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IMPACT OF INTER-PANEL CONNECTIONS ON VIBRATIONS OF CLT FLOORS

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ABSTRACT: Cross-laminated timber (CLT) floors are typically composed of multiple CLT panels. At design stage, such floors are usually modelled numerically either as a single solid slab or more frequently as a set of independent panels with no inter-panel connections. This paper aims to demonstrate numerically a significant effect of two common inter-panel connections, i.e. single surface spline and half-lapped joint, on vibration modes of CLT floors composed of two and three panels. The connections are modelled as an equivalent 2D elastic strip nested inbetween the CLT panels. This relatively simple yet robust numerical model can be used conveniently in design offices, regardless finite element (FE) software. The matching monolithic slabs and floors without the inter-panel connections are studied for comparison. The results showed that the difference is far too big to ignore.

KEYWORDS: vibration serviceability assessment, modal properties, low-frequency floor, high-frequency floor

1 – INTRODUCTION

Design of lightweight long-span building floors has increasingly been governed by vibration criteria, and CLT floors are no exception [1]. Having a high stiffness-to-mass ratio, CLT floors have increasingly been prone to pedestrian-induced vibrations causing serviceability issues, such as discomfort and frustration to floor occupants.

In Europe, design of CLT structural elements is guided by national annexes of the Eurocode 5 [2]. Regarding vibration serviceability assessment (VSA), Eurocode 5 limits the fundamental frequency of a floor to 8 Hz to prevent resonant walking-induced vibrations. This frequency limit has origins in a false assumption that walking loading above 8Hz has no energy to cause the resonant vibration response [3]. More recent studies suggest the frequency limit as high as 14 Hz [4]. Anyway, the cut-off frequency is just a formal treshold for floor classification to so-called “low-frequency floors” (LFF) and “high-frequency floors” (HFF). The former can exibit resonant build up due to walking loading, while the latter is typically a series of brief transient responses due to each footfall [3], [4]. Hystorically, the need to distinguish between LFFs and HFFs has been due to the total lack of walking force models that can describe its full amplitude spectrum of the actual walking loading [5]. Therefore, LFFs and HFFs feature two fundamentally different mathematical descriptions of the walking loading [6], [7]. In case of LFFs, it is portrayed as a Fourier series, while in case of HFFs the same excitation takes a form of so called “effective impulses”.

2 – BACKGROUND

A reliable VSA depends significantly on a reliable estimation of the floor modal properties. There are analytical solutions for rectangular floors with basic boundary conditions. However, modal properties of a more complex floor shape and structure are normally extracted from their numerical models, typically based on the finite element method (FEM). Moreover, in case of CLT floors the FEM feature the equivalent single layer (ESL) laminate theories [8].

CLT floors are composed of multiple panels connected together on-site using fasteners and self-tapping screws [9]. However, to simplify the FEM development, CLT floors are commonly modelled as “piano keyboards”, i.e. a set of independent adjacent panels spanning across the shorter edges. Recent studies found this modelling approach overly

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conservative, leading to significant errors in simulated vibration response [10].

3 – PROJECT DESCRIPTION

The focus of the study is twofold. First, a numerical modal analysis of rectangular two-panel CLT floors with different combinations of free (F) and simply supported (S) boundary conditions around the four edges. Second, simulations of their vibration response due to people walking.

Four connection types between the panels were studied: (i) rigid (monolithic) slab, (ii) absence of connections, (iii) single surface spline (Fig.1a) and (iv) half-lapped joint (Fig.1b). Natural frequencies, modal masses, modal stiffnesses and mode shapes were exported from FE models of the floors developed in Abaqus CAE [11].

Pedestrian-induced vibration response of both LFFs and HFFs is studied using the principles of widely popular CCIP-16 design guideline [12], which is an integral part of the latest American Mass Timber design guide [13] and will enter the new generation of Eurocode 5.

4 – NUMERICAL MODELLING AND SIMULATIONS

Although inter-panel connections are complex (Fig.1), in this study they are modelled using a simple equivalent two-dimensional (2D) homogeneous elastic strip that is linked rigidly to the neighboring panels (Fig. 2).

The geometric and mechanical properties of the elastic strip are determined to match the shear and rotational stiffnesses of the actual connection, as elaborated in Milojevic et al. [10]. For both connection types, the height of the strip h_{eq} is set equal to the height of the actual CLT panels, while the adopted width of the elastic strip is a_{eq} = 90mm [10].

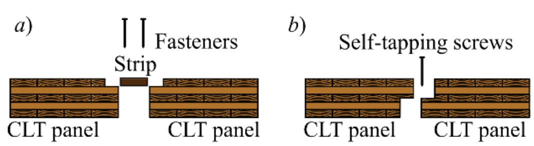

Figure 1. Two types of CLT inter-panel connections: a) single surface spline; b) half-lapped joint.

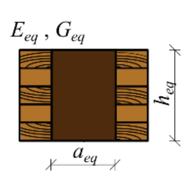

Figure 2. Equivalent elastic strip.

The resulting elastic strip properties are:

- for the single surface spline: E_{eq}=2.96 MPa, G_{eq}=10 MPa,
- for the half-lapped joint: E_{eq}=G_{eq}=4.105 MPa.

Although the model is suitable for both 2D and 3D FE modelling, focus of the present study is on 2D rectangular floors only.

In CCIP-16, the cut-off frequency between the LFFs and HFFs is 10.5 Hz. The walking force model pertinent to LFFs is a sum of four harmonics described by a Fourier series. The frequency of each harmonic is an integer multiple (i.e. 1-4) of the selected walking frequency (also called footfall rate) in the range 1.5-2.5Hz. The worst-case vibration response is the resonance with one force harmonic. On the other hand, walking loading for HFFs is a series of vertical impulses corresponding to each footfall. Vibration response between two successive footfalls has a transient character and dies out quickly due to typically large damping of HFFs. For more information about these and other available force models, the reader should refer to [6], [14].

Based on the modal superposition method [15], CCIP-16 provides the estimates of the peak and RMS vibration responses. In case of LFFs, vibration modes up to 15 Hz should be considered. There are examples of studies on pedestrian-induced vibrations of CLT floors, such as Weckendorf et al. [16] and Ussher et al. [17], [18] where the adopted limit is as high as 100 Hz. However, the energy content at such a high frequency has never been found, even in the walking force signals recorded using state-of-the-art medical equipment [4]–[7], [14], [19]. The present study sticks to the CCIP-16 recommendation but reports all modes up to 30 Hz for a closer comparison between floor models. In the case of HFFs and according to CCIP-16, all modes with frequencies less than twice the fundamental frequency were taken into account.

LFF example is a 5-layer square CLT floor with thickness h = 5x4cm = 20cm, composed of two 3x6m panels connected in various way explained in Section 3 and illustrated in Fig. 3. Similarly, HFF floor model is composed of two 4x2m CLT panels of the same thickness, as illustrated in Fig. 4.

The floor vibrations are studied for two different combinations of boundary conditions: (i) one-way simply supported along the shorter edges of the panels but free along the longer edges (SFSF) and (ii) simply supported along all four edges (SSSS). Moreover, there are two walking paths (WP) of interest - parallel (WP1) and perpendicular (WP2) to the inter-panel connection.

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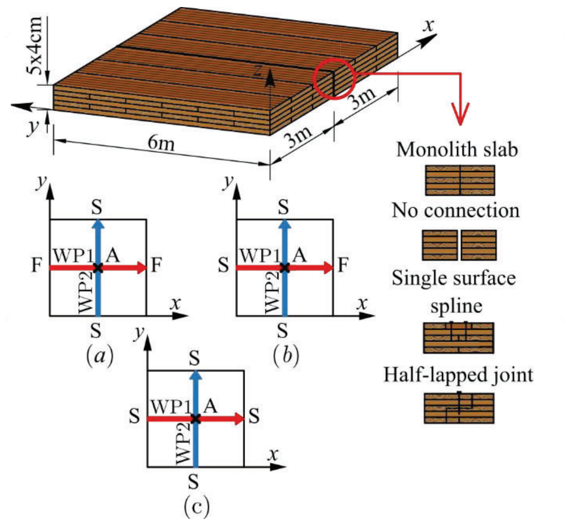

Figure 3. Low frequency floor (LFF).

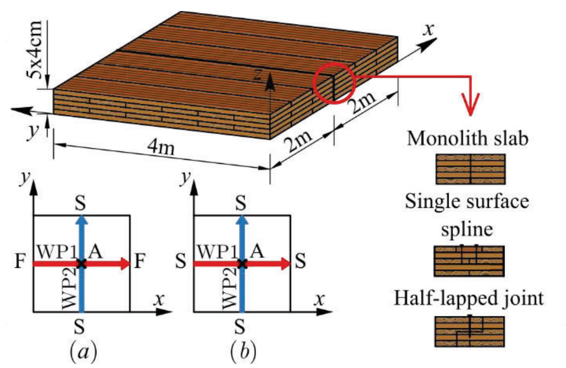

Figure 4. High frequency floor (HFF).

5 – RESULTS

This section summarises the results of the modal analysis and vibration simulations due to people walking.

5.1 LOW FREQUENCY FLOOR

Mode shapes and natural frequencies for the two sets of boundary condions are shown in Figs. 5 and 6. All mode shapes are arranged according to different number of half-sine ways in the two main diresctions. The monolith floor is selected as a benchmark for comparison, so its natural frequencies are arranged in the increasing order. Note that this is not the case for other connection types.

In case of no connection, the corresponding modes clearly stand out from the rest. Each panel is an independent (local) floor with its own modal properties.

There is little difference for modes that do not flex along the connection line. On the other hand, in modes where the panels flex around the inter-panel connection, the difference gets higher as the mode order increases.

This indicates that the rotational stiffness of the connection is a key modelling parameter [9].

The floors composed of two connected panels show very close results and consistently lower natural frequencies than the corresponding monolith plate. Moreover, there are almost no differences between the modal properties of the floors with the single surface spline and half-lapped joint connections, for the majority of the modes.

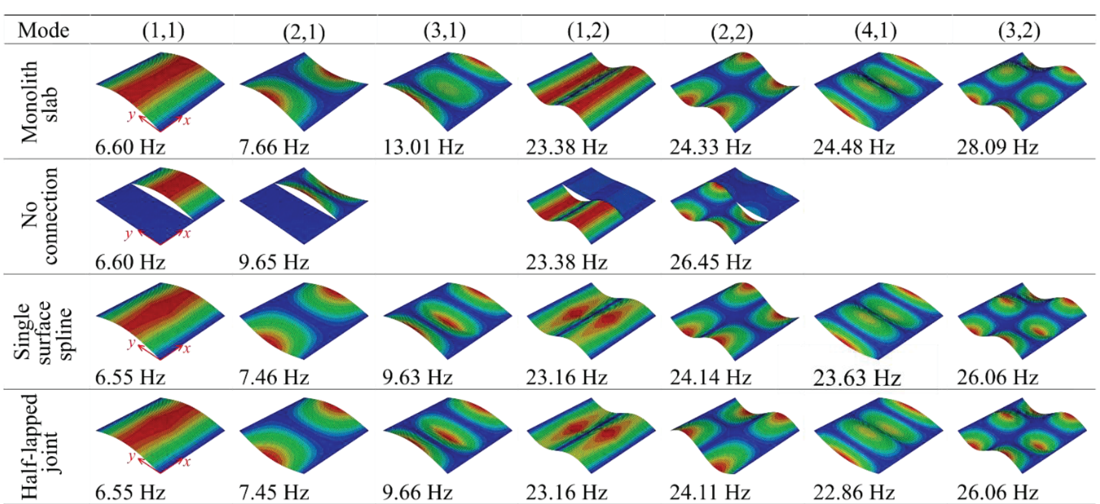

Figure 5. Modal properties of SFSF floor with different inter-panel connections.

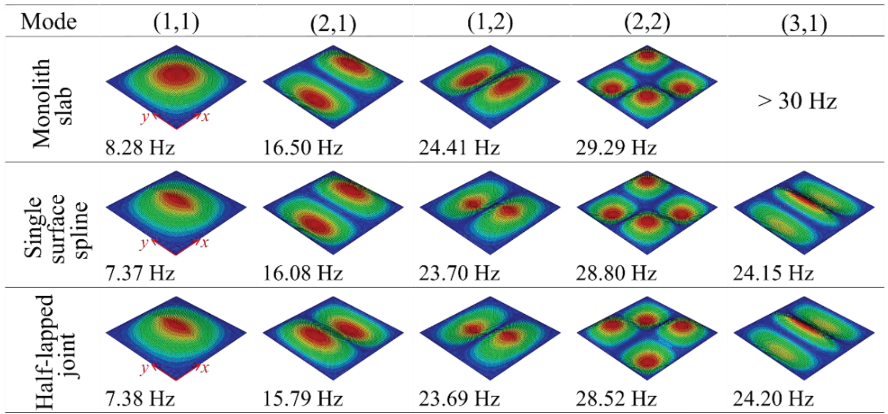

Figure 6. Modal properties of SSSS floor with different inter-panel connections.

Modal properties for all connection cases are utilised in conjunction with a bespoke code in Python [20] to simulate the corresponding vibration responses due to a single pedestrian walking. Assumed damping ratios are 2.5 and 3.5% for SFSF and SSSS floor, respectively [21]. Walking frequency was selected to induce resonance of the first vibration mode with the third harmonic of walking. As the steady state of the resonant response cannot be always achieved due to short walking paths, the running (i.e. moving average) 1s-RMS trend for the acceleration of LFFs and the velocity of HFF are calculated in conjunction to the achieved peak acceleration response. The results are summarised in Tables 1 and 2.

Table 1: Peak acceleration and maximal value of moving average of SFSF floor with different inter-panel connections.

Scenario	**Walking path 1**		**Walking path 2**	
	a_{peak} $[m/s^2]$	$a_{RMS,max}$ $[m/s^2]$	a_{peak} $[m/s^2]$	$a_{RMS,max}$ $[m/s^2]$
Monolith slab	0.302	0.178	0.237	0.143
No connection	0.662 (+119%)	0.321 (+80%)	0.632 (+167%)	0.348 (+143%)
Single surf. spline	0.390 (+29%)	0.197 (+11%)	0.314 (+32%)	0.178 (+24%)
Half-lapped joint	0.389 (+29%)	0.196 (+10%)	0.307 (+30%)	0.176 (+23%)

Table 2: Peak acceleration and maximal value of moving average of SSSS floor with different inter-panel connections.

Scenario	**Walking path 1**		**Walking path 2**	
	a_{peak} $[m/s^2]$	$a_{RMS,max}$ $[m/s^2]$	a_{peak} $[m/s^2]$	$a_{RMS,max}$ $[m/s^2]$
Monolith slab	0.342	0.218	0.344	0.212
Single surf. spline	0.394 (+15%)	0.242 (+11%)	0.445 (+29%)	0.274 (+29%)
Half-lapped joint	0.394 (+15%)	0.242 (+11%)	0.444 (+29%)	0.274 (+29%)

5.2 HIGH FREQUENCY FLOOR

A nominal analysis to HFFs is carried out here, too. Mode shapes and the corresponding natural frequencies of the HFFs are illustrated in Figs. 7 and 8. As in the case of LFF, notable differences are present in modes that flex and rotate most around the connection line.

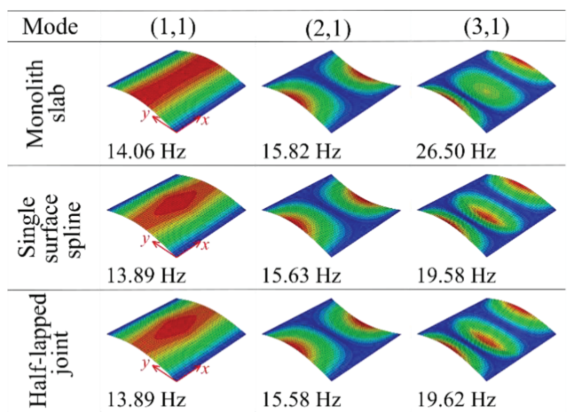

Figure 7. Modal properties of SFSF floor with different inter-panel connections.

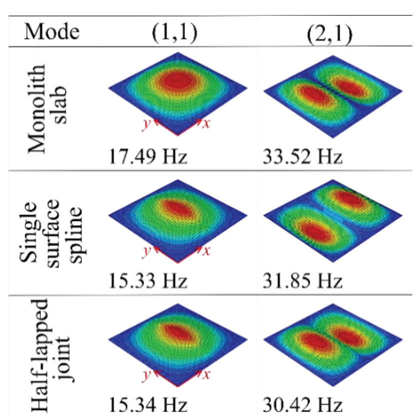

Figure 8. Modal properties of SSSS floor with different inter-panel connections.

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Walking paths (Fig. 4) are shorter than in the case of LFFs (Fig. 3). Assuming a step length of 0.75 m, it takes five successive steps to cross the floor. A damping ratios of 2.5% and 3.5% were adopted for SFSF and SSSS floor, respectively, according to the literature [21].

Velocity rather than acceleration is most frequently used vibration response to assess serviceability of HFFs. Tables 3 and 4 summarise the results simulated at point A (Fig. 4).

Table 3: Peak velocity and maximal value of moving average of SFSF floor with different inter-panel connections.

Scenario	Walking path 1		Walking path 2	
	v_{peak} [cm/s]	$v_{RMS,max}$ [cm/s^2]	v_{peak} [cm/s]	$v_{RMS,max}$ [cm/s^2]
Monolith slab	0.511	0.175	0.496	0.159
Single surf. spline	0.760 (+38%)	0.233 (+33%)	0.865 (+74%)	0.265 (+67%)
Half-lapped joint	0.761 (+38%)	0.233 (+33%)	0.876 (+77%)	0.267 (+68%)

Table 4: Peak velocity and maximal value of moving average of SSSS floor with different inter-panel connections.

Scenario	Walking path 1		Walking path 2	
	v_{peak} [cm/s]	$v_{RMS,max}$ [cm/s^2]	v_{peak} [cm/s]	$v_{RMS,max}$ [cm/s^2]
Monolith slab	0.489	0.183	0.489	0.183
Single surf. spline	0.767 (+57%)	0.302 (+65%)	0.859 (+76%)	0.339 (+85%)
Half-lapped joint	0.769 (+57%)	0.302 (+65%)	0.859 (+76%)	0.339 (+85%)

6 – CONCLUSIONS

Contemporary design codes and guidelines perceive CLT floors either as monolithic slabs or as "piano keyboards", i.e. a set of panels with no connections. Numerical models of CLT floors studied in this paper showed that the inter-panel connections are indispensible in the modal analysis. In case of no connections, each panel behaves dynamically as an individual floor. Hence, the results are not comparable to the cases with connections. Ideally, the connections would mean a rigid link between the panels, making no difference between a multi-panel floor and its monolith counterpart. In reality, the connections have a degree of flexibility, so some differences in modal properties are naturally expected.

Two commonly used inter-panel connections, i.e. single surface spline and half-lapped joint, were modelled based on the analogy with the equivalent elastic strip. The strip properties were calculated to match the rotational and shear stiffnesses of the actual connections. Based on the observation of mode shapes and comparisons between the natural frequencies of floors modelled as monolithic slabs and panels with connections, it could be concluded that the differences are the biggest for modes in which the modal coordinates are the largest along the connection line. This is when the connection line moves dominantly with respect to the rest of the floor. Moreover, such a comparison suggest that the modal properties are more sensitive to the rotational stiffness of the connection than to the bending stiffness. Changing boundary conditions also made a difference. Adding supports parallel to the panel orientation resulted in mode shapes flexing also perpendicularly to the connection line (the minor direction). The connections affect significantly mode shapes and the bending stiffness of the floor in the minor direction when they coincide with the peak of the mode shape.

The models of floors with single surface spline and half-lapped joint produce nearly the same modal properties. A logical extension of the presented study should include a comparative analysis between the modal properties of floors with various models of the interpanel connections, once these models have been made readily available in the academic literature.

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