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Preliminary report

Effects of material uncertainties on vibration performance of cross laminated timber floors*

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ABSTRACT

Variety of wood species and complexity of their structure make the reliable material properties of cross-laminated timber (CLT) difficult to obtain, which can lead to inaccurate prediction of CLT behavior. Due to high stiffness-to-weight ratio, CLT floors can suffer from vibration serviceability issues. This paper aims to quantify the uncertainties induced by material properties and investigate their effect on vibration performance of CLT floors. Analysis based on Monte Carlo simulations, considering material properties as random variables, is developed. Based on the conducted analysis, appropriate conclusions have been derived.

1 Introduction

During the 20th century, reinforced concrete was found to be the most economical and thus the most commonly used construction material in civil engineering. At the end of the century, as environmental awareness was growing, new materials with low carbon footprint that could be competitive with mineral based materials were needed. This led to renaissance of timber as construction material and development of a novel wood engineering product: cross-laminated timber (CLT). It is a plate-like product, composed of several wooden layers bonded together in a crosswise manner. Modern manufacturing techniques and high structural strength of timber make CLT an element with great stiffness properties and unique aesthetic appeal. CLT structures are characterized by high level of prefabrication, fast and simple transport and assembly, good fire resistance, thermal insulation capacity and ability to tolerate chemically aggressive environments. All these facts increased global interest in CLT and led to many projects on research and development of CLT products [1-2].

One of the main advantages of CLT compared to reinforced concrete is high stiffness-to-weight ratio, which enables large span lightweight floors to be designed. However, CLT floors under human-induced dynamic load may exhibit vibration serviceability issues such as human discomfort and malfunction of vibration sensitive equipment. Consequently, accurate and reliable prediction of dynamic properties of CLT floors is required [3-4].

Variety of wood species and complexity of its structure make the reliable material properties of cross-laminated timber (CLT) difficult to obtain. Effects of annual ring patterns on material properties of wood have been studied by Labonnote et al. [5]. Material uncertainty, as well as uncertainties in boundary conditions and pedestrian dynamic load can lead to inaccurate prediction of dynamic response of CLT floors [6].

Research in order to quantify the effect of material uncertainty on modal properties of wooden floors has been conducted by Persson el al. [7] and Lim & Manuel [8]. Vibroacoustic response of wooden and CLT floors with material parameter variability has been studied by Persson & Floden [9] and Qian [10]. All analyses demonstrated great influence of material uncertainties on the natural frequencies and acoustic performance of investigated wooden floors.

Currently, material properties of CLT are differently regulated in technical approvals [11], which might lead to significant differences between the actual mechanical properties and those defined in the design guidelines and recommendations. Material properties depend on the strength class of CLT as well as the strength class of the base material.

The aim of this paper is to quantify the uncertainties induced by material properties and investigate their effect on vibration performance of CLT floors. Material properties, in terms of mass density, elastic modulus EL and shear moduli GLT and GRT are considered as random variables, while other properties as deterministic. Two different sampling techniques to generate random variables have been applied and analysis based on Monte Carlo (MC) simulation has been carried out. Numerical modelling and analysis of the investigated CLT floor have been performed using the finite element (FE) models in Abaqus CAE software package [12]. Models have been automatically generated using the Python scripting. Obtained results are statistically analyzed and conclusions have been derived.

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2 Modal analysis of CLT floor

2.1 CLT properties and numerical model

Wood is an orthotropic material with three principal material axes: the longitudinal axe is aligned with the fiber direction (*L*), while the radial (*R*) and tangential (*T*) axes are orthogonal to annual rings (Figure 1a). Each layer (*k*) of CLT panel exhibits elastic orthotropic material behavior defined as:

$$\begin{Bmatrix} \varepsilon_L \\ \varepsilon_T \\ \varepsilon_R \\ \gamma_{TR} \\ \gamma_{LR} \\ \gamma_{LT} \end{Bmatrix}^{(k)} = \begin{bmatrix} 1/E_L & -\nu_{TL}/E_T & -\nu_{RL}/E_R & 0 & 0 & 0 \\ -\nu_{LT}/E_L & 1/E_T & -\nu_{RT}/E_R & 0 & 0 & 0 \\ -\nu_{LR}/E_L & -\nu_{TR}/E_T & 1/E_R & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{TR} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{LR} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{LT} \end{bmatrix}^{(k)} \begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_R \\ \tau_{TR} \\ \tau_{LR} \\ \tau_{LT} \end{Bmatrix}^{(k)} \tag{1}$$

where E_L, E_T and E_R are elastic moduli in the longitudinal, transverse, and radial direction, respectively, ν_{ij} are the Poisson's ratios, and G_{ij} are the Poisson's ratios, and Gij are the shear moduli. CLT floor panel used in the analysis is presented in Figure 1b. Panel's dimensions are 4x8m, and it is composed of 5 layers, bonded in crosswise manner, with stacking sequence (0/90/0/90/0). Height of each layer is 0.03m. Such panel can be used as floor structure in common residential or commercial building. Material properties for C24 timber class [11] are applied (Table 1). The outer layers of CLT panel are oriented in the span direction (L = 4m).

Finite element-based model has been created using Abaqus CAE software package. The finite element mesh consists of 800 S4R shell elements (quadrilateral 4-node shell element with reduced integration) with assigned composite cross section.

Simply supported boundary conditions have been assigned to the two longer floor edges, while the other two remained free. Material axes of the layers are oriented by angle 0° or 90° with respect to the laminate coordinates. Thus, the constitutive relations given in Eq. (1) must be transformed from the material to the global coordinate system, using the well-known transformation matrix.

2.2 Free vibration analysis

Based on the material properties given in Table 1, dynamic properties of CLT floor panel have been determined. Natural frequencies and modal masses of the first five and the twelfth mode, respectively, have been calculated and elaborated in Table 2. First five modes are the bending modes, while the twelfth mode corresponds to the first shear mode. Mode shapes are shown in Figure 2. Calculated modal masses correspond to the unity scaled mode shapes.

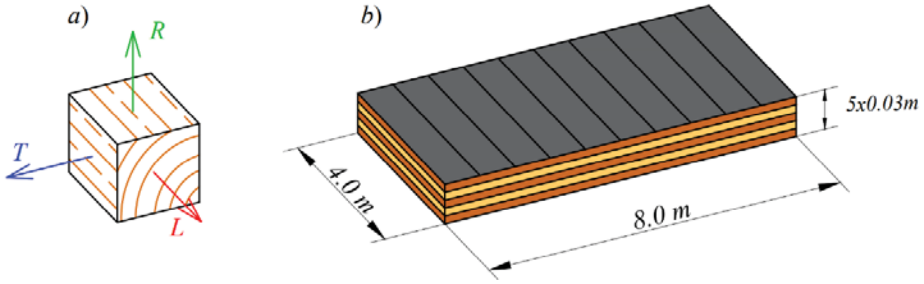

Figure 1. (a) Principal material axes, (b) Layout of CLT floor

Table 1. Mean values of material properties for C24 timber class of CLT panel

ρ [kg/m^3]	E_L [MPa]	E_R=E_T [MPa]	G_{LR}=G_{LT} [MPa]	G_{RT} [MPa]	ν_{LT}	ν_{LR}	ν_{RT}
450	11000	370	690	69	0.49	0.39	0.64

Table 2. Dynamic properties of the considered 5-layer CLT floor (4 x 8 m)

Mode No.	Mode type	Natural frequency [Hz]	Modal mass [kg]
1	1st bending	18.06	968.62
2	2nd bending	18.73	403.23
3	3rd bending	21.48	315.45
4	4th bending	28.13	285.69
5	5th bending	39.74	284.05
12	1st shear	77.43	1078.3

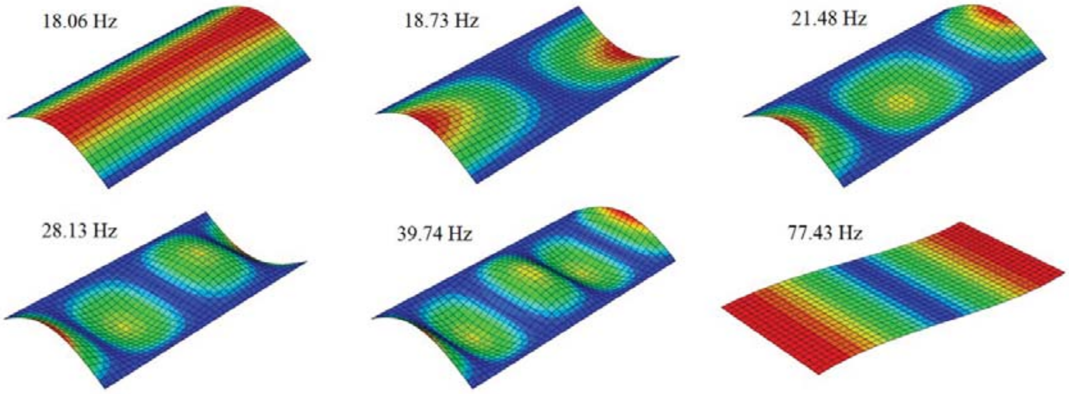

Figure 2. Mode shapes of the considered 5-layer CLT floor (4 x 8 m)

3 Material uncertainty

3.1 Local sensitivity analysis

In order to determine the sensitivity of natural frequencies to random changes in material properties, local sensitivity analysis has been performed. For that purpose, one individual material parameter has been considered as random and all the remaining as deterministic. Normal distribution for four material parameters: mass density ρ, longitudinal elastic modulus E_L, and shear moduli G_{LT} and G_{RT}, respectively, was assumed, with mean values defined in Table 1. Coefficient of variation (COV) of random variables has been increased up to 20% and COVs of the five bending and first shear natural frequencies were calculated. The results after 2,000 conducted MC simulations are presented in Figure 3. Natural frequencies are affected the most by the variability of the mass density. Moreover, it can be noticed that all modes are affected equally by the random change of this parameter. Influence of modulus E_L on the bending modes is significant. The highest influence of E_L is observed in the first mode and it decreases with higher bending modes, while the shear mode has found to be unaffected. On the other hand, variation of the shear modulus G_{LT} has strong impact on the first shear mode and low impact on the natural frequencies of bending modes. The change in the shear modulus G_{RT} induces small change in bending modes, and no change in the natural frequency of the first shear mode.

3.2 Global sensitivity analysis

In the global sensitivity analysis, four material parameters, namely ρ, E_L, G_{LT} and G_{RT}, are simultaneously treated as random variables. It is assumed that all parameters follow the normal distribution, with mean values given in Table 1 and COVs of 10%. Two different sampling techniques have been used: pseudo-random and Latin hypercube. After generating samples of the uncertain parameters, 10,000 Monte Carlo simulations have been performed.

Generation of Abaqus input files with different set of mechanical parameters has been carried out using Python scripting. After the calculation of the natural frequencies, modal masses and (unity scaled) mode shapes, they have been automatically collected from the output files created by Abaqus.

The results of the statistical analysis of the dynamic properties of CLT floor are presented in Figures 4 and 5. COV of 10% for the four input mechanical parameters resulted in the COVs of 6.91%, 6.68%, 6.26%, 6.07% and 6.02% for the natural frequencies of the first five bending modes, respectively, and 7.26% for the first shear mode, following the lognormal distribution when the input parameters are generated by using pseudo-random sampling technique. When Latin hypercube sampling technique is applied, the calculated COVs for the investigated natural frequencies are 6.79%, 6.57%, 6.16%, 5.97%,

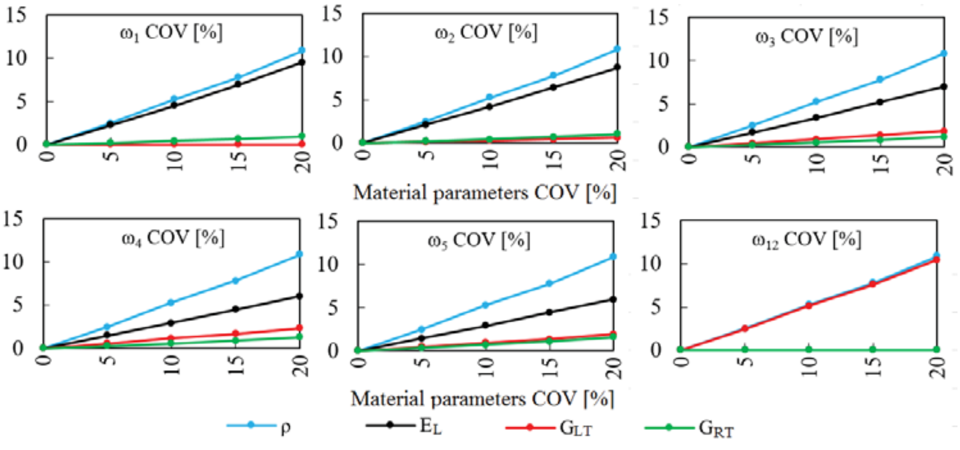

Figure 3. Variation of natural frequency COV with individual change of random variables

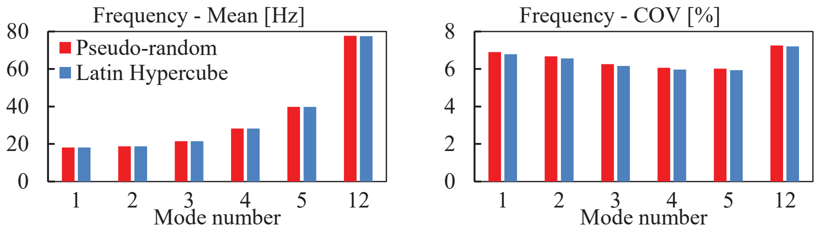

Figure 4. Statistical properties of natural frequencies of CLT floor, considering different sampling techniques

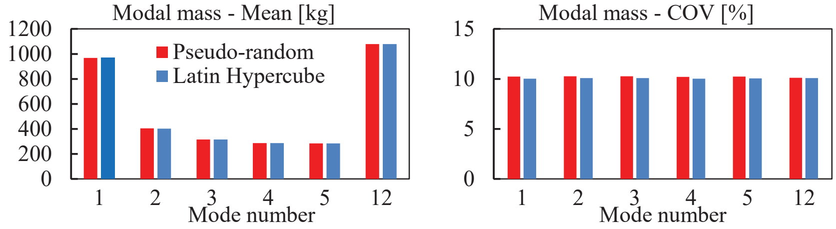

Figure 5. Statistical properties of modal masses of CLT floor, considering different sampling techniques

5.94% and 7.21%. The average difference in the natural frequencies COVs between two sampling techniques is 1.5%. Variations of input parameters resulted in modal masses following the normal distribution, with the COV of 10.27% (pseudo-random) and 10.03% (Latin hypercube).

In addition, the influence of number of simulations on the statistical results for both sampling techniques has been investigated. Mean values and COVs of the natural frequencies regarding the number of simulations are presented in Figure 6 (pseudo-random) and Figure 7 (Latin hypercube). Mean values of the investigated natural frequencies, for both sampling techniques, are nearly constant. The average difference in mean values while comparing 100 and 10,000 simulations is below 1%. The Latin hypercube technique resulted in adequately determined COVs of all investigated natural frequencies after 2,000 simulations.

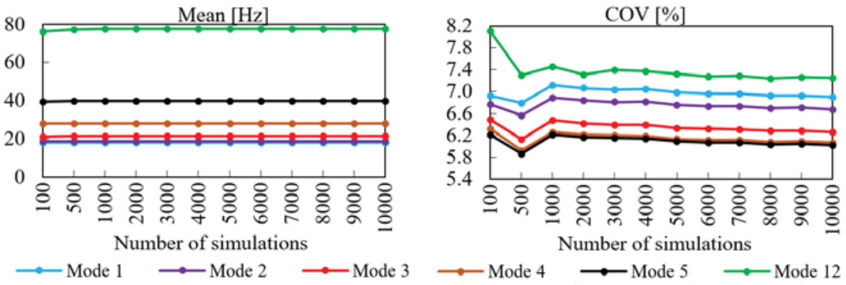

Figure 6. Statistical properties of natural frequencies in regard to number of simulations generated by pseudo-random sampling techique

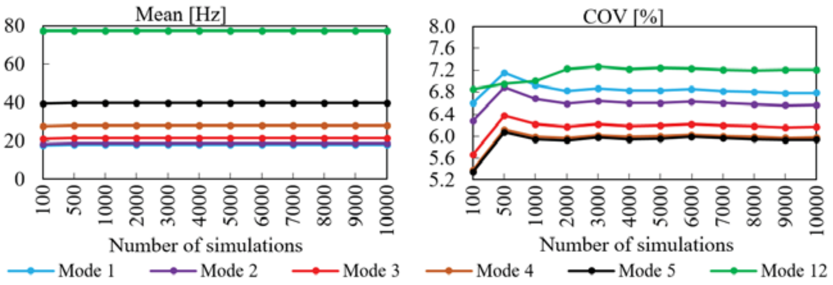

Figure 7. Statistical properties of natural frequencies in regard to number of simulations generated by Latin hypercube sampling technique

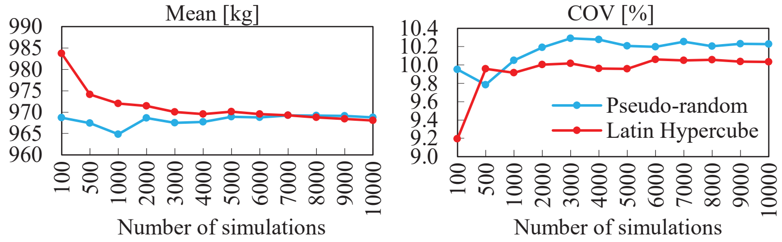

Figure 8. Statistical properties of modal mass of the first mode in regard to number of simulations

The difference between COVs calculated after 2,000 and 10,000 simulations is less than 0.5%. When pseudo-random sampling is used, slight decrease of natural frequencies COVs after 2,000 up to 10,000 simulations is noticeable.

Modal masses of all modes are affected equally by the random changes in material properties. In Figure 8 the mean value and COV of modal mass of the first mode against the number of simulations for both sampling techniques are presented. If less than 2,000 simulations are performed, the differences in mean values and COVs calculated by using two sampling techniques are significant. When number of simulations is greater than 2,000, both techniques resulted in similar statistical parameters.

4 Conclusions

The influence of material uncertainty on the dynamic properties of CLT floor has been investigated numerically. Four material parameters, mass density ρ, longitudinal elastic modulus E_L, and shear moduli G_{LT} and G_{RT}, respectively, are considered as random variables, and the remaining parameters as deterministic. Uncertainty quantification analysis based on Monte Carlo simulations had been performed and the following conclusions were derived:

– Natural frequencies are most affected by the changes in mass density and all modes are equally affected. The longitudinal elastic modulus E_L has great impact on the natural frequencies of bending modes, while the changes in the shear modulus G_{LT} affect only the natural frequency of shear mode.

– Normal distributed uncertain material parameters with 10% COVs resulted in the lognormal distributed natural frequencies and normal distributed modal masses for both sampling techniques. When pseudo-random sampling is used, COVs of natural frequencies are insignificantly higher compared to the Latin hypercube technique. In both cases, COVs are approximately 6-7% for bending modes and 7.2% for the shear mode. COVs of modal masses are also similar for both sampling techniques, about 10%.

– Mean values of natural frequencies can be accurately calculated after 100 simulations, while 2,000 simulations are needed for adequately determination of COVs when both sampling techniques are applied.

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