PREDICTION OF MAXIMUM FAST TIME-WEIGHTED VELOCITY LEVELS FROM A RUBBER BALL IMPACT ON A TIMBER FLOOR

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ABSTRACT

The ISO rubber ball is used in measurement standards to assess heavy impacts on floors such as from footsteps in bare feet or children jumping. This paper investigates the prediction of impact sound insulation using the Finite Element Method (FEM) and Transient Statistical Energy Analysis (TSEA). FEM is used to model the rubber ball impact on a timber floor by simulating the rubber ball and the floor. The contact force is then applied directly into the FEM model to reduce computation time and is found to introduce negligible error. An experimentally validated FEM model of a small timber floor is compared with TSEA in terms of the spatial-average maximum time-weighted vibration level on the surface of the timber floor using a TSEA model that only considers the chipboard walking surface.

Key words: Rubber ball; Timber floor; FEM; TSEA

1. INTRODUCTION

Timber floors are widely used in Europe and to assess impact sound insulation at the design stage it is useful to be able to predict the noise generated by footsteps in bare feet or children jumping. For laboratory and field measurements, the rubber ball was developed to assess these types of impacts [1] with measurement procedures described in International standards [2-4]. For heavyweight concrete floors, it has been shown that Transient Statistical Energy Analysis (TSEA) can be used to predict the maximum Fast time-weighted sound pressure level [5-7] and this has been extended to include a floating floor [8]. It has also been shown to be feasible to use the Finite Element Method (FEM) with a concrete floor radiating into a room [9]. However, there is a need for validated prediction models for lightweight floors.

In previous work by the authors on a timber floor, FEM has been used to simulate the transient response of a floor by modelling the rubber ball and the impact [11]. For a small floor this is feasible with FEM but it is likely to be time consuming when both sound and vibration fields need to be modelled to determine the Fast time-weighted maximum sound pressure level in a room inside a timber frame construction. For this reason, this paper investigates whether the process could be split into two parts: 1) the interaction between the ball and the floor that gives the applied force and 2) the coupling between the floor and the receiving room in which the contact force extracted from FEM in the first part is applied to the floor as a load. The applicability of this approach is assessed in this paper for excitation of a chipboard plate. The force input is then used in TSEA to predict the spatial-average maximum Fast time-weighted vibration level, $L_{\mathrm{v,Fmax}}$. The TSEA approach is assessed by a numerical experiment of rubber ball drops on a chipboard plate, and a physical experiment of the rubber ball drops on a mock-up timber floor.

2. METHODOLOGY

2.1 FEM modelling of a rubber ball impact

All finite element modelling was carried out using Abaqus v6.14-2. A time domain model was used to simulate the ball impact on a plate, and the force was compared.

The rubber ball is assumed to drop from a 1m height onto a 22mm thick plate (1.8m × 1.2m). The ball is modelled as a linear elastic sphere with a density of 1188 kg/m^3 a Young's modulus of 3.2×10^6 N/m^2, and Poisson's ratio of 0.48 [10]. The plate is assumed to be homogeneous and isotropic with the measured properties of chipboard that was used in the mock-up timber floor, density of 676 kg/m^3, a quasi-longitudinal wave speed of 2200 m/s and an estimated Poisson's ratio of 0.3.

The drop location is one-third of the way along the diagonal line on the plate (see Figure 1). A simply supported boundary condition is applied on the four edges of the plate. The velocity response was assessed at positions R1 to R5 as shown in Figure 1.

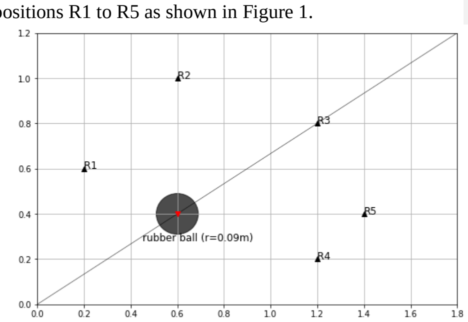

Figure 1. FEM model for the rubber ball impact on a chipboard plate.

2.1.1 Rubber ball – chipboard plate contact model

The rubber ball is modelled as an elastic sphere using a general-purpose conventional shell element, S3R, with an element dimension of 15 mm, and shell thickness of 30 mm; this modelling approach was validated in [9-10]. The chipboard is considered as isotropic solids using 'S4R' shell elements with an element dimension of 15 mm.

The transient response analysis with rubber ball excitation was determined using Abaqus/Explicit. This is a general 'Hard' contact applied to the coupling between the rubber ball and the timber floor. The Rayleigh damping (α=37.156 and β=0) was used for the chipboard in the FE model. The total simulation time was 1s and the fixed time step was 1.22×10^{-4}s.

2.1.2 Contact force - chipboard model

The transient contact force from the previous FEM model was extracted and applied to the chipboard in the normal direction as a load at the excitation positions indicated in in Figure 1. Two steps were created using Abaqus: modal analysis and modal dynamics. The Rayleigh damping for the chipboard was the same as in the model described in section 2.1.1.

2.2 TSEA

TSEA has been proved to be an efficient tool for predicting the rubber ball drops on force plate and concrete floor. The TSEA is calculated using

$$E_i(t_{n+1}) = E_i(t_n) + \Delta t \left[W_{in,i}(t_n) + \omega \left(\sum_{j(j \neq i)} \eta_{ji} E_j(t_n) - \eta_i E_i(t_n) \right) \right] \quad (1)$$

where $E_i(t_n)$ is the energy of the i^{th} subsystem at the n^{th} time step. If the spatial-average energy of one subsystem is known, it can be converted to a time-varying mean-square velocity for structures as below:

$$v_i^2(t_n) = \frac{E_i(t_n)}{m_i} \quad (2)$$

where ρ_0 is the density of air, c_0 is the speed of sound in air, V_i is the volume of subsystem i and m_i is the mass of subsystem i. In this paper, the time-varying mean-square velocity is used to calculate the Fast time-weighted maximum vibration level in frequency bands using

$$L_{v,\tau}(t) = 10 \lg \left[\frac{\frac{1}{\tau} \int_{-\infty}^{t} v^2(\xi) \exp\left(\frac{-(t-\xi)}{\tau} \right) d\xi}{v_0^2} \right] \quad (3)$$

where $\tau = 0.125$ s is the exponential time constant for the Fast time-weighting, ξ is a dummy variable of time integration, v is the instantaneous square sound pressure and v_0 is the reference velocity. The maximum Fast time-weighted velocity level $L_{v,Fmax}$ is the maximum value of $L_{v,\tau}(t)$ within a defined time interval. Two main parameters need to be determined for TSEA, the transient power input and the loss factors as described in [5].

2.2.1 Transient power input

The transient power input is calculated using the mean square force from the ball, F^2, combined with the driving-point mobility, Y_{dp}, of the structure

$$W_{in} = F^2 \Re e\{Y_{dp}\} \quad (4)$$

TSEA model requires the losses per radian cycle to occur in every time step; hence the transient power input is applied over the duration of the actual force which is carried out as described in [5].

For the chipboard plate the driving-point mobility is calculated from infinite plate theory. For the mock-up timber floor, the measured driving-point mobility at Ref1 and Ref2 is used to calculate the transient power input.

2.2.2 Loss Factors

For a rubber ball drop directly onto the chipboard plate, the plate is the only subsystem in the TSEA model. The Total Loss Factor (TLF) for the plate is the same as that used in the FEM model.

For the mock-up timber floor (described in Section 3), the Internal Loss Factor (ILF) of both the joists and the chipboard sheets were measured via Experimental Modal Analysis (EMA), from which the damping of the entire floor was also measured and then was used to calculate the TLF to be applied in the one-subsystem TSEA model.

3. EXPERIMENT

A standard rubber ball (RION) was dropped from a 1m height onto a mock-up timber floor. Two excitation positions were identified (see Ref1 and Ref2 on Figure 3); the first is close to the mid-point of the floor between joists and the second is close to a joist. Underneath each of these excitation positions was an accelerometer (B&K Type 4371) which was fixed using cyanoacrylate glue; this formed a reference signal to allow measurement of a complex transfer function for each response point. To measure all response points shown in Figure 3, six accelerometers were used to cover all the 432 sample points during 72 steps. Note that this excluded the two excitation points where the accelerometer was underneath. The FFT frequency span was 1.6k Hz with 3200 FFT lines and a 7 Hz high-pass filter.

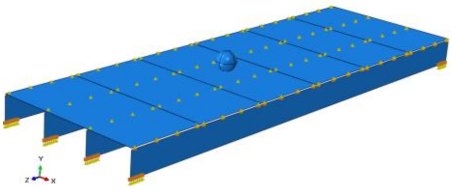

Figure 2. FEM model of the mock-up timber floor with rubber ball.

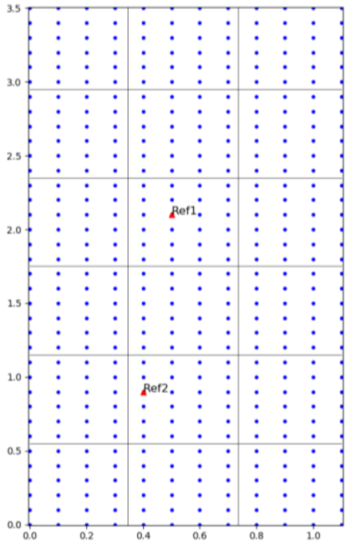

Figure 3. Measurement points (blue dots) and two reference excitation positions.

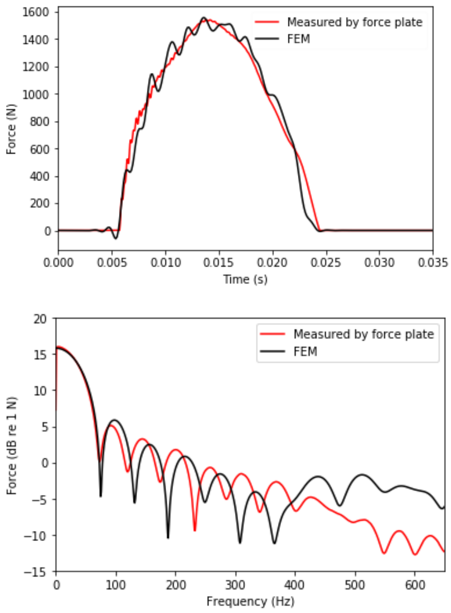

Figure 4. Contact force from the FEM of the rubber ball drops on the chipboard plate, and measured by a rigid force plate. The upper figure is for is the force in time domain, the lower is in frequency domain.

4. RESULTS

4.1 Contact force from FEM

The contact force extracted from the FEM simulation of the rubber ball drops on the chipboard plate is shown in Figure 4 for comparison with the blocked force measured using a rigid force plate [10].

In the time domain, FEM and the force plate measurement both have a peak force of approximately 1.5kN with a time period of 18.8s for the transient, even though the chipboard board has a relatively high mobility. Above 80Hz, there is frequency shift which requires more investigation and future work will make more comparisons with different thickness plates.

4.2 Vibration response of the chipboard plate

The two FEM models were compared with each other in terms of the velocity response at the five positions. From Figure 5, it can be seen that there is no significant difference between these two FEM models at frequencies up to 500Hz. Therefore the impact force extracted from the FEM model can be applied as a load directly to the chipboard to improve computational efficiency.

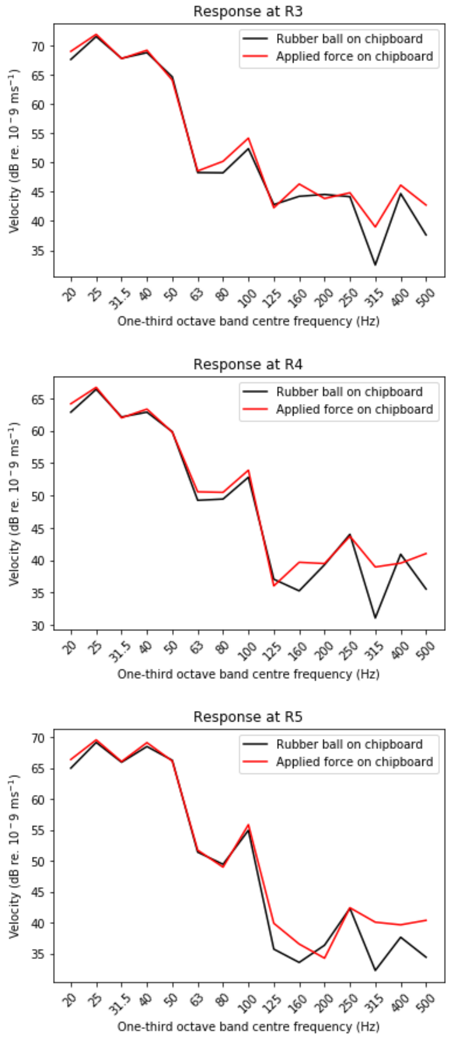

Figure 5. Comparison of velocity response at R1-R5 between the two FE models.

4.3 Comparison between TSEA and FEM for rubber ball drops on chipboard plate

$L_{\mathrm{v,Fmax}}$ from TSEA was compared with the spatial-average $L_{\mathrm{v,Fmax}}$ from five positions determined with FEM. The difference is within 4dB below 630Hz, and 6dB at 500Hz indicating that the TSEA model can reasonably predict the vibration response in terms of $L_{\mathrm{v,Fmax}}$.

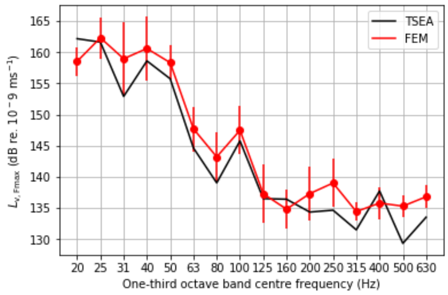

Figure 6. Comparison of $L_{\mathrm{v,Fmax}}$ from FEM (average value from the different receiver positions with 95% confidence intervals) and TSEA.

4.4 Comparison between TSEA and measurements for a rubber ball drop on the mock-up timber floor

The contact force from FEM was extracted and used to calculate the transient power input from the rubber ball. As the contact force and driving-point mobility are different, the transient power input is different at Ref1 and Ref2 and therefore $L_{\mathrm{v,Fmax}}$ calculated from TSEA is different for these two excitation positions.

Figure 7 indicates reasonable agreement between TSEA and measurements at Ref1 and Ref 2. There is a 5dB difference in the frequency range between 25Hz and 630Hz, but at most frequencies, the difference is within 3dB.

FEM also shows agreement with the measurements. For excitation position Ref1, FEM works as well as the simple TSEA model. But for excitation position Ref2 which is near the joist, TSEA works better than FEM between 31.5Hz and 63Hz. This is unexpected and indicates that further investigations are needed into the FEM model.

Note that the TSEA model only comprises of one plate subsystem by distributing the mass of the joist and chipboard equally for the plate. This model will be expanded to include the joists in future work.

5. CONCLUSIONS

In this paper, a FEM model of the rubber ball dropping on a single chipboard has been used to determine the contact force. By applying this contact force as an external load it is possible to simplify the FEM model which increases computational efficiency without incurring significant errors.

For a chipboard plate TSEA was used to predict the $L_{\mathrm{v,Fmax}}$ on due to a rubber ball impact. The close agreement between TSEA and FEM model indicates that efficient modelling could be carried out using FEM to predict the force input and TSEA to propagate the transient sound and vibration for lightweight structures.

For a mock-up timber floor there was reasonable agreement between measurements, FEM, and a simple one-subsystem TSEA model when predicting $L_{\mathrm{v,Fmax}}$ for the chipboard plate. Improvements to these TSEA and FEM models will be developed in future work.

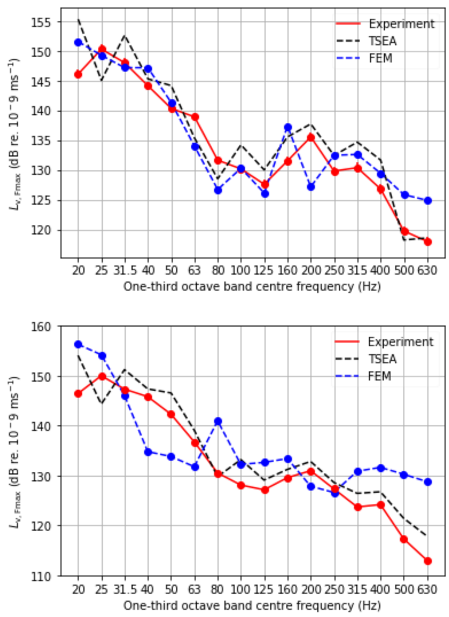

Figure 7. Comparison of $L_{\mathrm{v,Fmax}}$ from TSEA and experiments of rubber ball drops on timber floor. Upper figure is for Ref1, the lower one is for Ref2.

6. ACKNOWLEDGEMENTS

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