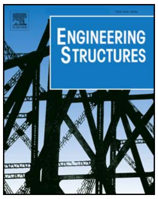
Engineering Structures 157 (2018) 27–41

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct



A multi-level model correlation approach for low-frequency vibration transmission in wood structures

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ARTICLE INFO

Keywords:
Structure-borne sound
Vibration transmission
Wood buildings
Finite element method
Model correlation

ABSTRACT

The main challenge in predicting structure-borne sound in wood buildings is to accurately model the vibration transmission between the source and the receiving room. Large variations in model parameters make it difficult to predict absolute vibration levels and to make conclusions regarding the relative effects of different designs. A step towards establishing reliable models is to investigate the possibilities and limitations of using deterministic methods, which requires correlations between simulations and measurements. In this paper, we present a multi-level model correlation approach for low-frequency vibration transmission in wood buildings. We apply the proposed approach to a scaled-size experimental structure representing a part of a two-storey wood building, and we evaluate the results for frequencies up to 100 Hz. We perform correlations between simulations and measurements four different levels: structural components (viz. beams and boards), planar structures (viz. floor, ceiling and walls), room structures and the complete structure. The results indicate that the dynamic behaviour of the experimental structure was to a great extent captured by the developed model. Based on the observations made in the multi-level correlations, we discuss important model parameters and propose modelling guidelines. We conclude that it is possible to employ deterministic methods in order to simulate the low-frequency vibration transmission in wood buildings provided that measurement data for calibration purposes are available. The developed numerical model can be used as a reference model for investigations on the effects of variations and uncertainties in the modelling.

1. Introduction

1.1. Background

Many residents in multi-storey wood buildings perceive structure-borne sound as being annoying, even though the buildings may fulfil regulations regarding sound insulation. This issue has been given much attention by researchers during the last decades, and the low-frequency sound transmission has been pointed out as the main reason behind the complaints [1–8]. In [8], the impact sound insulation in eight wood buildings was measured according to standardised procedures. The measured impact sound insulation was compared to subjective ratings obtained from residents, and it was found that it is necessary to evaluate frequencies below 100 Hz in order to correlate measurements to subjective ratings. These observations prove the need for improved low-frequency structure-borne sound insulation in wood buildings. To improve the sound insulation, and thus the acoustic comfort levels of residents, it is important to obtain accurate numerical models to enable the prediction of the effects of noise-reduction measures. By performing numerical simulations, the performance of reduction measures can be optimised. Another benefit of using numerical simulations is that they provide additional insight into the physics governing noise and vibration transmission; the results of simulations can be visualised in more detail compared to experimental results, and parametric studies can be carried out to demonstrate the effects of changes in specific design parameters.

Prediction of structure-borne sound in buildings can be divided into three tasks: (1) predicting the input force caused by the source, (2) predicting the transmission of structural vibrations from the source to the receiving room, and (3) predicting the sound pressure caused by the vibrations in the receiving room. Attempts to predict all three steps for the low-frequency transmission in wood buildings are presented in [10–13] for the case when the ISO tapping machine [9] is used as source. Comparisons of results obtained from finite element (FE) analyses and measurements show poor accuracy in all of the studies. In [12], the structure-borne sound transmission through a cross-laminated timber structure was tested in a laboratory and compared to simulated results. It was concluded that the radiated sound power in the receiving

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https://doi.org/10.1016/j.engstruct.2017.11.062
Received 22 December 2016; Received in revised form 3 November 2017; Accepted 23 November 2017

(a) *Rendering of the structure when cut perpendicular to the primary beams in the floor and in the ceiling. Wood beams are shown in beige, particleboards in brown, plasterboards in grey and elas-*

(b) *Photograph of the experimental setup for the structure.*

Fig. 1. The experimental wooden building structure studied in the paper. The structure represents part of a two-storey TVE building.

room can be predicted with good accuracy when measured vibrations in the ceiling of the receiving room are used as input. Hence, the main challenge in predicting structure-borne sound in wood buildings is to accurately model the structural vibration transmission between the source and the receiving room.

The model correlation studies we present in this paper were performed for an example case representing a part of a timber volume element (TVE) building. Such buildings are constructed by stacking prefabricated volume elements with elastomeric isolators between storeys to reduce vibration transmission. The volume elements are composed of frames of wood beams covered with plates, usually particleboards and plasterboards. TVE buildings account for 10–15% of newly developed apartments in Sweden, and the market share is increasing steadily [14], which makes the buildings suitable for use as example cases in the studies.

There are several publications presenting model correlation studies for finite element (FE) models of low-frequency vibrations in wood buildings. Those publications focus on, for example, joints between beams and boards [15,16] and elastomeric vibration isolators used in wood buildings [17–19]. However, there is a lack of model correlation studies that thoroughly investigate the vibration transmission between storeys, which is the focus of this paper. It is challenging to develop deterministic models of wood buildings because of several uncertainties, such as how to model the many joints between structural components. Another uncertainty relates to determining how to account for the variations in the material properties of wood as well as the mechanical behaviour of joints, which cause variations in vibration transmission among buildings, which are identical in theory. Variations may be considered in deterministic models by using, for example, Monte Carlo simulations. However, it is inevitable that the deterministic strategy fails outside a certain frequency range because of the increasing effects of details at higher frequencies. The question is to what extent the deterministic strategy is relevant for the frequency range of interest, and when to accept a less detailed modelling strategy, such as statistical energy analysis (SEA). SEA methods are widely used for the analysis of high-frequency noise transmission in residential buildings. Such methods consider the energy flow between subsystems and require high modal density of the subsystems to yield accurate results. This is not the case at lower frequencies in which small sets of vibration modes govern the response. Compared to SEA methods, deterministic methods have the advantage of allowing for a more detailed description of the structure under study, and they therefore facilitate studies of design modifications.

1.2. *Aim and objective*

The aim of this research is to develop numerical models and strategies for the prediction of low-frequency (0–100 Hz) vibration transmission in wood buildings. A step towards establishing such models is to investigate the possibilities and limitations of using deterministic methods, which requires correlations between model output and measurement data. In this paper, we present a multi-level model correlation approach for low-frequency vibration transmission in wood buildings. We apply the multi-level approach to an experimental wooden building structure representing a part of a two-storey building. The objective is to establish a correlated deterministic numerical model that can be used as a reference model for investigations on the effects of variations and uncertainties in the modelling. We evaluate the accuracy of the model developed in the study in order to determine how well the vibration transmission can be predicted when measurement data for calibration purposes is available. Based on the observations that are made in the multi-level correlations, we discuss important model parameters and propose modelling guidelines.

1.3. *Outline of the multi-level approach*

Correlations between FE simulations and measurements were performed for the experimental wooden building structure shown in Fig. 1. The FE model of the structure was calibrated and correlated to measurements by employing the multi-level approach illustrated in Fig. 2. Here, we define the term ’model correlation’ as any type of comparisons between simulated and measured results which aim to identify and reduce modelling errors. The comparisons presented in the paper are based on the normalised relative frequency difference (NRFD) and the modal assurance criterion (MAC), which are objective measures of the errors in eigenfrequencies and mode shapes. Calibration, on the other hand, is defined as the procedure of improving estimates of uncertain model parameters. The steps in the multi-level approach can be summarised as follows:

1. **Initial numerical model.** An initial FE model was created by using material parameters obtained from the literature and by connecting parts using simple joint models. The model was used as a starting point for the model correlation studies and to perform pre-test analyses of the experimental setups.
2. **Correlation of structural components.** FE models of the wood beams, particleboards and plasterboards were calibrated in order to obtain the material parameters that result in the best correlation between simulated and measured eigenfrequencies.
3. **Correlation of planar structures.** Simulated eigenfrequencies and mode shapes of the floor, ceiling and walls were correlated to measurement results. The effects of using the optimised material parameters obtained in step 2 were investigated and errors in the modelling of the joints between beams and boards were identified.