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The effect of modelling acoustic media in cavities of lightweight buildings on the transmission of structural vibrations

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ABSTRACT

Determining the dynamic behaviour of lightweight buildings by means of finite element analyses requires models representing the geometry involved in great detail, resulting in systems having many millions of degrees of freedom. It is, therefore, important to avoid unnecessarily detailed models by carefully considering what is essential to include in the models and the level of details required for describing the phenomena of interest accurately. In the study presented here, it was investigated whether or not air and insulation in cavities of multi-storey wood buildings affect the transmission of low-frequency structural vibrations. It was concluded, by means of numerical studies, that including air and insulation in cavities, modelled as acoustic media, affects the transmission from a floor to the underlying ceiling and surrounding walls.

1. Introduction

In 1994, a century-old ban on the construction of wooden buildings more than two storeys in height in Sweden was lifted, leading to the reintroduction of such structures. Compared to heavier structures, the lightweight buildings are more sensitive to vibrations, making it difficult to construct multi-storey wood buildings in such a way that noise and disturbing vibrations in the different storeys and rooms are avoided. Specifically problematic is the issue of low-frequency vibrations [1]. Wooden constructions involving long spans have low resonance frequencies that, in combination with low damping, are easily excited by loads with low-frequency content. The vibrations can be caused by, for example, footsteps, airborne sound, vibrating machines and external sources such as railway and road traffic. To design buildings of adequate performance regarding sound and vibrations, it is desirable to have tools for predicting the effects of structural modifications prior to construction. Testing prototypes and performing experiments are both time-consuming and expensive, the long-term aim therefore being to develop prediction tools that are valid for general load-cases by making use of finite element (FE) models.

Accurately assessing the dynamic behaviour of multi-storey lightweight buildings, even at lower frequencies, requires FE models representing the geometry in considerable detail, resulting in the models being very large. The number of degrees of freedom of such models easily exceeds the limits of computer capacity, at least for computations to be performed within reasonable time. It is, therefore, important to avoid unnecessarily detailed models by carefully considering what is essential to include in the models and the level of details required for describing the phenomena of interest accurately. The issue considered here is whether or not air and insulation in cavities of multi-storey wood buildings affect the transmission of structural vibrations.

The acoustic pressure field in a room can interact with the vibrations in the floor, ceiling and walls. For heavier structures, the acoustic pressure waves usually have a negligible effect on the structural vibrations. It is, therefore, possible to analyse the acoustic pressure field by applying the structural displacements, obtained from a precedent analysis of the structural domain, as boundary conditions. Moreover, the effect of the acoustic media in a structure, on the transmission of structural vibrations, depends on the flexibility of the structure, a more flexible structure tending to interact more with the acoustic media. It was concluded in [2] that the acoustic pressure field in the rooms is negligible also for lightweight buildings; studies on a 2D FE model of a two-storey wood building showing that the effect of including air in the rooms, on the displacements of the building, is small for frequencies below 250 Hz. The air was modelled to have a realistic acoustic damping, which is present in buildings due to objects and porous materials such as curtains and carpets.

In multi-storey wood buildings, there are acoustic media not only in the rooms, but also in the many cavities containing both air and insulation. The effect of modelling air in cavities of lightweight

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double-plate wall panels was investigated in [3,4]. In [3], the vibration transmission was investigated for a model including two double-plate wall panels connected in an L-shape, with and without air in the cavities. Both eigenvalue and steady-state analyses showed that the inclusion of air in the cavities of the structure has a large effect on its dynamic characteristics at high frequencies and a noticeable effect already at the first eigenfrequency. In [4], the response of a double-plate wall panel, with and without air in the cavities, exposed to diffuse field excitation was investigated. Simulations in terms of eigenvalue and steady-state analyses showed that the air has a negligible effect on the dynamic characteristics of the structure, contradicting the results in [3].

The studies presented here aim at determining whether or not air and insulation in cavities have to be considered when performing numerical analyses of the low-frequency vibration transmission in multi-storey lightweight buildings. The low-frequency range is defined here as frequencies below 200 Hz. As a first step, different porous material models for modelling of the insulation were compared, a frame of a double-plate wall panel being employed as a test model. Subsequently, numerical studies were carried out for a section of a multi-storey wood building constructed with timber volume elements (TVEs), such buildings being described in Section 1.1. The response of a floor, exposed to a harmonic point load, and the vibration transmission from the floor to the underlying ceiling and the surrounding walls were investigated, comparing FE models including air and insulation as acoustic media in cavities to models without acoustic media.

The models employed in the numerical studies are representative for a wide range of residential wood buildings of the type studied here, in terms of both dimensions and material properties. It is, therefore, believed that the conclusions presented in the paper are valid for such structures. Moreover, a wide range of frequencies are considered, resulting in the same phenomena being captured also for models having slightly different dimensions, as the shift in eigenfrequencies in such cases is small compared to the width of the frequency range.

1.1. Timber volume element buildings

The conceptual layout of a TVE building is illustrated in Fig. 1. A TVE is a prefabricated volume module consisting of wood framed floor-, roof- and wall-elements, each TVE typically constituting a small apartment, one room or part of a larger room. As much of the construction work as possible is performed indoors at a factory, including electrical installations, flooring, cabinets, wardrobes etc. The prefabricated modules are transported to the construction site where they are stacked to form a complete building. In between the TVEs, several elastomer blocks are introduced to reduce the flanking transmission of vibrations. Each elastomer block has an interface area of approximately $0.1 \times 0.1\ \mathrm{m}^2$ and is placed between the walls of two stacked modules. The only additional connection between modules is through a number of tie plates, ensuring the global stability of the building. Vibrations transmitted in TVE buildings are, therefore, mainly passing through the elastomer layers or through the air and the insulation in the cavities of the buildings. The FE models employed in the numerical studies presented here were constructed according to the drawings shown in Fig. 2.

2. Governing theory

2.1. Structure–acoustic analysis

Structure–acoustic systems can be analysed by deriving FE formulations for both the structural domain and the acoustic fluid domain. By imposing continuity conditions for displacements and pressures at domain-separating boundaries, the domains form a coupled FE equation system. Vibrations in lightweight buildings are usually of such amplitudes that any non-linear behaviour can be neglected and, therefore, linear behaviour is assumed here for both domains. In the following derivations, a subscript S denotes a quantity in the structural domain, whereas a subscript F indicates a quantity in the acoustic fluid domain.

2.1.1. Structural domain

The equations describing the structural domain follow the notation in [6]. For a detailed derivation of the FE formulation of a solid, see e.g. [6,7]. The differential equation of motion for the continuum formulation of a three-dimensional solid, occupying the domain Ω_S, is given by

$$\tilde{\nabla}^T \boldsymbol{\sigma}_S + \mathbf{b}_S = \rho_S \frac{\partial^2 \mathbf{u}_S}{\partial t^2}, \tag{1}$$

where $\boldsymbol{\sigma}_S$ is the matrix representation of the stress tensor, $\mathbf{b}_S$ is the body force vector, ρ_S is the mass density, $\mathbf{u}_S$ is the displacement vector, $\tilde{\boldsymbol{\nabla}}$ is a differential operator matrix and t is the time [8]. A FE discretisation and use of Galerkin's method results in a FE formulation in the structural domain, given by

$$\mathbf{M}_S \ddot{\mathbf{a}}_S + \mathbf{K}_S \mathbf{a}_S = \mathbf{f}_{l,S} + \mathbf{f}_{b,S}, \tag{2}$$

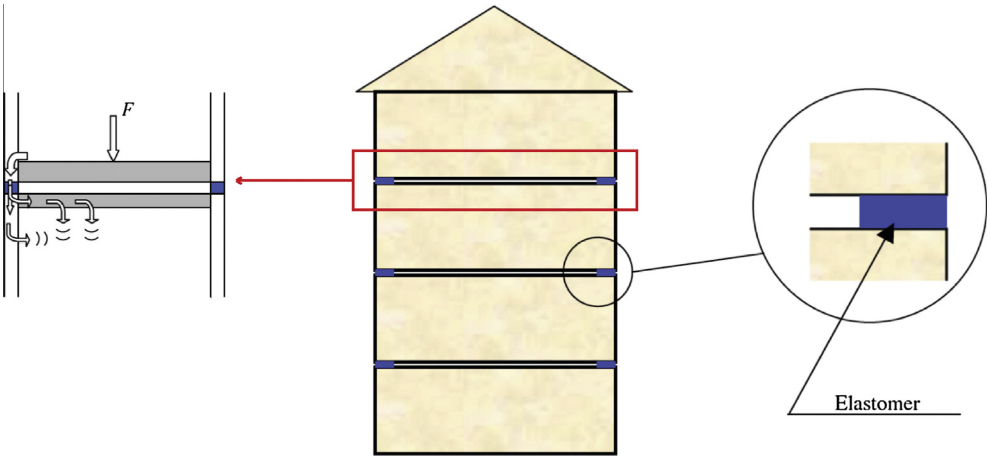

Fig. 1. Sketch of a TVE building [5]. The path of structural vibrations between storeys is illustrated in the figure to the left and an elastomer block is illustrated in the figure to the right.