NUMERICAL METHODS FOR PREDICTING VIBRATIONS IN MULTI-STOREY WOOD BUILDINGS

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ABSTRACT: To design multi-storey wood buildings of adequate performance regarding noise and disturbing vibrations, it is desirable to have methods for predicting effects of structural modifications prior to construction. In this paper, the issues involved in obtaining reliable and computationally efficient numerical models are discussed. An overview of published research is given and ongoing research is presented.

KEYWORDS: Multi-storey buildings, Wood, Vibrations, Finite element method, Model validation, Model order reduction

1 INTRODUCTION

Compared to buildings with heavier load-bearing systems, it is more difficult to build lightweight structures in such a way that noise and disturbing vibrations are avoided. Multi-storey wood buildings are examples of lightweight buildings, traditionally constructed using low-stiffness panels mounted on high-stiffness beams. Many of the residents in such buildings perceive the impact sound as annoying even though the buildings fulfil the requirements for sound insulation, see for example [1-7]. Examples of impact sources in residential buildings are footfalls and dropped objects. Residents often describe the noise caused by the impacts as low-frequency “thumps” [1]. An illustration of transmission paths for impact sound is shown in Figure 1. In [2], a number of buildings were investigated by measuring sound insulation parameters according to ISO standards and collecting subjective ratings of the residents. The ratings indicated a high degree of annoyance to impact sound for those living in traditional wood buildings. Moreover, the correlation between impact sound insulation and annoyance as perceived by the residents was weak for such buildings. The impact sound insulation was measured according to ISO 16283-2, which accounts for frequencies above 50 Hz. The correlation was improved considerably by changing the lower limit of the frequency range to 20 Hz. These observations emphasise the need for improved low-frequency impact sound insulation in wood buildings.

To design buildings of adequate performance regarding noise and disturbing vibrations, it is desirable to have methods for predicting effects of structural modifications prior to construction. Testing prototypes and performing experiments is both time-consuming and expensive. A time- and cost-effective alternative is to employ numerical models for the predictions. In the development of such models, it is necessary to perform validations to experimental data to ensure that the predictions are made with sufficient accuracy. The finite element (FE) method is suitable for creating the numerical models as it can be used for problems involving complex geometries and many details, which is the case for the sound transmission in wood buildings. The numerical models easily become very large, exceeding the limits of computer capacity, at least for computations to be performed within reasonable time. The computational efficiency can be improved by employing model order reduction, which

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reduces the size and computational cost of the models without affecting the accuracy appreciably.

Since low-frequency noise from impacts is an apparent cause of annoyance for residents in multi-storey wood buildings, it is of particular importance to enable its prediction. The prediction of an acoustic pressure field can be divided into three parts: 1) predict the force caused by the impact source, 2) predict the transmission of vibrations from the location of the impact to the receiving room, and 3) predict the acoustic pressure field caused by the vibrations in the ceiling, walls and floor of the receiving room. In [8], numerical studies employing a 2D FE model showed that the acoustic pressure field in the rooms of multi-storey wood buildings has negligible effect on the transmitted vibrations. Hence, the second part of the prediction can be carried out independent of the third part. The research discussed in this paper focuses on the second part in the prediction.

1.1 AIM AND OBJECTIVE
The aim of the ongoing research is to improve the vibroacoustic comfort for residents in multi-storey wood buildings. To accomplish this, numerical models for predicting low-frequency vibrations in such buildings are developed for use in the design process. The objective is to create accurate and time-efficient models by validating them to experimental data and performing model order reduction of substructure models. Furthermore, the experimental and numerical studies contribute to an increased knowledge about the physics governing the vibration transmission. This facilitates the development of vibration reduction measures.

1.2 OUTLINE
Different matters related to the development of numerical models for predicting vibrations in wood buildings are discussed in the paper. An overview of published research is given and ongoing research is presented. In Section 2, building systems in wood are discussed, focusing on timber volume element (TVE) buildings, which are used as example case in many of the studies discussed in the paper. In Section 3 and Section 4, literature reviews and ongoing research related to validation and reduction of the numerical models are presented. Examples of studies using the models of wood buildings for engineering applications are presented in Section 5.

2 MULTI-STOREY WOOD BUILDINGS
The building systems for multi-storey wood buildings can be divided into three types [9]: 1) column-beam systems, 2) plate systems, such as cross-laminated timber (CLT) buildings, and 3) traditional wood-frame systems, where low-stiffness panels are mounted on frames of wood beams. A trend towards a higher degree of prefabrication has been observed in Sweden in recent years [9]. Traditional wood-frame systems are attractive from this perspective as they allow for a high degree of prefabrication; their load-bearing system can be divided into prefabricated volume elements and the light weight allows for transportation of rather large elements. An example of such a building system is TVE buildings, which have increased their market share in Sweden substantially during the last decades.

2.1 TIMBER VOLUME ELEMENT BUILDINGS
The conceptual layout of a TVE building is illustrated in Figure 2. Each TVE contains, for example, a small apartment or one room of a larger apartment. The floor, the ceiling and the walls consist wood-frames covered with particleboards or plasterboards or both. As much of the construction work as possible is performed at the factory, including electrical installations, flooring, wardrobes etc. An example of a TVE is shown in Figure 3. At the construction site, the prefabricated TVEs are stacked to form a complete building. In between the TVEs, elastomer blocks are placed to reduce the vibration transmission between storeys. The only additional connection is through a number of steel tie plates, ensuring the global stability of the building.

3 MODEL VALIDATION
In order to validate a model, there are a number of steps to be taken. First, the use and purpose of the model have to be defined so that appropriate validation requirements can be established and validation experiments can be carried out. The validation requirements specify the degree of accuracy for which the model is considered validated when comparing its predictions to the validation experiments. Having defined the use and purpose, an initial computational model has to be created by deciding on conceptual assumptions, mathematical descriptions
and numerical implementations. By performing calibrations and correlations, for example tuning material parameters and modifying connection models, the goal is to improve the model until it is able to generate predictions fulfilling the validation requirements. An introduction to model validation in structural dynamics can be found in [10-13] where the steps mentioned above as well as methods for modelling variations and uncertainties are discussed. An example of a validation procedure is presented in [14].

Ultimately, the purpose is to use the models discussed here for predicting acoustic pressure fields caused by impact sources. The pressure field will be predicted based on the vibrations in the ceiling, walls and floor of the rooms. Consequently, the use of the models discussed here is to predict the structural vibrations in the receiving room. The required accuracy of the predictions depends on the specific use of the model. If absolute vibration levels are sought, the requirements are likely to be different compared to situations where comparative studies are performed, for example investigating the relative effectiveness of different vibration reduction measures. No reliable models for predicting impact sound transmission in wood buildings exist as of today. The focus of today’s research is therefore not on performing pure validation tests, but rather on investigating the effect of making different conceptual choices in the models and on how to consider uncertainties and variations in the models. Nevertheless, it is important to keep in mind the ultimate use of the models so that the investigations are relevant and contribute to developing models that eventually can be validated against measurements on real buildings.

A conceptual assumption made in all the publications referenced in Section 3.1 is that the vibrations are of small amplitudes, so that any geometric or material nonlinearities can be neglected and linear models can be employed. The assumption is made because loads caused by impact sources in residential buildings, such as footfalls and dropped objects, are of relatively low amplitude. The dynamic behaviour of wooden building structures is rather complex due to the periodic structure of wood-frames and due to the many interfaces between beams and plates. This results in a need for a detailed description of the geometries, making the FE method a suitable choice for numerical implementation of the models. The FE models easily become very large, implying a need for model order reduction to improve the computational efficiency. This matter is discussed in Section 5.

3.1 LITERATURE REVIEW
There are a number of publications regarding correlation and validation of numerical models for predicting vibration transmission in wood buildings. Some publications, for example [15-18], discuss all steps in the prediction, including the impact force, the transmission through the building structure and the resulting acoustic pressure field in the receiving room. Those publications aim at developing computational models describing the standardised tests of impact sound insulation, in which a tapping machine is used as vibration source. In other publications, for example [19-27], the focus is on predicting the dynamic behaviour of the building structures.

In [15], FE models for predicting the impact sound generated by a tapping machine were developed and tested against results from laboratory measurements. The models considered, for example, air and insulation inside cavities between floor and underlying ceiling and the interaction between tapping machine and floor structure. Calibrations were performed for parameters of material models and of connection models by running an optimisation scheme, where the objective function was based on the difference between mobility functions from simulations and measurements. Probabilistic models were established for the calibrated parameters and included in stochastic models of the buildings structures. Monte Carlo simulations were used for the stochastic models to determine the variations of the output. The acoustic pressure field in the receiving room was predicted using the vibrations in the ceiling surface as boundary conditions, assuming a one-way coupling. The predictive capabilities of the numerical models were tested by performing laboratory studies with a setup similar to that in Figure 1, having a wooden floor-ceiling structure separating the two stacked rooms. The velocities in the ceiling surface and the impact sound pressure level in the receiving room were studied in the frequency-domain for third-octave bands up to 200 Hz. Results from measurements and modelling were presented, the latter both for a deterministic model and for a stochastic model in terms of confidence intervals. Although the predictions display trends similar to the measured ones, they are not convincing around the first resonance frequency. It is not possible to point out any dominating source of error as no eigenvalue analyses are presented and since the third-octave bands can comprise several resonances. An important conclusion from the studies is that the predicted force spectrum of the tapping machine can be regarded as deterministic, so that the force spectrum can be calculated by using a deterministic model of the floor. In [16], a similar study is presented. It focused on the prediction of the force spectrum, the modelling of the damping and the calculation of the acoustic pressure field, while less attention was given to the FE modelling of the structure. As in [15], the pressure field in the receiving room was assumed to not affect the structural vibrations and it was, hence, calculated by using the vibrations as boundary conditions. Predictions of impact sound levels are presented in third-octave bands between 50 and 2000 Hz and compared to measurement results for similar floors, tested in different laboratories. The measured impact sound levels are presented in intervals calculated as the mean value ±2 standard deviations, resulting in ranges of up to 15 dB per third-octave band. It is therefore difficult to draw any conclusions regarding the accuracy of the predictions. In [17], a CLT floor was investigated, focusing on the FE modelling of the floor and on the prediction of the radiated sound power in the receiving room. The floor consisted of a number of CLT plates, the
Models were created for 22 experimentally tested floors. All floors consisted of wood-frames covered with plywood or oriented strand board, some of them having lateral reinforcement between the wood beams. Material properties of the wood beams were determined from measurements on each beam. Values of the slip modulus were taken from literature whereas the withdrawal moduli were determined from static measurements on several types of connections. Sensitivity analyses showed that the fundamental frequency was insensitive to changes in the withdrawal modulus. The slip modulus, however, had a larger effect on the frequency. Similar models were developed in [23], but without measuring the material properties of each beam. The correlation in eigenmodes and eigenfrequencies was studied for the first five modes of six experimentally investigated floors. It was concluded that modelling the elasticity of the junctions and of the supports, was important for improving the accuracy. The correlation in eigenfrequencies for the final models was, however, relatively poor.

In [24], a FE model was created for an experimental wooden assembly consisting of a floor connected by elastomers to three underlying walls. The elastomer junction in the assembly resembles the sort found in TVE buildings. The simulated eigenmodes were compared to results from an experimental modal analysis. Discrepancies between the two sets of mode shapes were identified. For example, the building parts were interacting more in the experimental mode shapes. The

Figure 4: The experimental wooden floor-wall structure investigated in [20].

Figure 5: The first eigenmode from simulations of the wooden floor-wall structure investigated in [20].
authors pointed out the modelling of the elastomers as a likely source of error. The elastomers were modelled as spring-dashpots in three directions, not taking the rotational stiffness into account and neglecting any frequency-dependence of the elastomer properties. In [25], an elastomer junction similar to the ones found in many wood buildings was studied experimentally and numerically for frequencies below 100 Hz. The junction consisted of an elastomer strip connected to steel parts on two sides. The steel parts had eigenfrequencies well above the 100 Hz limit. Numerical modal analysis of the setup showed that using the static stiffness of the elastomers resulted in large errors, leading to the conclusion that it is necessary to consider the acoustic media. It remains to determine how they should be handled. As of today, there are no studies investigating how the variations in a TVE structure affect the sound level at a receiver, which is likely to contribute to the sound level in the receiving room. Also, neglecting the walls introduces errors in the boundary conditions for the floor and the ceiling. Another uncertainty as of today is how the air and insulation in cavities of the buildings should be modelled in order to accurately predict the vibration transmission. In [18], it was concluded that it is necessary to model the air using acoustic finite elements in order to predict the transmission from a CLT floor to its suspended ceiling. The connections between the CLT floor and the ceiling are very different from the connections in a TVE building, in which the floor is separated from the ceiling so that the shortest transmission path is through the elastomers placed between the walls of the different storeys. Another difference between the structures is that the cavities in TVE buildings contain insulation, whereas the cavity in the structure studied in [18] comprised only air. The effect of modelling air and insulation in cavities of TVE buildings was investigated in [27]. It was concluded that modelling the air and insulation by using acoustic finite elements had a marked effect on the vibration transmission from a floor to the ceiling and walls of the storey below. It was, however, not investigated if simpler models of the acoustic media, such as a spring-dashpot representation, could be used to predict the transmission.

The illustration in Figure 1 shows examples of transmission paths for vibrations originating from impact sources. The studies in [15-18] have in common that they consider only the direct transmission and neglect the remaining paths. As of today, there are no studies investigating the effect of neglecting the transmission to the walls, which is likely to contribute to the sound level in the receiving room. Also, neglecting the walls introduces errors in the boundary conditions for the floor and the ceiling. Another uncertainty as of today is how the air and insulation in cavities of the buildings should be modelled in order to accurately predict the vibration transmission. In [18], it was concluded that it is necessary to model the air using acoustic finite elements in order to predict the transmission from a CLT floor to its suspended ceiling. The connections between the CLT floor and the ceiling are very different from the connections in a TVE building, in which the floor is separated from the ceiling so that the shortest transmission path is through the elastomers placed between the walls of the different storeys. Another difference between the structures is that the cavities in TVE buildings contain insulation, whereas the cavity in the structure studied in [18] comprised only air. The effect of modelling air and insulation in cavities of TVE buildings was investigated in [27]. It was concluded that modelling the air and insulation by using acoustic finite elements had a marked effect on the vibration transmission from a floor to the ceiling and walls of the storey below. It was, however, not investigated if simpler models of the acoustic media, such as a spring-dashpot representation, could be used to predict the transmission.

3.2 ONGOING AND FUTURE WORK

There are several uncertainties to be investigated before reliable numerical models for predicting vibration transmission in multi-storey wood buildings can be established. An example is the effect of variations between nominally identical structures caused by, for example, the material properties of wood and the mechanical properties of junctions, which depend on the workmanship. The variations can be accounted for in the models by using probabilistic parameters. However, this increases the computational cost significantly, so it should be carefully investigated how the variations should be modelled. Another uncertainty that needs to be addressed is the effect of details such as windows, floors, surface layers and furniture. Moreover, and as mentioned above, it remains to be investigated how much of the buildings geometry that needs to be included in the models to obtain realistic boundary conditions and to account for all the possible sound radiation sources in the receiving room. The different uncertainties can be investigated by performing sensitivity analyses. An example is to propagate the probabilistic distributions of material properties through an FE model in order to study the distribution of the output. In order to perform the sensitivity analyses, it is necessary to develop a deterministic model to use as benchmark model. An ongoing project carried out by the authors of this paper, the aim is to establish such a model. The model is being developed by performing calibration and correlation experiments for a wooden building structure representing parts of two stacked rooms in a TVE building. A drawing of the structure is shown in Figure 6. It includes a floor in the upper room, a ceiling in the lower room and walls in both rooms. The only connection between the two stacked rooms is through a number of elastomer blocks. The structure was scaled-down in size compared to real buildings, the scaling procedure being described in [28].

Further research is required for the modelling of acoustic media in cavities. The results in the literature discussed in Section 3.1 indicate that it is necessary to consider the acoustic media. It remains to determine how they should

Figure 6: The wooden building structure investigated in an ongoing project carried out by the authors of this paper.
be modelled, for example: which porous material models should be employed, in which parts of the buildings do they need to be considered, and can their effect be accounted for in a simpler manner than using acoustic finite elements. Involving acoustic finite elements increases the computational cost significantly and should therefore be avoided if possible.

4 SUBSTRUCTURE MODELLING

Substructure modelling is a methodology frequently used for reducing large numerical models. The methodology is illustrated in Figure 7. It is based on the division of structures into substructures, which are reduced in size and assembled to form reduced global models. In structural dynamic analysis, substructure modelling provides a flexible and practical framework, enabling a combination of full numerical models and reduced order models of the substructures. The framework also allows for integration of experimental substructures represented by measured data into assemblies of numerical models. For a description of the historic development of substructuring and a classification of methods, see [29].

The computational cost of analysing models of the sort described in Section 3.1 varies and is a consequence of the physical phenomena considered in the models as well as the level of details and the discretisations in both space and time (or frequency). Some models can be analysed on desktop computers in the matter of minutes, whereas others require days to be analysed even with the use of modern computer cluster. It is, however, beneficial to reduce the computational cost regardless of whether the analyses takes minutes, hours or days, as the reduction allows for a greater number of analyses of the models. A reduction in computational cost is especially valuable when developing vibration reduction measures since short computation times enables the use of optimisation algorithms that require a large number of analyses. A reduction also allows for more extensive parameter studies to be performed, which in turn can facilitate the understanding of the physics involved in the vibration transmission.

The division into substructures of FE models of wood buildings can be performed in many different ways. The choice of the partitioning affects the computational efficiency of the reduced global model. It also affects the computational cost involved in establishing the reduced basis for each substructure. All methods for model order reduction involve analyses of the full model for establishing the reduced basis. Consequently, a benefit of substructure modelling is that it enables reduction of models that are too large for analyses to be feasible, since the substructures can be reduced independent of each other. The division into substructures should be performed with the model use in mind. For example, if the model is used for parametric studies of a specific detail in the building, it can be suitable to consider the detail as a separate substructure. The reason is that changing the parameters of the detail affects only that substructure, whereas the remaining substructures are unaffected and can be reused without recalculating the reduced bases.

4.1 LITERATURE REVIEW

In [30], different methods for model order reduction were applied to FE models of wooden building structures, without considering the acoustic media. A wide range of methods for model order reduction were, for two example models of wooden floors, compared in terms of their effect on the relative error in eigenfrequencies and in amplitudes of transmitted vibrations. The two floor structures that were studied are of the type used in TVE buildings, i.e. primary wood beams supporting a particleboard plate. In the reduced models, the physical dofs were retained at the interfaces where such floor structures could be connected to the surrounding walls. The retained physical dofs were, for some of the reduction methods employed, complemented by sets of generalised dofs. The computational efficiency of the reduced order models depends on the number of retained physical dofs at its interfaces. For substructures having a large number of such dofs, interface reduction methods can be applied to improve the computational efficiency. In [31], different methods were compared when being applied to interfaces between wooden building structures and elastomers. As in [30], the acoustic media in cavities were not considered. The example case studied was an FE model of a wood floor and an underlying wood ceiling, connected through a number of elastomer blocks. The floor-ceiling structure resembles the ones found in TVE buildings. It was found that a significant reduction in the number of interface dofs was possible without affecting the accuracy appreciably, provided that suitable methods are employed. Together, the results in [30] and [31] can be utilised to create computationally efficient assemblies of substructure models of wooden building structures. In [15], an FE description of the acoustic domain was used in the model of a floor-ceiling structure. The model was reduced by calculating the reduced bases of the structural and
acoustic domains separately and coupling those bases. No results were, however, presented regarding the effect of the reduction on the computation time and accuracy of the model under study.

4.2 ONGOING AND FUTURE WORK

In ongoing research by the authors, it is investigated how the reduction of interfaces between elastomers and wooden structures (as discussed in [31]) can be supplemented with a reduction of internal dofs of the elastomer models. Through such a reduction, the idea is to replace the FE models with coupling elements represented by only a few dofs that can be used for assembling substructure models of the wooden building structures. The coupling elements account for the frequency-dependent properties as well as different types of deformations (bending, shear and torsion) of the elastomers. The computationally efficiency of the coupling elements is comparable to conventional linear spring-damper models when performing steady-state analyses of the substructure assemblies.

As research on how to model acoustic media in cavities of wood buildings proceeds, there is a need to investigate different methods for integrating those models into assemblies of reduced substructure models. The approach adopted in [15], where FE models including both structural and acoustic domains were reduced by considering the two domains separately, is not necessarily the most efficient. An alternative is to include the floor, the ceiling and the acoustic media in a single substructure. The reduced basis of that substructure is then constructed through analyses of the coupled structure-acoustic system. There is always a trade-off between accuracy and computational cost when creating a model, made with the model use in mind. Increased knowledge regarding the accuracy and computational cost associated with different methods for reducing the structure-acoustic models will facilitate the choice of methods.

5 ENGINEERING APPLICATIONS

Once validated models are established and efficient enough for analyses to be feasible, they can be employed for predicting the effects of structural modifications. As of today, most of the studies regarding the efficiency of vibration reduction measures in wood buildings are purely experimental, see for example [32]. A numerical study was, however, performed in [33] by employing a model based on the results in [30, 31]. In that study, it was investigated to which extent different designs of elastomer junctions in TVE buildings affect the transmission of low-frequency vibrations (below 100 Hz). Parametric studies were carried out, considering different properties and placements of the elastomers. It was found, for example, that a too stiff elastomer could result in an amplification of the transmitted vibrations for certain frequencies.

REFERENCES


