Engineering Structures 148 (2017) 602–620

Contents lists available at ScienceDirect

Engineering Structures

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

Structural dynamics of a dowelled-joist timber floor in the low-frequency range modelled using finite element simulation

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ARTICLE INFO

Article history:
Received 22 February 2017
Revised 3 July 2017
Accepted 4 July 2017

Keywords:
Timber floor
Dowel connections
Vibration
Modal analysis
Vibration serviceability
Eurocode 5

ABSTRACT

This paper concerns the development and validation of Finite Element Methods (FEM) to simulate the dynamic response of a dowelled-joist timber floor. This is a solid floor comprised of timber joists connected using timber dowels with individual assemblies connected using inclined metal screws. The focus is on the structural dynamics in the low-frequency range up to 200 Hz which is the relevant range for impact sound insulation and vibration serviceability. Dowel connections between the joists that formed each assembly were modelled using either rigid or spring connectors in the FEM models. The validation against experimental modal analysis showed that both approaches were valid in terms of the eigenfrequencies, Modal Assurance Criterion (*MAC*) and the spatial-average velocity with point excitation. Whilst the FEM model with spring connectors had a higher number of correlated modes in the *MAC* analysis, this required removal of many spurious modes before predicting the response. The validated models were used to demonstrate the potential in predicting assessment parameters for vibration serviceability that are contained in EN 1995-1-1 (Eurocode 5). This predictive approach to the evaluation of vibration serviceability has the advantage in that it can be used for non-standard timber floors with non-standard boundary conditions or floor plans.

1. Introduction

Timber floor systems are used as separating floors between dwellings in multi-storey buildings as they are a sustainable, economical, lightweight solution. For commercial and residential buildings in Switzerland there is interest in producing a solid floor with timber joists connected using timber dowels. These form wooden assemblies which can be connected to each other using inclined metal screws. This work concerns the development and validation of a model to describe the dynamic response of this dowelled-joist timber floor in the low-frequency range using Finite Element Methods (FEM). The aim is to produce experimentally-validated FEM models for the dynamic behaviour. Such models would allow future development of prediction models for impact sound insulation and inform assessments of vibration serviceability; hence the validation focuses on the low-frequency range that is relevant to these applications.

Impact sound insulation is important because typical timber joist floor systems tend to provide lower insulation than concrete floors in the low-frequency range (below 200 Hz) [1,2]. For this reason the prediction of impact sound insulation is critical at the design stage. Prediction models tend to be based on deterministic approaches such as Finite Element Methods (FEM) (e.g. [3]), modal methods (e.g. [4,5]), Fourier methods (e.g. [6,7]) or a statistical approach such as Statistical Energy Analysis (SEA) (e.g. [1,8]). The choice of model for any new type of floor such as the dowelled-joist timber floor primarily depends on having an understanding of the dynamic behaviour of the floor; hence this is considered in this paper.

Vibration serviceability is important for timber floors to minimise the likelihood of annoyance from floor vibration due to human activity (e.g. see [9,10]). The requirements for residential floors are described in the European Standard EN 1995-1-1 [11] which implements Eurocode 5. However, other standards exist and Zhang et al. [12] have assessed EN 1995-1-1 against other design standards used for timber floors in Europe. They conclude that there is significant variation in the design equations and limit values. EN 1995-1-1 describes calculation of the fundamental

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http://dx.doi.org/10.1016/j.engstruct.2017.07.009

frequency, f_1, for a single-span, rectangular, timber joist floor that is simply supported on all four sides using

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}} \tag{1}$$

where m is the mass per unit area (kg/m^2), L is the floor span (m), and $(EI)_L$ is the equivalent plate bending stiffness of the floor about an axis perpendicular to the beam direction (N m^2/m).

Many timber floors are only supported on two sides for which Zhang et al. [12] note that some countries also use Eq. (1). Dowelled-joist timber floors (like many other timber floors) are usually supported on two sides, are not always simply supported, can potentially be multi-span [10] and can have different length assemblies that are connected together to form non-rectangular floor plans. For these reasons it is proposed in this paper that validated FEM models could be used to assess different floor layouts and support conditions at the boundaries.

EN 1995-1-1 uses the fundamental frequency to give a design limit for the unit impulse velocity response. The unit impulse velocity response, v, is the maximum initial value of the vertical velocity caused by an ideal unit impulse of 1 N s applied at the point of the floor which gives the maximum response, and should satisfy [11]

$$v \leqslant b^{(f_1\zeta - 1)} \tag{2}$$

where ζ is the modal damping ratio (if unknown, it is recommended to assume $\zeta = 0.01$) and b is a function of the deflection of the floor under 1 kN point load, a (mm). EN 1995-1-1 gives information regarding the calculation of parameters a and b with National annexes giving specific values for each country.

For a rectangular floor which is simply supported along four edges, the unit impulse velocity response can be calculated using [11]

$$v = \frac{4(0.4 + 0.6n_{40})}{mBL + 200} \tag{3}$$

where B is the width (m), L is the length (m) and n_{40} is the number of first-order modes with eigenfrequencies up to 40 Hz (this has also been shown to be appropriate for timber floors supported on two edges [13]). The value of n_{40} may be calculated from [11]

$$n_{40} = \left[\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\left(\frac{B}{L}\right)^4 \frac{(EI)_L}{(EI)_B}\right]^{0.25} \tag{4}$$

Zhang et al. [12] note that several countries do not make use of the unit impulse velocity due to its theoretical complexity and the difficulty in obtaining it through measurement. This provides the motivation in this paper to validate FEM models for a timber floor such that the unit impulse velocity can be calculated using FEM for all practical permutations of different boundary conditions and non-rectangular floor plans that exist in real buildings. Other approaches, such as Hamm et al. [14] consider eigenfrequencies, stiffness and analysis of the acceleration in certain cases, and these could also be assessed with FEM.

The majority of research on dowel-connected timber has focussed on the fundamental factors that affect the performance of dowel-type joints in terms of their strength, stiffness and ductility [15]. Due to the large investment of time in the design of timber joints, it has proven useful to have validated numerical models for their mechanical behaviour, particularly for failure. Examples include Chen et al. [16] who developed a FEM model for a steel dowel joint in timber to assess failure modes that were validated against experimental data. Reynolds et al. [17,18] also investigated the stiffness of steel dowel connections in timber by using an analytical model and measurements with a 1 Hz oscillating load. Like most timber constructions, dowel-connected timber also uses screws and FEM has been used to assess failure. For screwed timber joints, Meghlat et al. [19] validated FEM models using a beam element for the screw to predict stress and strain distributions along them. Avez et al. [20] used FEM to model inclined screws connecting timber that was separated by a large gap, and used shear and pull-out tests to calibrate the model. For post-and-beam connections, Hong et al. [21] validated FEM models for nails in timber. However, the literature does not seem to extend to FEM modelling for the dynamic behaviour of large dowelled-timber assemblies as considered here.

This paper concerns the validation of FEM models for the dynamic behaviour of a dowel-connected timber floor at frequencies up to the 200 Hz one-third octave band. Two models are considered for the dowels that use either rigid or spring-like connections. These are validated in terms of their eigenfrequencies, eigenfunctions and spatial-average response. The models are then used to assess vibration serviceability by calculating the maximum initial value of the vertical vibration velocity due to an ideal unit impulse.

2. Materials and methods

2.1. Materials

The dowelled-joist timber floor has a thickness of 200 mm and is formed from three assemblies (denoted as A, B and C). Each assembly consists of Spruce joists (45 mm width, 200 mm depth) connected using two rows of Beech dowels (16 mm diameter) as shown in Fig. 1a and b. The assemblies are joined together using self-tapping metal screws (240 mm length) inclined at an angle of ≈45° and an average screw spacing of ≈313 mm (see Fig. 1a). Three assemblies (900 mm width, 5500 mm length) were provided by Nägeli AG (Switzerland) to construct the dowelled-joist timber floor for the experimental work. The excitation positions are shown in Fig. 1c.

2.2. Finite element modelling

2.2.1. Analysis methods

The finite element models are implemented using Abaqus (Version 6.12) [22]. All eigenvalue extraction used the Lanczos solver.

The steady-state response to a point force used subspace-based, steady-state dynamic analysis [22]. The transient response to an ideal unit impulse used transient modal dynamics analysis [22]. The latter gives the temporal response based on a defined time-dependent loading where the structure's response is based on a subset of the system modes because only modes with eigenfrequencies up to 40 Hz are considered according to the recommendations in EN 1995-1-1. An ideal unit impulse is defined with the area under the force versus time curve being equal to 1 N s. This is applied using a triangular profile at the position where there is maximum displacement in the eigenfunction. The duration of the load, t_d, is 0.002 s and the time increment, Δt, is 0.001 s. The total time, t, of the analysis is 1 s. Note that for $t_d < T_n/4$ (where T_n is the period) the maximum response is controlled by the pulse area and is independent of the pulse shape [23]; hence a triangular profile is equivalent to other shapes such as a rectangular or half-sine pulse. Two excitation positions are considered: (1) in the middle and (2) at the edge of the floor.

2.2.2. Timber joists

Shell elements were selected to model the timber joists rather than one-dimensional beam elements because it was necessary to incorporate a zig-zag pattern of dowel connections as well as