following two subsections illustrate results of the modal analysis and the response under pedestrian-induced loading for different configurations of considered complex-shaped CLT floors.

2.1. Modal properties of complex-shaped CLT floor

Natural frequencies, modal masses and mode shapes were exported from FE models developed in Abaqus CAE [19]. The multilayer CLT panels were modelled using S4R finite elements, while each layer was modelled as a C24 unidirectional lamina with the material properties listed in Table 1. The mesh size was 0.1 m. In all examples the additional mass of non-structural elements was 20 kg/m^2, uniformly distributed over the top surface of the CLT floor. The simply supported boundary conditions were assigned to the red marked edges by constraining displacements according to the Figure 1a. The edges drawn with dashed line remained free (F).

Table 1. Mechanical properties of C24 timber class lumber used in the CLT panels.

E_L	$E_T = E_R$	$G_{LT} = G_{LR}$	G_{RT}	ν_{LT}	ν_{LR}	ν_{RT}	ρ
11000 MPa	370 MPa	690 MPa	50 MPa	0.49	0.39	0.64	420 kg/m^3

Modal properties for all modes up to 30 Hz are listed in Tables 2 and 3. The corresponding mode shapes are illustrated in Figures 3 and 4.

Table 2. Modal characteristics of complex-shaped CLT floor with panels oriented in x direction.

Mode	Monolith slab		Single surface spline	
	Frequency [Hz]	Modal mass [kg]	Frequency [Hz]	Modal mass [kg]
1	8.68	773.42	7.61	594.18
2	18.78	233.64	17.10	559.41
3	24.43	325.65	23.05	145.42
4	25.39	193.40	24.75	421.60

Table 3. Modal characteristics of complex-shaped CLT floor with panels oriented in y direction.

Mode	Monolith slab		Single surface spline	
	Frequency [Hz]	Modal mass [kg]	Frequency [Hz]	Modal mass [kg]
1	11.75	520.93	10.78	540.97
2	15.72	608.92	14.06	481.53
3	26.03	419.51	19.91	365.02
4	> 30	/	29.60	459.53

The monolith floor whose outer fibers were oriented in *x* direction resulted in a smaller fundamental frequency than the monolith floor whose outer fibers were oriented in *y* direction. This was expected, as the span in the *x* direction is longer, resulting in a more flexible floor. Due to this difference, the two floors were categorised into two distinct types [20]. With a fundamental frequency below 10.5 Hz, *x*-oriented floor was classified as a "low-frequency floor" (LFF). Conversely, *y*-oriented floor was considered a "high-frequency floor" (HFF). Furthermore, the change from *x* to *y* direction caused the first mode shape amplitude to shift from the center to the opening. In the second mode, both monolith floors exhibited two half-sine waves that were oriented in the minor direction of the floor. For the higher modes, there is an apparent mismatch between the mode shapes.

Both floor configurations resulted in lower natural frequencies when the inter-panel connections were modelled. This is because the connections reduced the stiffness of the floors. The *x*-oriented floor exhibited a more significant difference in the fundamental mode, with a 12.5% decrease in the

fundamental frequency compared to the corresponding monolith floor. The *y*-oriented floor, on the other hand, resulted in a difference of approximately 10% for the fundamental mode. With a fundamental frequency of 10.78Hz, this floor is now really close to the cut-off frequency of 10.5Hz. However, it was considered HFF strictly following the instructions in [20]. For both *x* and *y*-oriented floors, one connection line lies near the second mode's half-sine amplitude, resulting in about 10% drop in the corresponding natural frequencies. However, the most significant difference of 23.5% was observed between the third frequency of monolith and multi-panel *y*-oriented floor. In this case, both connection lines coincided with the amplitude of the half-sine waves, which means that the rotational stiffness of both equivalent strips was fully engaged.

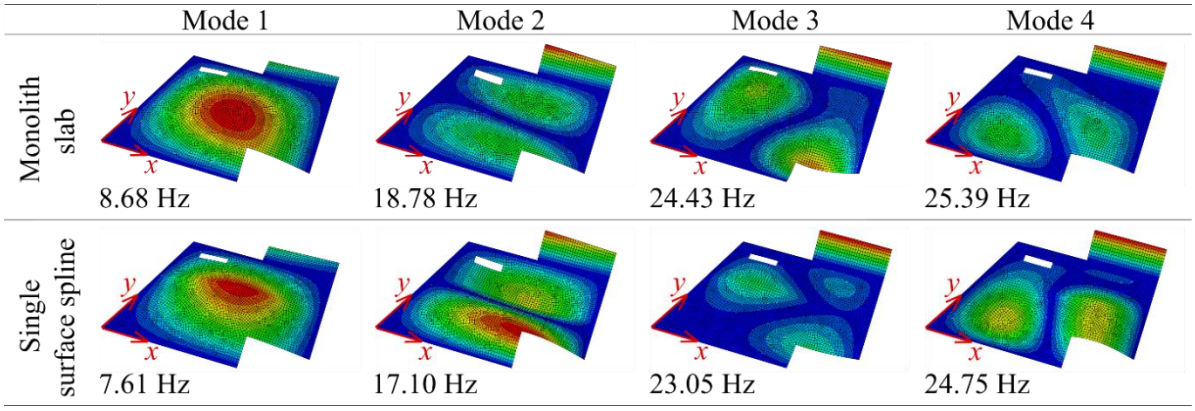

Figure 3. Modal characteristics of complex-shaped CLT floor oriented in x-direction.

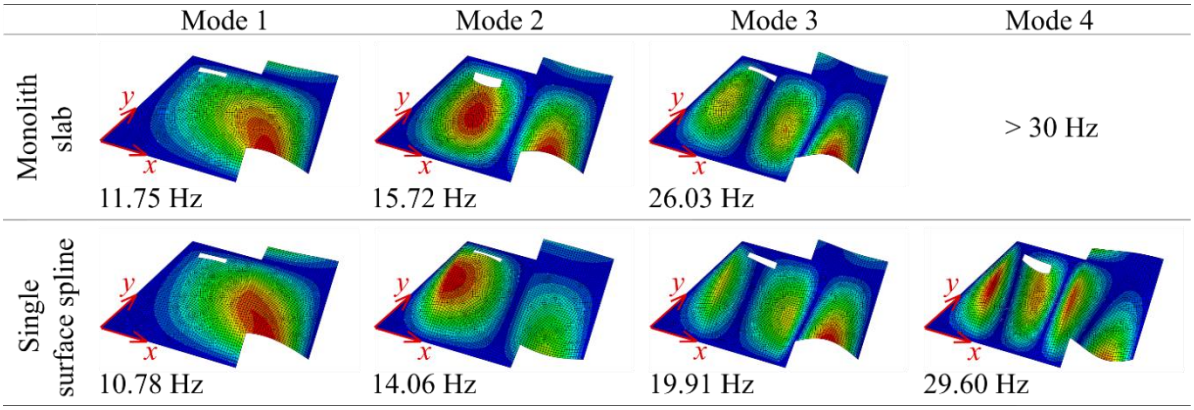

Figure 4. Modal characteristics of complex-shaped CLT floor oriented in y-direction.

2.2. Vibration response under pedestrian-induced loading

Modal properties of all considered floors were used in conjunction with Arup's footfall models for LFFs and HFFs [20] to calculate vibration responses induced by a single pedestrian walking. Two straight walking paths (WPs) showed in Figure 5 were studied in vibration simulations. For an adopted step length of 0.5m, a pedestrian needs ten steps to cross the floor along WP1 and fourteen steps along WP2. Considering that the lengths of the WPs are rather short, 5m (WP1) and 7m (WP2), a shorter step length than the average of 0.75m was chosen. This provides pedestrian with more time to cross the floor and increases chances of reaching the maximum resonant vibration amplitude.Walking frequencies were selected to induce resonance of the first vibration mode of *x*-oriented floors with the fourth harmonic of walking. Hence, for the monolith floor the walking frequency was 2.17 Hz, while for the multi-panel floor the walking frequency was 1.903 Hz. The walking frequency for *y*-oriented floors were assumed 2.35 Hz for the monolith and 2.156 Hz for the multi-panel floor. Although resonance is out of the

question in the case of HFFs, these frequencies are exactly five times lower than the corresponding fundamental frequencies of the floor.

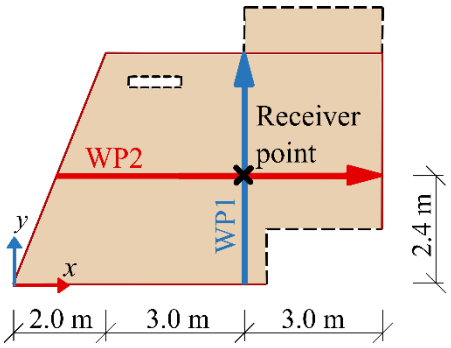

Figure 5. Walking paths and receiver point.

Peak acceleration at the selected vibration receiver point (marked **x** in Figure 5) are summarised in Table 4. A more flexible *x*-oriented monolith floor resulted in over 50% higher peak acceleration than *y*-oriented floor for both WPs. Multi-panel *x*-oriented floors showed a lower response than corresponding monolith floor. This is due to the shift of the highest amplitudes of its fundamental mode shape towards the connection line, which is further away from the WP2 and the position of the vibration receiver. On the contrary, WP1 was located near the half-sine amplitudes of the first and the third mode of multi-panel *y*-oriented floor, amplifying its impact on the floor's response. This resulted in peak acceleration values that were, on average, 60% higher than those of the corresponding monolithic floor. In addition, these values were 8% and 17% higher than the multi-panel *x*-oriented floor for WP1 and WP2, respectively.

Table 4. Results of the performed vibration analysis in terms of the peak acceleration.

Scenario		Walking path 1	Walking path 2
		a_{peak} [m/s^2]	a_{peak} [m/s^2]
x-oriented floor	Monolith	0.963	1.015
	Single surface spline	0.950	0.915
y-oriented floor	Monolith	0.616	0.662
	Single surface spline	1.028	1.069

3. Conclusions

Reselience of CLT panels has made possible a range of floor layouts but requires careful consideration of panel arrangement and orientations. Numerical simulations of the complex-shaped CLT floors presented in this paper showed that changing the panel orientation led to significant differences between their fundamental frequencies. Moreover, it may affect classification of the floor to LFF and HFF, yielding potentially huge errors in vibration serviceability assessment due to pedestrian loading.

The current codes and design guidelines treat multi-panel CLT floors as monolith slabs or independent panels. The present study showed that this leads to notable errors in estimated modal properties and vibration responses. The differences in natural frequencies were the biggest for modes whose amplitudes coincide with the connection line. The connections significantly impacted the vibration response of HFF, resulting in a 60% higher peak acceleration than the corresponding monolith floor. However, placing the connection line away from the walking path and recipient point position may positively influence the vibration response of floors. Hence, they should be diverted from walking paths by a clever arrangement of structural and non-structural elements.

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