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ON FINITE ELEMENT MODELLING AND MODEL UPDATING OF MULTI-STOREY TIMBER BUILDINGS

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ABSTRACT: The results of three case studies of timber and hybrid timber buildings have been reviewed. For each case study, experimentally obtained modal data was available. A detailed numerical finite element (FE) model of each building has been developed and used to carry out sensitivity analysis on the uncertain FE modelling parameters and model updating of the most influential input parameters. The importance of several modelling parameters and assumptions is discussed: perpendicular to the grain deformations of floor slabs, connections between cross-laminated timber panels, floor slab deformability, vertical foundation stiffness, and stiffness effect of the façade.

KEYWORDS: tall timber buildings, case studies, finite element model, model updating, modal properties

1 INTRODUCTION

In the last decades, there has been a large increase in the use of timber for multi-story buildings. One of the reasons is that it shows a potential for being a sustainable alternative to mineral-based materials [1]. This has been found through LCA studies showing significant reductions in embodied emissions when substituting timber for concrete [2] [3] [4]. Due to its light weight, timber might play an important role in sustainably densifying the cities [5], mainly by refurbishing existing buildings by adding new storeys or building new and taller buildings onto the existing foundation.

The structural design of a building is often governed by serviceability criteria [6]. For tall timber buildings, a key limitation regarding the serviceability is wind-induced vibrations [7] [8]. To satisfy current comfort criteria (e.g. ISO 10137 [9]) for wind-induced vibration an estimate of the fundamental frequency is needed. A simplistic estimation of the first natural frequency as $46/h$, where h is the height of the building in meters, is offered by Annex F of Eurocode 1 [10]. However, if wind-induced vibrations are governing design criterium, a more accurate estimation method might be desired. Often a finite element (FE) model is built, but there are some uncertainties when it comes to decisions about modelling assumptions.

Connections between CLT panels have been found to govern the behaviour of CLT buildings under seismic loads [11], however, there is no evidence to support similar claims for wind loads. Another uncertainty is connected to the contribution of non-structural elements to the global stiffness of the building. It was often found that for standard steel and concrete multi-storey buildings such non-structural elements increase the first natural frequency of the building [12] [13] [14] [15]. Additionally, for 3-storey OSB sheathed light-frame timber building it was found that non-structural elements increase the natural frequency of the building. It was also found that with increasing amplitude of excitation of the building contribution of the non-structural elements is smaller. Another study on laboratory-based 6-storey light timber-framed building [16] showed that both plasterboards and masonry façade significantly increase the natural frequency of the building. However, how to take them into account in the modelling of timber building is not clear. A large uncertainty is also attributed to the material properties of timber. For the shear modulus of CLT panels mean values of 450 MPa and 650 MPa have been proposed, based on whether narrow sides of boards are glued or not and whether cracks are present [17]. Besides the high variance of material properties of wood by itself, there is a large dependency of material properties on moisture content [18] which initially decreases after construction but then also changes seasonally [19].

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2 CASE STUDIES

Three case studies were conducted to learn about the as-built stiffness characteristics of the buildings. They followed a similar procedure.

In each, forced vibration tests were carried out, identifying modal properties (natural frequencies, mode shapes and damping ratios). For each of the three buildings, a numerical FE model was built to calculate the modal properties of the building. The FE natural frequencies and mode shapes were compared against the experimental. As a measure of mode shape correlation modal assurance criterion (MAC) was used. The model was then changed by adopting different modelling assumptions to see how the model can be improved. The influence of different modelling parameters was tested with the sensitivity analysis. The more influential parameters were then chosen to be updated in order to find the best match with the experiments. The objective function consisted of measures for comparing natural frequencies and mode shapes. After the model updating the updated parameter values were informative about the modelling error of the initial model. Individual findings and implications will be presented in the next section.

The first case study is Yoker (see Figure 1a) – a seven-storey timber building located in Glasgow, UK [20] [21]. It is fully constructed out of CLT in platform frame type. It has a distinct irregular shape of the building that strongly determines the dynamic properties of the building. The modal testing resulted in eight identified modes of vibration [22], though only the first six were successfully connected with the FE model.

The second observed building is Trinity College student residential five-storey building (see Figure 1b), located in Cambridge, UK [23]. It is a timber-concrete hybrid building with the basement and ground floor constructed out of reinforced concrete and the remaining four floors of the superstructure out of CLT. The building is cladded with a 100 mm self-supporting masonry wall, which is connected with the CLT load-bearing structure with steel horizontal ties. The building is located in a tight urban environment and is being in contact with the abutting building on one end. Modal testing identified three modes of vibration.

The third one is the Hyperion tower in Bordeaux (see Figure 1c), France, with a height of 56 m and 16 storeys. The first three levels are made of concrete and the 13 upper ones are composed of a concrete core, steel peripheral columns with infilled pre-manufactured timber-frame façade, CLT floors, and glue-laminated beams. Three modes of vibration have been identified with forced vibration tests.

3 FINDINGS FROM CASE STUDIES

The three buildings are substantially different in regard to their structural systems, heights and shapes. Each case study was a very unique investigation work to find a model that matches the experiments well. The most difficult was to obtain good MAC values and in each building, a different set of effects were identified that were crucial to obtaining good results. However, two effects had repeated:

1. Vertical stiffness is lower than what is anticipated when the foundation is modelled as rigid and the load-bearing structure is modelled with mean material properties. Not only compliance of the foundation is a possible cause for that, but also perpendicular to the grain deformations of floor slabs in platform frame type buildings could be a reason.

2. The shear stiffness of the CLT walls is higher than what is anticipated when only load-bearing structure is modelled and mean stiffness material properties are adopted. The most probable reason for that is a significant contribution of non-structural elements (such as façade, partition walls, plasterboards etc.), but also the uncertainty of material properties could play an important role. This effect was not found in the hybrid building with concrete core - Hyperion.

In regard to those two effects, several modelling assumptions are discussed below.

(a) (b) (c)

Figure 1 Three studied buildings: (a) Yoker, (b) Trinity, and (c) Hyperion.

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3.1 PERPENDICULAR TO THE GRAIN DEFORMATION

The two main types of framing for timber buildings are balloon and platform frame type. A well-known limitation of a platform frame are perpendicular to the grain deformations. Due to orthotropic material properties, with elastic modulus perpendicular to the grain being much lower than along the grain elastic modulus, floor slabs are being squeezed between the walls, as illustrated in Figure 2. The large weight of the building acting on a small area under the walls causes local deformations that might result in a damaged façade or plasterboards if the vertical differential movement is not allowed for in the design of those elements.

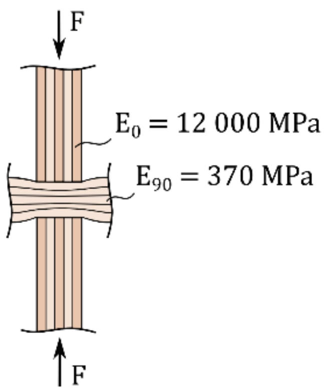

Figure 2 Perpendicular to the grain deformations of CLT floor slabs.

The same effect is observed when the global stiffness of the building is considered. Despite the almost negligible thickness of floor slabs, their vertical deformations are of comparable magnitude to those of the walls. The effect is explained more in detail in [20]. Calculations estimated that a reduction of up to 50 % in overall stiffness in the vertical direction is possible.

These local softening effects are difficult to model accurately when using shell elements. In Yoker and Trinity, this effect was modelled as a reduction of the elastic modulus of vertical layers of CLT walls (while horizontal layers remain unchanged).

Model updating of Yoker resulted in a 40-50% reduction of elastic modulus in the vertical direction, which parallels well with the simplified estimates of this effect's influence. However, reducing the stiffness of the foundation in the vertical direction causes a similar change in the model and, therefore, it is not certain which effect plays a more important role or how their influences are distributed.

This effect was also modelled for Trinity, but no conclusive results were obtained. The reason for that is the low influence of this parameter on the modal properties of the building as was shown with sensitivity analysis. Trinity is not as slender building and its fundamental modes are characterized more by shear rather than bending of the structure.

This effect was not present in Hyperion as loads of columns are not transferred over CLT floor slabs. The columns are stacked directly on top of each other.

Further research in a controlled environment is needed to more clearly understand the effect of perpendicular to the grain deformations on the overall stiffness of the building.

3.2 CONNECTIONS BETWEEN CLT PANELS

Connections between CLT panels pose a large uncertainty when it comes to their contribution of the dynamic properties of the building. In seismic design, connections seem to be the weakest link, however, when exposed to small amplitude excitation they might not contribute as much to the stiffness of the structure. The distinction here should be made between the connections that conjoin CLT walls and floors (in platform frame building), where large friction forces are to be exceeded before the connections are engaged and connections where no large axial forces help join CLT panels (e.g. in-plane connections between floor slab panels).

The stiffness of the connections between CLT walls (in Yoker and Trinity) was not directly modelled, rather a rigid bond was assumed. The contribution of the connections to the modal properties of the building is expected to be found indirectly from model updating. If the in-plane shear modulus of the CLT walls results in a lower value than what is proposed by its producers, connections might be responsible for such a reduction of stiffness. However, both case studies (Yoker and Trinity) concluded that the in-plane shear stiffness of the walls is higher than what was anticipated based on the mean material properties. In Yoker, the in-plane shear modulus was found to be around 60% higher than anticipated. In Trinity, shear stiffness was found to be at least 25% higher. This suggests that connections do not significantly reduce the overall stiffness of the building for small amplitude vibration.

In Hyperion, CLT panel are only used for floor slabs. They will be discussed in the following section.

3.3 FLOOR SLAB IN-PLANE DEFORMABILITY

Floor slabs being modelled as rigid diaphragms is a common assumption, but it may not always be suitable. For all three case studies, it was tested on the models and compared with the assumption of deformable CLT panels. The latter is considered as a more accurate model.

In Yoker, the assumption of a rigid diaphragm gives sufficiently good results for the first three modes (bending and torsion modes), however, to obtain higher modes, modelling floor slabs as deformable was necessary. Namely, higher modes consisted of substantial in-plane deformations of floor slabs. The study of Yoker also suggested that the connections between CLT panels of floor slabs might reduce the stiffness of the floor slabs,

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which differs from what has been discussed about the connections between walls and floor slabs in the previous section. Perhaps due to lower axial forces not offering strong friction between floor slab panels.
In Trinity, even the first modes needed floor slabs to be modelled as deformable. This was expected due to its low height.

In Hyperion, the assumption of rigid diaphragm doesn't change the first three natural frequencies significantly. It seems that the assumption is suitable for slender structures.

3.4 FOUNDATION MODELLING

Boundary condition that models soil structure interaction has a paramount influence on the dynamic properties of the building. Commonly, only a rigid foundation is assumed due to a lack of information and large uncertainty connected to the properties of the soil. For timber buildings, which are normally significantly lighter than reinforced concrete buildings, also significantly less material is used to form foundation. Its effect might be far from negligible. For the three observed buildings, the influence of the foundation was studied.

In Yoker, reducing the vertical stiffness of the building was necessary to improve the matching of the model to the experiments. Besides perpendicular to the grain deformations, which were discussed in Section 3.1, soil-structure interaction could be the reason behind the reduced stiffness of the building. In model updating, both vertical and horizontal stiffnesses of the foundation were included. Updated values suggested a rigid boundary condition for horizontal stiffness, but slightly compliant in the vertical direction.

In Trinity, modelling of foundation as flexible in the vertical direction was crucial to obtain a good match with the experimental modal properties. The updated value of the foundation stiffness reduced the stiffness of the building by at least 7% and 26% in the x and y directions, respectively.

Model updating of Hyperion also suggested that the foundation should be modelled as flexible in the vertical direction, whereas, constrained horizontal deflections do not worsen the accuracy of the model. If accurate modelling is desired, the stiffness of the foundations should not be neglected.

3.5 INFLUENCE OF FAÇADE

There is a variety of different façade solutions. Their stiffness properties and mounting to the load-bearing structure vary greatly, therefore, general conclusion for the façade are not possible. However, the three case studies may present an illustrative example.

In Yoker, the in-plane shear modulus of the walls was updated to a 60% higher value that the one proposed by the producers. Façade (together with other non-structural elements) could be the reason for this increase. Though the façade – acrylic brick slips – is quite thin and might not offer significant support.

In contrast, the façade of Trinity consists of 100 mm thick masonry cladding (self-supported masonry wall, connected to the load-bearing structure by horizontal steel ties). It was shown that the inclusion of the masonry cladding was needed and an important contribution to the modal properties of the building. Even when masonry cladding was modelled as an additional rigidly-bonded layer to the CLT, the in-plane shear modulus was updated to a value between 125 % and 210 % of the initial value (proposed by the producer). If the masonry façade was neglected almost a 400 % increase of CLT in-plane shear modulus was obtained from the model updating. This suggests a significant influence of masonry cladding on modal properties of the building.

Prefabricated elements are used for the façade of Hyperion. They are made of 10 mm cladding, 12 mm and 18 mm layers of OSB and 12 mm gypsum panels. The layers are connected with battens to make space for almost 0.5 m insulation and ventilation layers. Model updating of Hyperion did not provide definite conclusions on whether such a façade influences dynamic properties significantly. The governing structural system defining dynamic properties was a reinforced concrete core.

4 CONCLUSIONS

Three case studies of timber and hybrid timber buildings have been reviewed, and their findings are compared. In each, forced vibration testing has been performed to obtain at least 3 modes of vibration, finite element model has been constructed and updated based on the experimental results.

All three case studies showed that modelling foundation as slightly compliant in the vertical direction offers a more accurate prediction of modal properties. The updated stiffness of the foundation differed between the case studies. Two case studies of CLT buildings updated the shear stiffness of the walls higher than initially anticipated based on the assumption of mean material properties of the CLT (and neglecting non-structural elements such as plasterboards, façade, and partition walls). One of the case studies of a platform frame CLT building found a significantly reduced vertical stiffness due to perpendicular to the grain deformations of floor slabs. Case studies showed that the modelling assumption of the rigid diaphragm for floor slabs was suitable for tall and slender buildings in predicting the first three modes. The lower building was not successfully modelled with such an assumption.

The model updating of such complex systems can only be used to obtain such broad findings. For more precise conclusions (perhaps about the effect of connections between CLT panels), testing in a more controlled environment should be performed.

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