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VIBRATION SERVICEABILITY ASSESSMENT OF THREE CLT BUILDINGS

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ABSTRACT: The comfort criterion with respect to peak accelerations induced by wind was assessed for three existing cross laminated timber (CLT) residential buildings (two from UK and one from Norway). The peak accelerations were calculated using Annex B of Eurocode EN 1991-1-4:2005 for the first two fundamental (bending) natural frequencies - their measured values were available - and checked against the comfort criterion from ISO 10137. The values for basic wind velocity were taken from the respective national annexes. The damping ratio was conservatively assumed as 1.2 %. It was found that two buildings do not fulfill the comfort criterion, which indicates an importance of a good estimate of natural frequencies, damping ratios and mass of the building during the design, because the peak accelerations depend on them considerably. However, a good estimate might be a challenge to get: for the considered buildings, a fairly detailed, best-engineering-judgement finite element models missed the experimental values of the natural frequencies by 1 to 12 % for the first two vibration modes.

KEYWORDS: multi-storey timber buildings, CLT, vibration serviceability, comfort criterion, finite element modeling

1 – INTRODUCTION

Design of a multi-storey timber building involves checking the serviceability limit states. The checks relate to vertical deformations of floors and beams, lateral movements of walls and columns, vibrations of floor slabs and vibrations of the whole building. For the multi-storey timber buildings, the wind-induced vibrations of the whole building is often the decisive criterion for serviceability [1, 2]. The wind-induced vibrations can also be the governing design criterion, as was the case for a 14-storey timber building [3] designed using Eurocodes with national annexes for Norway.

The wind-induced vibrations can produce excessive sway and/or high accelerations causing discomfort in occupants of the building. There is a substantial variability in individual physiological and psychological responses to identical motion, which complicates a definition of the serviceability limit state relating to comfort of occupants. The various peak values of motion associated with displacement, velocity, acceleration or its derivatives can be considered as a measure of comfort [4]. The peak acceleration seems to be the preferable choice in structural design. Standardized limit curves provided by two ISO codes are frequently used: ISO 10137 [5] restricts 1-year peak accelerations (depending on the commercial or residential use of the building), and ISO 6897 [6] restricts 5-year root-mean-square horizontal accelerations.

The ISO design codes propose comfort criteria which is natural frequency dependent. This calls for evaluation of natural frequencies of the building. For buildings taller than 50 m, EN 1991-1-4:2005 [7] proposes an empirical equation for the fundamental frequency: $f = 46/h$ (in Hertz), where h is the height of the building in meters. The applicability of this equation for timber buildings is questionable, because it was proposed for the reinforced concrete buildings. Also, little was know about dynamic characteristics of as-built multi storey timber buildings at the time of its proposal. The equation is restricted to buildings surpassing 50 m, but wind-induced vibrations can be the governing design criterion for much lower timber buildings as shown in [3]. A new empirical equation for the fundamental frequency of timber buildings (and hybrid timber buildings) was recently proposed in [8].

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(a) (b) (c)

Figure 1: The considered buildings. (a) Case study 1: seven-storey CLT building in Glasgow, UK. (b) Case study 2: five-storey hybrid CLT-concrete building in Cambridge, UK. (c) Case study 3: eight-storey CLT building in Ås, Norway.

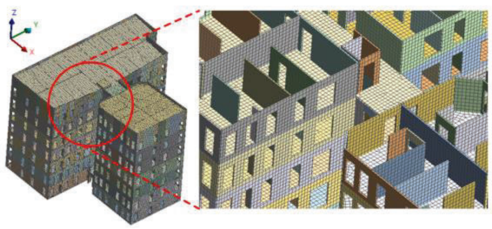

Figure 2: FE model for Case study 1.

Characteristic peak accelerations due to wind-induced vibrations may be calculated for the fundamental vibration modes using Annex B of Eurocode EN 1991-1-4:2005 [7]. A good estimate of natural frequencies, damping ratios and mass of the building is of importance, because the calculated peak accelerations are sensitive to variation of these data. As regarding the damping of tall timber buildings, quality data were obtained in the framework of DynaTTB research project [9]. For a more accurate prediction of natural frequencies, the above mentioned empirical equation should be replaced by the finite element (FE) based modal analysis, which calls for a rather complex FE model of a whole building.

2 – BACKGROUND

For the three existing cross laminated timber (CLT) buildings shown in Fig. 1, the modal properties (i.e. the natural frequencies and damping ratios) were measured during the DynaTTB research campaign [9]. Their modal properties were also estimated numerically by fairly detailed FE models; for illustration purposes, the FE model for the building in Fig. 1 (a) is shown in Fig. 2. The stiffnesses of the parts of the buildings (as well as the stiffness of the soil below the structure and uncertain mass) were estimated by subsequent (deterministic and Bayesian) model updating processes. For more details on the buildings, their FE modelling and the results of the model updating, we refer to [10-13].

Figs. 3-5 show how much the computed frequencies differ from the measured ones. The relative error of the i^{th} computed frequency, $\text{err}_{i,\text{freq}} = (f_{i,exp} - f_{i,FE})/f_{i,exp}$, is shown, where $f_{i,exp}$ and $f_{i,FE}$ denote experimental and FE values. In spite of detailed FE models, the relative error for the two basic bending vibration modes is between -11.6 % and 0.7 % ($f_{i,FE}$ overestimates experimental natural frequency for $\text{err}_{i,\text{freq}} < 0$). It seems likely that the design prediction of the fundamental frequency of a multi-storey timber building (either by a simple empirical equation or by a FE model) will contain a significant error.

Reported measurements show that the damping ratio ζ of the fundamental frequency of a multi-storey timber building is between 1.2 % and 2.3 %, most commonly, between 1.5 % and 2.0 %, e.g. [14, 15]. For hybrid timber buildings, higher damping ratios were identified, between 1.5 % and 3.0 % [16], or even as high as 4.0 % [12]. In the case of long-term monitoring [16, 17], a large variance was observed for the identified damping ratio that may even be amplitude dependent. For the buildings from Fig. 1, the following ζ were identified for the first two vibration modes: 1.38 % and 1.74 % for Case study 1, 4.0 % and 3.0 % for Case study 2, and 1.5 % and 1.7 % for Case study 3.

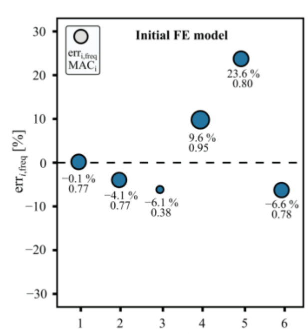

Figure 3: Comparison between computed and measured frequencies for Case study 1.

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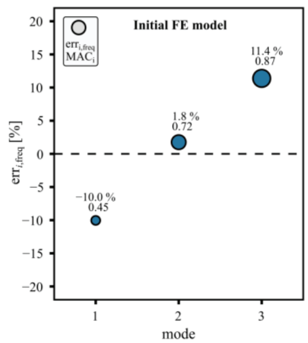

Figure 4: Comparison between computed and measured frequencies for Case study 2.

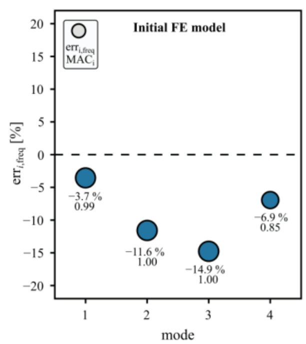

Figure 5: Comparison between computed and measured frequencies for Case study 3.

3 – COMFORT CRITERION CHECK

The first aim of the study was to check if the considered buildings fulfil the ISO 10137 [5] comfort criterion for the peak accelerations calculated in accordance with the procedure given in Annex B of EN 1991-1-4:2005 [7]. The first two bending vibration modes were considered.

The parameters used for calculation are shown in Table 1. The values for basic wind velocity were taken from the respective national annexes. For the natural frequencies, the measured values reported in [12-14] were used. The procedure from [7] assumes that the shape of the vibration mode is of the form $\phi(z) = (z/h)^{\xi}$, where z is coordinate in the direction of the height h of the building ($z = 0$ is at the ground). The damping ratio was conservatively assumed to be 1.2 %, so that the damping ratios identified with measurements (and reported above) were not taken into account initially. Calculations according to Appendix B of EN 1991-1-4:2005 take damping in the form of logarithmic decrement d, which is related to the damping ratio ζ as $d = 2\pi\zeta/\sqrt{1-\zeta^2}$ (for ζ =1.2 %, $d = 0.075$).

The second aim of the study was to check how changing some of the parameters listed in Table 1 affect the calculated characteristic peak acceleration and consequently the fulfilment of the comfort criterion.

As mentioned above, there is a lot of uncertainty about the damping. As for the design basic natural frequency (obtained by either empirical formula or FE model), it may substaintaly miss the measured natural frequency of the subsequently constructed building. Figs. 3-5 show for how much detailed best-engineering-judgement numerical FE models missed the experimental values. In five of six cases (looking only for the first two modes), the computed natural frequency was too high.

To see how variations of input parameters affect peak accelerations computed by [7], the following was done: (i) natural frequencies were changed for ± 20 %, (ii) damping ratio ζ was increased from an initial 1.2 % to 4.0 %, covering the values identified from measurements (reported above in Section 2), and (iii) the exponent ξ that defines the shape of the vibration mode in Appendix B of EN 1991-1-4:2005 was changed from the initial value of 1 to 0.6 and 1.5, covering the values found in [7].

4 – RESULTS

The results are presented in Figs. 6-9. Fig. 6 checks the comfort criterion for the data from Table 1. The Case study 1 just barely exceeds the limit curve for residential buildings. The Case study 2 is well below the curve due to its low height and high mass. Interestingly, the second mode has significantly higher peak acceleration value. For Case study 3, the calculated peak acceleration for the first mode significantly exceeds the proposed maximal values.

Fig. 7 shows how higher damping decreases peak accelerations. Taking measured values 1.38 % and 1.74 % for ζ for Case study 1, the latter fulfils the comfort criterion for a small number. Taking measured values 1.5 % and 1.7 % for ζ for Case study 3, the latter still misses significantly the comfort criterion for the first mode.

Fig. 8 shows that natural frequency error has a significant effect on calculated peak acceleration and consequently on the fulfilment of comort criterion. For too high estimation of natural frequency (with respect to the natural frequency of as-built structure), the error becomes favourable to the criterion. In other words, for an overestimated natural frequency, the design may fulfil the comfort criterion but the constructed building may not. For the buildings from Fig. 1, all but one computed natural frequencies were overestimated (looking only at the first two modes of vibration).

Table 1. Data for calculating characteristic peak along wind acceleration using Appendix B of EN 1991-1-4:2005 [7] for three buildings from Fig. 1.

Parameter	Case study 1	Case study 2	Case study 3
Basic wind velocity v_b	25.5 m/s	22.2 m/s	22 m/s
Terrain category	2	2	2
Height h	22 m	16 m	27 m
Mass of the building	1300 t	2000 t	1000 t
Equivalent mass m_e	59.1 t/m	125 t/m	37.0 t/m
Reduction factor for rounded corners ψ_r	1	1	1
Mode shape exponent ξ	1	1	1
The 1st natural frequency n_1	2.85 Hz	4.48 Hz	1.88 Hz
The 2nd natural frequency n_2	2.93 Hz	4.90 Hz	2.42 Hz
Logarithmic decrement d	0.075	0.075	0.075

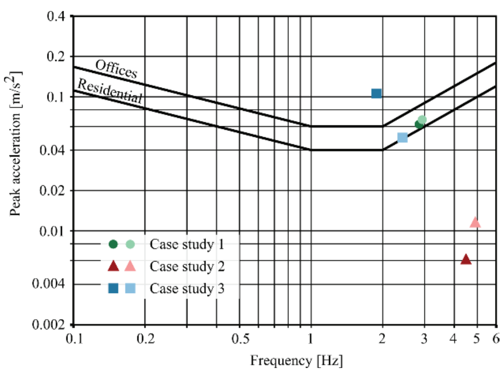

Figure 6: Comfort criterion check for the first two natural frequencies for the considered buildings.

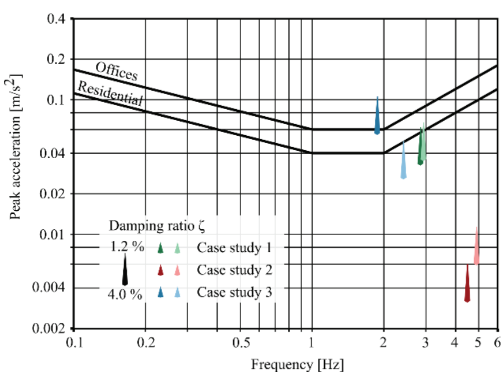

Figure 7: Change of peak accelerations for a variation of damping.

Comparing Figs. 7 and 8, it can be concluded that error in natural frequency has a greater impact on results then error in damping. Finally, Fig. 9 shows that assumption of the shape of vibration mode has a small effect on computed peak accelerations.

5 – CONCLUSION

The comfort criterion from ISO 10137 was checked for two CLT buildings and one hybrid concrete-CLT building. The peak accelerations entering the comfort criterion were computed for the first two vibration modes using measured data for natural frequencies and damping. The peak accelerations were computed by procedure proposed in Annex B of Eurocode EN 1991-1-4:2005.

It was found that eight-storey CLT building does not fulfil the comfort criterion, and that seven-storey CLT is just on the borderline of meeting the criterion.

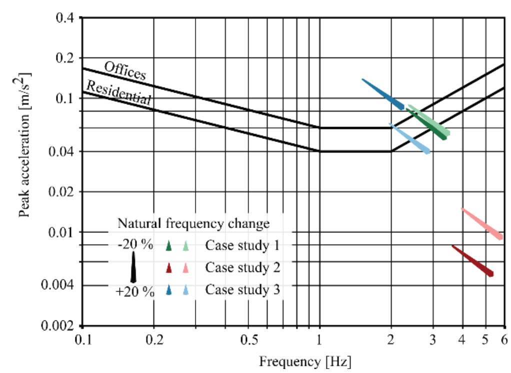

Figure 8: Change of peak accelerations for a variation of natural frequency.

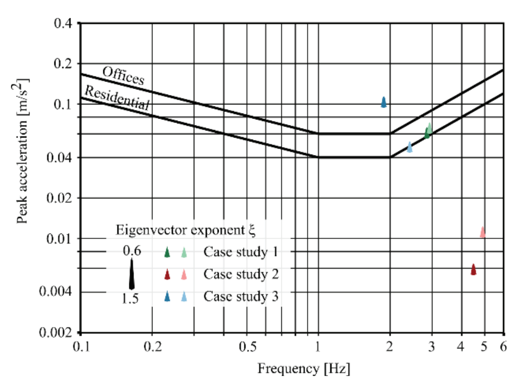

Figure 9: Change of peak accelerations for a variation of assumed mode shape.

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Furthermore, it was found that error in estimation of the natural frequency has significant effect on the fulfilment of the criterion. For a relatively small overestimation of natural frequency, the design may fulfil the comfort criterion but the constructed building may not. The errors related to damping and mode shape also affect the fulfilment of comfort criterion, but to a lesser extent.

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