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Poster C09

Simplified finite element model for natural frequencies estimation of CLT-concrete composite beams using notched connectors

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Context and objective

Cross-laminated timber (CLT) is an engineered wood product made of multiple glued layers to form a panel. Each layer of the CLT is oriented perpendicular to the adjacent one. This type of structural element is widely used recently and notably suitable for the floor system. Recently, large residential building design demands timber floor systems with long spans (from 8 to 10 m). A conventional CLT floor usually has a maximum clear span of about 6-7 m. From medium to long-span floor systems, the vibrational condition is commonly the factor that controls the design. The solution is adding a concrete layer with the composite action between timber and concrete, increasing the floor stiffness. However, for the CLT-concrete composite (CCC) structure, the concrete slab usually does not collaborate with the CLT layer as a composite structure. The reasons are the high cost of the composite connector and lack of knowledge about the impact of the composite effect on CCC floors vibrational performance.

This study proposes a simplified unidimensional model to estimate the natural frequencies of CCC beams using notched connectors. Three CCC beams were subjected to vibration tests to determine their natural frequencies and modal damping. Experimental results were then compared to numerical results from the FE and analytical models.

Experimental approach

Specimens: The CLT has grade E1 complying with the standard PRG-320 (2019). The local supplier provided the concrete material with the indicated class of C35. The compression test conducted on the cylinder specimens yielded a mean compression strength f_c of 36.8 MPa and a mean modulus of elasticity E_c of 26773 MPa.

Three CCC beams (Fig. 1) with the dimensions of 9 × 1m (length × width) had been fabricated. The beams had different composite levels. The first one (beam 1, icon as) had no notches, hence, non-composite. The two others (beam 2 and beam 3) had a different number of notches (beam 2 has one row of 10 connectors while beam 3 has 26 connectors distributed in 3 rows), consequently have low- and high-level composite. The beam span, the distance between the supports, is of 8.7m. The CLT panels were delivered with pre-cut notches with dimensions of 200×200×25mm (length×width×depth). The individual notched connectors specimens were fabricated and tested under another test campaign to determine their stiffness and resistance. The connector stiffness (k), obtained from the static shear test, was 242 kN/mm with the coefficient of variation (CoV) of 13%. The load-slip curves of tested specimens could be found in the study of Thai et al. (2020).

Fig. 1: Plan of beam 3 and real image of the beams before concrete casting

Vibration test: A vibration measurement generally requires several hardware components. The basic hardware element consists of a source of excitation (exciter) for providing a force to the structure, a transducer to convert the structure motion into an electrical signal (Ljunggren 2006). Fig. 2 shows the grid of acquisition points on the beams, with the accelerometer and the hammer impact locations. The desired frequency range conditioned the longitudinal spacing of the grid. In our case, it is up to the fifth bending mode, *i.e.*, ~100 Hz. Since point 15 was optimal for the measurement (exciting both flexion and torsion mode), all the vibration tests had it as a reference point.

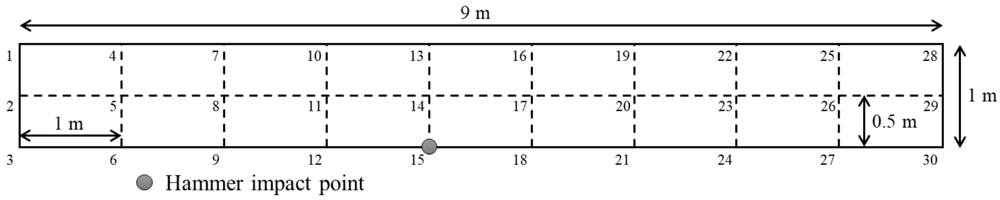

Fig. 1: Accelerometer plan with the hammer impact location

Models for natural frequencies estimation

Analytic models: The natural frequencies could be determined by the analytic expression proposed by Wu et al. (2007). Based on the Euler-Bernoulli beam theory, the exact solution of frequency for a composite section with two sub-elements of different materials can be obtained

$$f_n = \frac{n^2\pi}{2}\sqrt{\frac{EI_{eff}}{mL^4}}, \quad EI_{eff} = \overline{EI}\left[1 - \frac{\beta^2 - 1}{\frac{\tilde{\alpha}^2}{(\boldsymbol{n}\pi)^2} + \beta^2}\right] \qquad (1,2)$$

with

$$\tilde{\alpha}^2 = \frac{k}{s}L^2\left(\frac{1}{E_1A_1} + \frac{1}{E_2A_2} + \frac{h^2}{\Sigma EI}\right); \quad \beta^2 = \frac{\overline{EI}}{\Sigma EI}; \quad \overline{EI} = \Sigma EI + \frac{E_1A_1E_2A_2}{E_1A_1 + E_2A_2}h^2; \qquad (3,4,5)$$

where $\overline{EI}$ is the flexural stiffness of a fully composite beam, β is a parameter related to the geometry and modulus of elasticity of the materials, $\tilde{\alpha}$ is a parameter involving the stiffness of the shear connector, m and L are the mass and the length of the beam, k denotes the shear stiffness of the connector, s is the connector spacing.

Finite element model: the model needed to be simple for engineering implementation and future optimization study. Therefore, the unidimensional model was built in Abaqus CAE software. The model used beams elements in a plane B21 (2-node linear beam) for both timber and concrete materials. The beam elements are shear deformable and account for finite axial strains. They have three degrees of freedom at each node: two translational and one rotational about the normal to the model plane. Connectors were modeled as springs elements in the horizontal direction. The stiffness of the spring element was defined as a constant. The concrete was modeled as isotropic material. The information about concrete material was based on the compression stress of cylindrical specimens. The average MOE in compression of concrete 28 days after casting was of 26.8 GPa. The timber was also modeled as isotropic material with bending MOE along the major strength axis E_b as the modulus. The bending MOE of timber was taken from a preliminary dynamic calibration. Timber Poisson ratio and density are 0.2 and 2450 kg/m^3, respectively. The model schematic of CLT-concrete beams is presented in Fig. 3 where h_c and h_t are thickness of concrete and timber layer, respectively.

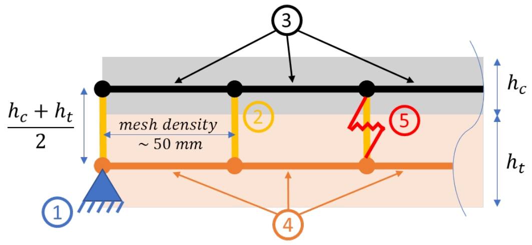

Fig. 3: Composite beam FEM model

1. Support
2. Vertical strut elements, rigid in terms of axial stiffness
3. Concrete elements
4. Timber elements
5. Horizontal connector elements, a spring element with defined horizontal stiffness (connector stiffness)

The mesh density is the question addressed adequately elsewhere (Turmo et al. 2015). It is known that the distance between vertical strut influences the results of the analysis: the smaller distance would lead to a more accurate result. In this study, mesh density is the length of individual concrete (or timber) element. The element size (distance between vertical struts) was fixed at 50 mm based on the mesh sensitivity study (Fig. 4). The blue points were the results of the analytical expression presented in Eq. 1-5. The calculation time per simulation was about less than 1 second.

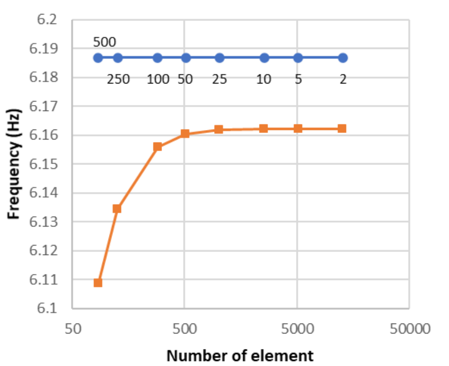

Fig. 4: Mesh sensitivity, data labels represent the corresponding element size

Results and discussion

Tab. 1 presents the vibration test results of bare CLT beams and the CCC beam 28 days. The fundamental frequency results showed an increase of 15%, 24%, and 28% in beam 1, 2, and 3, respectively. The presence of connector systems also enhanced the fundamental frequency by 8% (beam 1 vs. beam 3 at 28 days)

Tab. 1 : Experimental results of bare CLT beams and CCC beams at 28 days

	Beam 1		**Beam 2**		**Beam 3**	
Bare CLT beams						
Mode	**Freq.**	**Damping**	**Freq.**	**Damping**	**Freq.**	**Damping**
1	4.30 Hz	0.6 %	4.26 Hz	0.5 %	4.17 Hz	0.6 %
2	16.49 Hz	1.0 %	15.70 Hz	0.2 %	15.50 Hz	0.9 %
CCC beams at 28 days						

1	4.95 Hz	2.1 %	5.27 Hz	1.2 %	5.35 Hz	0.6 %
2	16.02 Hz	2.9 %	18.11 Hz	1.9 %	18.52 Hz	1.6 %

The confrontation model – experiments carried out based on the test results of CLT-concrete composite beams. Tab. 2 presents the CLT panel and connector characteristics and natural frequencies from experimental tests and models. Normalized relative frequency difference NRFD (in %) was defined as:

$$NRFD = \frac{\left|f_{experiment} - f_{model}\right|}{f_{experiment}} \tag{6}$$

The frequency calculated by Wu et al. (2007) method and the finite element model were in good agreement, especially in the low- and high-composite beams. The FE could predict the natural frequencies with relatively low NRFD. There is an unexpected high fundamental frequency in the non-composite beam. Both analytical and numerical models cannot capture the fundamental frequency of beam 1. This implied that other phenomena might occur, such as friction at the interface or viscous-elastic properties of timber during the vibration.

Tab. 2 : Natural frequencies comparison between experiments and models results

Beams	**CLT**	**Connector**	f_1 (Hz)			f_2 (Hz)			$NRFD\ f_1$(%)		$NRFD\ f_2$(%)	
	$E_b\ (GPa)$	$k\ (kN/mm)$	Exp.	Wu	FE	Exp.	Wu	FE	Exp-Wu	Exp-FE	Exp-Wu	Exp-FE
1	9.2	0	5,0	2,9	2,9	16	12	11	42	41	28	28
2	9.0	334	5,3	5,0	5,0	18	17	15	4	6	7	15
3	8.5	1001	5,4	5,3	5,2	19	19	18	1	2	-4	5

Conclusion and perspective

The composite beams have a fundamental frequency of about 5.3 to 5.4 Hz and the damping about 1%. Correspondingly, they are 5.0 Hz and 2% for the non-composite beam. The addition of the concrete layer increased the performance of CLT panels significantly.

The proposed simplified finite element model could be used as a quick implementation to evaluate naturals frequencies, especially in complex structures. The application would not be limited to CCC beam structures but could be possible for the CCC floor systems. The only drawback of a simplified model is that they cannot describe the notched connector influence (depth, length, the distance between notches) locally.

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