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VIBROACOUSTIC FINITE ELEMENT MODELLING OF AIRBORNE SOUND INSULATION OF A CROSS LAMINATED TIMBER FLOOR

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ABSTRACT

Cross Laminated Timber (CLT), as a lightweight floor, typically provides lower sound insulation than concrete floors - particularly in the low frequency range. Although this is particularly related to impact sound transmission, airborne sound transmission is also an issue that needs to be considered with care in CLT floors. This paper concerns the development and validation of numerical models using Finite Element Methods (FEM) to predict airborne sound transmission in Cross Laminated Timber (CLT) floors. Vibroacoustic finite element models of a simply supported three-layer CLT panel were developed in COMSOL and validated against airborne laboratory measurements. Predictions are shown for two different FEM models, one using solid elements with material orientation and the other using shell elements with homogenized material properties.

Keywords: *FEM, CLT, Airborne sound insulation*

1. INTRODUCTION

Cross Laminated Timber (CLT) has been used as an alternative to reinforced concrete for about two decades, with an emphasis on walls, floors and roof slab application in low-rise and recently in multi-storey structures [1]. This occurred because CLT is renewable and has a considerably lower carbon footprint than concrete [2]. In addition, compared to other timber products, CLT shows enhanced stiffness and load-carrying characteristics [1]. Lightweight floors can exhibit undesirable vibration serviceability performance and typically provide lower sound insulation than concrete floors - particularly in the low frequency range [3]. Although this is more related to impact sound transmission, airborne sound transmission can be still an issue in lightweight floors such as CLT floors [4]. Thus, this research aims to use Finite Element Methods (FEM) to investigate the airborne sound transmission in CLT floors. This will enable better understanding in the design stages and avoidance of over – design.

FEM modelling of CLT floors often use solid elements with material orientation for each CLT layer [e.g., 5-6]. This results in large and computationally expensive FEM models especially above 200 Hz where more elements are needed to fulfil the requirement for at least six element per wavelength [7]. Using shell elements with homogenized material properties [8-9] allows modelling of only the mid-section of a CLT floor resulting in reduced computational time compared with solid elements. Thus, this paper investigates both modelling approaches to develop and validate FEM models for the prediction of airborne sound insulation in CLT floors. Vibroacoustic FEM models of a simply supported CLT panel are developed in COMSOL using solid and shell elements. The models are validated against airborne laboratory measurements in the frequency range between 100 Hz and 500 Hz, as 500 Hz was the upper frequency limit imposed by the available computational resources.

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2. METHODS

2.1 Experimental work

2.1.1 Test specimen

The CLT panel (3200 mm x 2200 mm) has a thickness of 99 mm and consists of three layers of Radiata Pine (33 mm each), with the layup 0º/90º/0º. The layers are nailed together.

2.1.2 Test setup

To carry out airborne sound transmission measurements, an acoustic enclosure (3200 mm x 2200 mm x 2510 mm) was built in the basement workshop of the University of Sydney (UTS). The CLT panel was placed above the enclosure, supported at both ends by steel beams and clamps to approximate pinned support conditions (see Fig.1).
The acoustic enclosure walls were double stud walls with each leaf comprised of two layers of 10 mm plasterboard and one layer of 12 mm particle board on timber studs and the cavity was filled with 50 mm mineral wool. The two wall leaves were also separated with 50 mm air cavity. The panel was independent of the external walls of the acoustic enclosure and mineral wool was fitted to seal the gaps between the CLT panel and the acoustic enclosure walls.

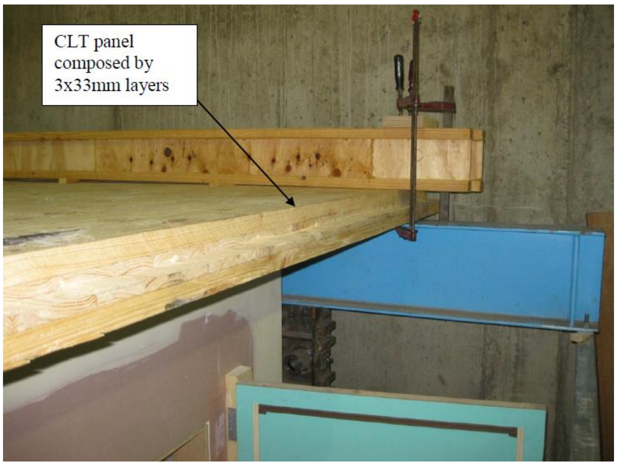

Figure 1. Test setup showing the CLT panel, the acoustic enclosure and the approximated pinned support conditions.

2.1.3 Airborne sound transmission measurements

Airborne sound transmission measurements were carried out using a JBL Eon 15PAK loudspeaker to create a pink noise sound signal in the source room. A calibrated precision sound level meter (Brüel & Kjær 2250 Type 1) loaded with the BZ 7228 building acoustics module was used to measure sound levels in the source (workshop) room and the receiving room (enclosure) using a moving microphone method. Two measurements were conducted in each room (i.e., one measurement for each loudspeaker position).

2.2 FEM modelling

All finite element models used COMSOL Multiphysics software (version 6.0), and frequency domain analysis was carried out in the frequency range between 100 Hz and 500 Hz using 1 Hz frequency step.

2.2.1 Material properties

Tab.1 shows the density and the orthotropic material properties for Radiata pine timber boards. The density was taken from [10]. Two grades of timber were considered: Grade F5 and grade F7 with modulus of elasticity parallel to grain, E_{xx} equal to 6.9 and 7.9 GPa, respectively [11]. The elastic moduli in the other two perpendicular directions E_{yy} and E_{zz} as well as the shear moduli G_{xy} and G_{xz} were taken to be $E_{xx}/30$ and $E_{xx}/16$ respectively according to EN-338 [10]. The shear modulus G_{yz} was approximated to be $G_{xy}/10$ [9,12]. Poisson's ratio for Radiata pine timber was taken from [5].
The damping ratio, ζ for the CLT panel was set to 1% according to the literature [6,13].

Table 1. Orthotropic material properties for Radiata pine timber boards.

Parameter	Grade F5	Grade F7
ρ (Kg/m^3)	550	550
E_{xx} (Pa)	6.9E09	7.9E09
E_{yy} (Pa)	2.3E08	2.6E08
E_{zz} (Pa)	2.3E08	2.6E08
G_{xy} (Pa)	4.6E08	5.3E08
G_{yz} (Pa)	4.6E07	5.3E07
G_{xz} (Pa)	4.6E08	5.3E08
ν_{xy} (-)	0.2	0.2
ν_{yz} (-)	0.21	0.21
ν_{xz} (-)	0.18	0.18

2.2.2 CLT panel

FEM model no.1 used solid elements with quadratic interpolation functions, considering material orientation for each layer of the CLT panel. The layers were modelled to be monolithically connected. FEM model no.2 used quadratic shell elements with homogenized orthotropic material properties. Both FEM models had at least six elements per wavelength up to 500 Hz and pinned support conditions ($u_x = u_y = u_z = 0$) were assumed along the two ends of the panel. In FEM model no.1, the pinned support condition was applied along the mid-nodes of both ends of the panel, as it is indicated in Fig.2.

Figure 2. Pinned support condition at FEM model no.1.

For a 3-layer CLT panel (see Fig.3) the homogenized elastic moduli are given by [8]

$$E_{h,xx} = \frac{\sum_{i=1}^{n}(E_{xx,i}\, h_i^{\,3}) + \sum_{i=1}^{n}(12E_{xx,i}\, h_i z_i^{\,2}) + \sum_{j=1}^{m}(E_{yy,j}\, h_j^{\,3})}{h^3} \quad (1)$$

$$E_{h,yy} = \frac{\sum_{i=1}^{n}(E_{yy,i}\, h_i^{\,3}) + \sum_{i=1}^{n}(12E_{yy,i}\, h_i z_i^{\,2}) + \sum_{j=1}^{m}(E_{xx,j}\, h_j^{\,3})}{h^3} \quad (2)$$

$$E_{h,zz} = E_{zz} \quad (3)$$

The homogenized shear moduli are given by [9]

$$G_{h,xy} = G_{xy} \quad (4)$$

$$G_{h,yz} = \frac{h}{\sum_{i=1}^{n}\left(\frac{h_i}{G_{yz}}\right) + \sum_{j=1}^{m}\left(\frac{h_j}{G_{xz}}\right)} \quad (5)$$

$$G_{h,xz} = \frac{h}{\sum_{i=1}^{n}\left(\frac{h_i}{G_{xz}}\right) + \sum_{j=1}^{m}\left(\frac{h_j}{G_{yz}}\right)} \quad (6)$$

The homogenized Poisson's ratios are given by [9]

$$\nu_{h,xy} = \frac{\sum_{i=1}^{n}(\nu_{xy} h_i) + \sum_{j=1}^{m}(\nu_{yx} h_j)}{h} \quad (7)$$

$$\nu_{h,yz} = \frac{\sum_{i=1}^{n}(\nu_{yz} h_i) + \sum_{j=1}^{m}(\nu_{xz} h_j)}{h} \quad (8)$$

$$\nu_{h,xz} = \frac{\sum_{i=1}^{n}(\nu_{xz} h_i) + \sum_{j=1}^{m}(\nu_{yz} h_j)}{h} \quad (9)$$

where i corresponds to the CLT layer parallel to the timber grain, j corresponds to the CLT perpendicular to the timber grain, h_i and h_j is the thickness of layers i and j respectively, z_i is the distance of layer i from the neutral axis of the CLT cross section and h is the total thickness of the CLT cross section.

Tab.2 shows the homogenized orthotropic material properties for the Radiata pine CLT panel after applying Eqns. (1-9).

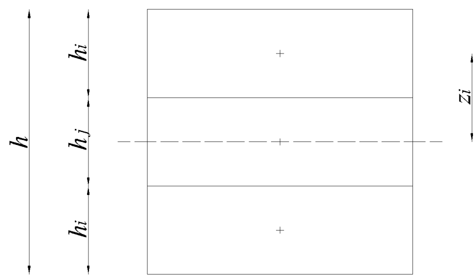

Figure 3. Cross section of a 3-layer CLT panel.

Table 2. Homogenized orthotropic material properties for Radiata pine CLT panel.

Parameter	Grade F5	Grade F7
ρ (Kg/m^3)	550	550
$E_{h,xx}$ (Pa)	6.7E09	7.6E09
$E_{h,yy}$ (Pa)	4.8E08	5.5E08
$E_{h,zz}$ (Pa)	2.3E08	2.6E08
$G_{h,xy}$ (Pa)	4.6E08	5.3E08
$G_{h,yz}$ (Pa)	6.6E07	7.6E07
$G_{h,xz}$ (Pa)	1.2E08	1.3E08
$\nu_{h,xy}$ (-)	0.14	0.14
$\nu_{h,yz}$ (-)	0.20	0.20
$\nu_{h,xz}$ (-)	0.19	0.19

2.2.3 Source and receiving rooms

In both FEM models no.1 and 2, the source and the receiving rooms had the same volume (3200 mm x 2200 mm x 2510 mm) and were modelled using quadratic solid elements (see Fig.4) with at least six elements per wavelength up to 500 Hz. The acoustic elements were coupled with the structural elements of the CLT panel by creating an acoustic-structure boundary. All the surfaces of the source room as well as the bottom surface of the receiving room were assumed to be hard boundaries and frequency dependent absorption coefficient for double plasterboard wall with 100 mm cavity filled with mineral wool was assumed for the walls of the receiving room (see Tab.3).

Table 3. Absorption coefficients for the receiving room walls

Octave band (Hz)	125	250	500
Absorption coefficient α (-)	0.30	0.12	0.08

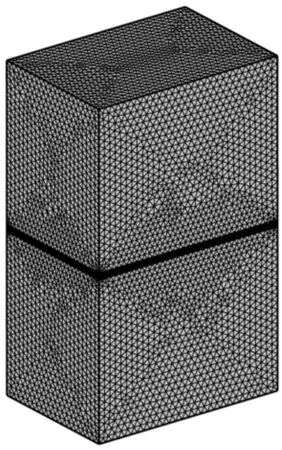

Figure 4. Vibroacoustic FEM model of a CLT panel.

2.2.4 Sound reduction index

The sound reduction index of the CLT panel was calculated according to BS EN ISO 140-3:1995. The sound reduction index is evaluated from [14]

$$R = L_1 - L_2 + 10lg\frac{S}{A} \qquad (10)$$

where L_1 and L_2 are the average sound pressure levels in the source and the receiving room (in decibels), S is the area of the CLT panel and A is the equivalent sound absorption area in the receiving room.

The source room in FEM models no.1 and 2 was excited using a monopole source in four positions (see Fig.5). For each source position the average sound pressure levels were calculated in both rooms using a 2x3x2 array of points as it is indicated in Fig.5. The spacing of the points in the array as well as their distance from the boundaries was defined according to BS EN ISO 140-3:1995.

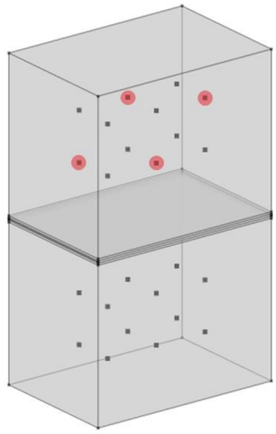

Figure 5. Positions of the monopole source (red circles) and of the array of points (black squares) where the acoustic pressures were calculated in FEM models no.1 and 2.

3. RESULTS

FEM model no.2 needed 25% less computational time than FEM model no.1 since the use of shell elements decreased the number of degrees of freedom in the vibroacoustic model.

Fig.6 and Fig.7 compare FEM models no.1 and 2 respectively, against the experimentally measured sound reduction index of the 3-layer CLT panel. For each model, results are shown for Grade F5 and F7 Radiata pine timber, in one-third octave bands (1 Hz frequency resolution in each band). In general, both models show comparable agreement with the laboratory measurements regardless of the material properties used. However, closer agreement was achieved with Grade F7 Radiata Pine, indicating that Grade F7 material properties approximate better the actual material properties of the CLT panel. It is also shown that the different material properties for timber affect mainly FEM model no.1 in the frequency bands below 160 Hz.

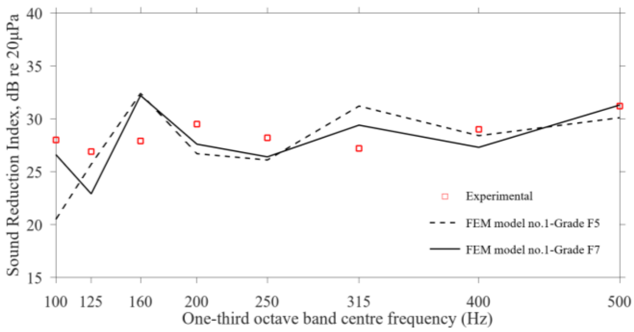

Figure 6. Comparison of FEM model no.1 against experimental sound reduction index for timber Grades F5 and F7.

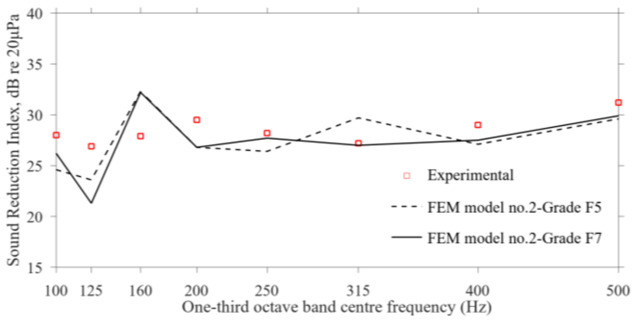

Figure 7. Comparison of FEM model no.2 against experimental sound reduction index for timber Grades F5 and F7.

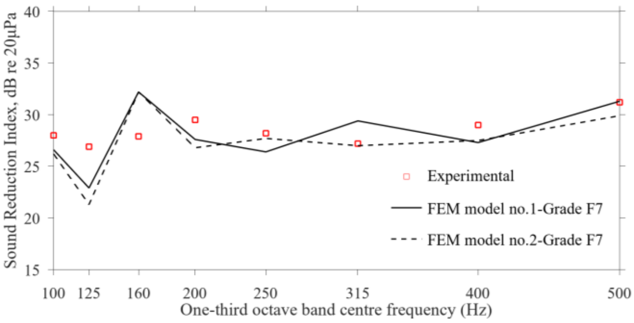

Figure 8. Comparison of FEM models no.1 and 2 against experimental sound reduction index for Grade F7 timber.

Fig.8 compare FEM models no.1 and 2 against the experimentally measured sound reduction index of the 3-layer CLT panel. Results are shown for Grade F7 Radiata pine timber, in one-third octave bands.

Both models resulted in similar sound reduction index curves between 100 Hz and 200 Hz. FEM model no.1 shows closer agreement with the laboratory measurements than FEM model no.2 with average differences of 2.9 and 3.6 dB, respectively. In the frequency bands above 200 Hz, close agreement (i.e., differences within 3 dB) was achieved for both models, although the sound reduction index curves differ. For FEM model no.1, the differences were between 0.1 and 2.2 dB whilst for FEM model no.2 the differences were between 0.2 and 1.5 dB.

On average, FEM model no.1 is in closer agreement with the laboratory measurements than FEM model no.2. This is reasonable since FEM model no.1 uses solid elements that consider the material orientation of the CLT layers.

4. CONCLUSIONS

Vibroacoustic FEM models were developed in COMSOL to study the airborne sound insulation of a CLT panel. The CLT panel was modelled using either solid elements with material orientation or shell elements with homogenized material properties. Two different timber grades were investigated. The FEM models were experimentally validated against laboratory measurements in terms of sound reduction index.

Both FEM models were in comparable agreement with the laboratory measurements regardless of the material properties used and closer agreement was achieved with Grade 7 Radiata pine. The material properties seemed to affect mainly the results of the FEM model that used solid elements with material orientation, below 160 Hz. The use of solid elements with material orientation increased the computational time by 25% and resulted in closer agreement with the laboratory measurements compared to shell elements with homogenized material properties.

Furure work will continue the validation of the FEM models against new laboratory measurements and will use hybrid FEM models to investigate the airborne sound insulation of CLT floors above 500 Hz.

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