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

THAI Minh-Van[1,2], ELACHACHI Sidi Mohammed[1], GALIMARD Philippe[1], MENARD Sylvain[2]

[1]I2M, University of Bordeaux, 33000 Bordeaux, France. [2]Université du Québec à Chicoutimi, Canada. minh-van,thai@u-bordeaux,fr

Context

- ❖ Cross laminated timber (CLT) is an engineered wood product suitable for floor systems
- ❖ CLT floors usually have maximum span from 6-7m. For long span timber floor (>8m), vibration criteria conditioned the design
- ❖ CLT-concrete composite (CCC) is a solution for long span floor

Objectives

- ❖ Propose a simplified FE model to estimate the natural frequencies of CCC floors
- ❖ Comparison between with analytical models, FE models and experimental results

Experimental approach

❖ **Specimens**: 3 composite beams fabricated from 3 bare CLT panels (9m x 1m) with different number of connectors. Effective span 8,7 m. (c.f. Figure 1)

Beam 1: No connector -> Non-composite

Beam 2: One row of 10 connectors -> Low-composite

Beam 3: Three rows of 26 connector -> High-composite

❖ **Materials**: Timber, concrete, steel mat 150x150 mm, thin film polyethylene to separate timber and concrete

Timber: CLT grade E1, thickness 175 mm

Concrete: C35, with E_c = 26773 MPa, thickness 80 mm

❖ **Connector system**: Notch reinforced by two vertical screws

Dimension: 200 x 200 x 25 mm (c.f. Figure 1)

Shear stiffness: 242 kN/mm, coefficient of variation 13% (Thai et al., 2020)

❖ **Vibration test:** roving accelerometer method

Excitation source: hammer impact (hit at point 15)

Data acquisition by a grid of 24 accelerometers (c.f. Figure 2)

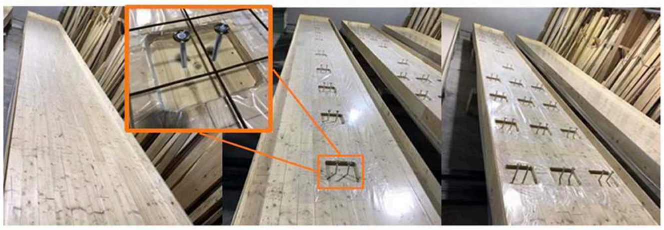

Figure 1: Bare CLT panel with notch connector on the upper surface. From left to right: beam 1, 2 and 3.

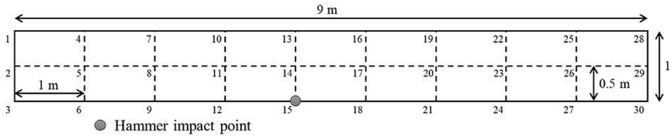

Figure 2: Accelerometer grid and hammer impact point

Models for natural frequencies estimation

Analytic models

Wu et al. (2007) proposed an exact solution of frequency of simple supported beam, based of Euler-Bernoulli beam theory.

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

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

- $(EI)_{eff}$: Effective bending stiffness of a partial composite beam,
- β : Parameter related to the geometry and modulus of elasticity of the materials,
- $\tilde{\alpha}$: Parameter involving the stiffness of the shear connector,
- m and L : Mass and Length of the beam,
- k : Shear stiffness of the connector

Finite elements models

Built in Abaqus CAE environment

Element: Plane B21 (2-node linear beam)

DOF at each node: two translational and one rotational

Timber: ν = 0,4, γ_t = 515 kg/m³, E_t varied by beam

Concrete: ν = 0,2, γ_c = 2450 kg/m³, E_c = 26,8 GPa

Diagram of model (c.f. Figure 3)

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)

Element size 50 mm based on mesh sensitivity analysis (c.f. Figure 4).

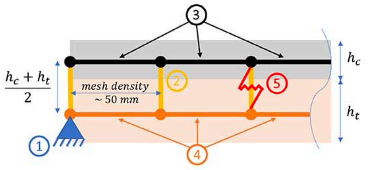

Figure 3: Diagram of FE model

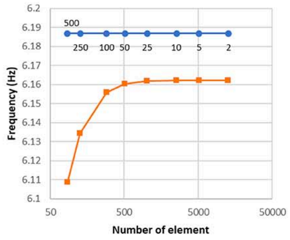

Figure 4: Mesh sensitivity analysis. Blue points represent analytic results using Wu et al. (2007) expressions. Red points represent FE model results

Result and discussion

Presence of concrete layer: Natural frequency increase 15%, 24% and 28% for beam 1, 2 and 3, respectively. (bare CLT beams vs. CCC beams) (c.f. Table 1)

Presence of connector systems: Natural frequency increase 8% (CCC beam 1 vs. beam 3) (c.f. Table 1)

FE model could predict natural frequency of CCC beam 2 and 3 (low and high composite) with relatively low NRFD (c.f. Table 2)

$$NRFD = \frac{|f_{experiment} - f_{model}|}{f_{experiment}}$$

Fundamental frequency of CCC beam 1 was underestimated by models (c.f. Table 1)

Mode	Beam 1		Beam 2		Beam 3	
	Frequency	Damping	Frequency	Damping	Frequency	Damping
Bare CLT beams						
1	4,3 Hz	0,6 %	4,3 Hz	0,5 %	4,2 Hz	0,6 %
2	16,5 Hz	1 %	15,7 Hz	0,2 %	15,5 Hz	1 %
CCC beams at 28 days						
1	5,0 Hz	2 %	5,3 Hz	1 %	5,4 Hz	1 %
2	16,0 Hz	3 %	18,1 Hz	2 %	18,5 Hz	2 %

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

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

Table 2: Natural frequencies comparison between experiments and models results

Conclusions and perspectives

- ❖ The contribution of concrete layer and connector systems enhance the vibrational performance of CLT panels.
- ❖ The FE models could be quickly implemented to evaluate naturals frequencies of beam or floor structure.
- ❖ Local behavior of notched connector required a more complex model.

References

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