VIBRATION TRANSMISSION IN TIMBER FRAMED BUILDINGS

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1. INTRODUCTION

Timber frame buildings are becoming more popular both in the United Kingdom and across Europe but they often suffer from poor sound insulation. Since the early 60's the use of timber framed construction has increased rapidly in the UK, and more than1,000,000 of these buildings have been built since 1965 [1]. Lightweight buildings are constructed using timber frame, plasterboard and plywood as common materials. They are very popular in Scandinavia and North America.

Until the 1990s, most of the calculation models used for predicting sound transmission were restricted to masonry buildings, where there are usually only a few elements that need to be considered in order to determine sound transmission between two rooms. In contrast, in timber frame buildings there are many more components that have to be considered, as can be seen in Figure 1 [2]. The complex interaction between all the components makes sound transmission much more complicated. However, this complexity provides much more opportunity to improve sound insulation as the overall transmission is not simply determined by a few parameters (such as mass or critical frequency) over which there is often little control.

New building regulations are currently being proposed for England and Wales [3] which aim to increase sound insulation by 3 dB. Many existing designs will not meet this higher standard and all but a few of the timber frame designs have been removed from the approved document. It has been estimated that 60% of timber constructions will fail the new regulations. There is therefore a need to understand the factors that affect sound transmission and to develop the models used successfully for masonry buildings, so that they can be used in lightweight buildings.

Attempts to model lightweight buildings using statistical energy analysis (SEA), or any other method, have had only limited success. Flanking transmission has been examined at the National Research Council in Canada but detailed measurements showed the difficulties of obtaining reliable measurements where there is no underlying theoretical model which provides a framework for interpreting the data [4,5]. The basic mechanisms of transmission (and in particular structural transmission) need to be understood so that measured data can be collected in a systematic manner and changes in design assessed.

Important studies related to predictive models in lightweight buildings include the direct transmission through lightweight parallel plate examined by Craik and Smith [6,7].

In this paper, vibration transmission through timber framed structures is examined. Appropriate methods for calculating the coupling between the individual frame members have been developed for comparison with measured data. This model will then be developed so as to allow transmission through a real structure to be predicted.

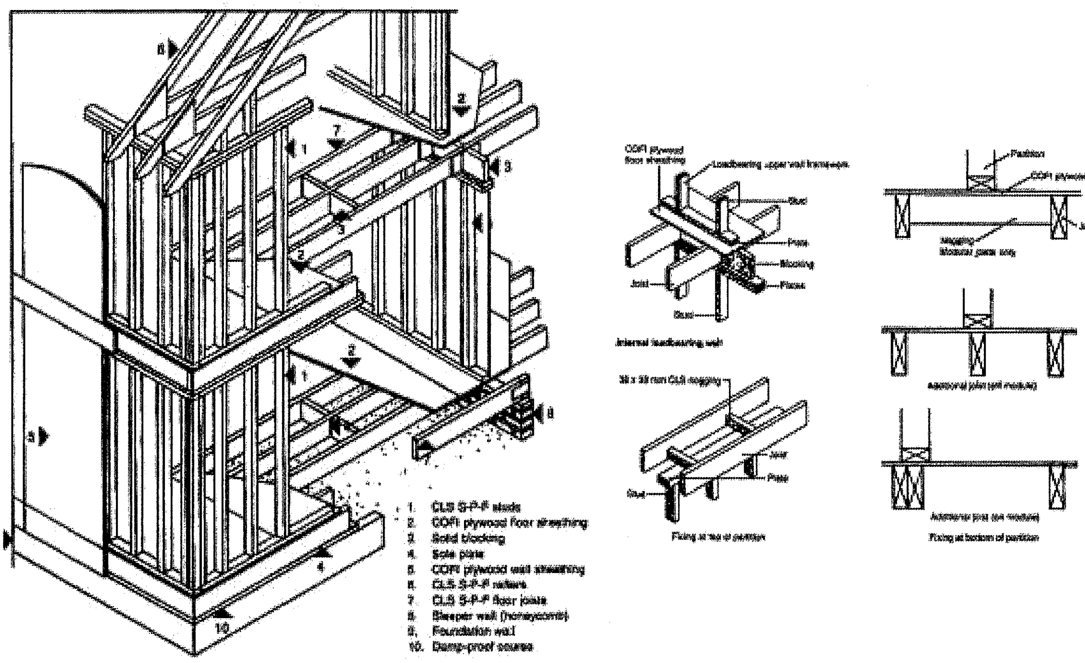


Figure 1 Example of a timber frame house showing details of the construction [2].

2. JUNCTION MODEL

2.1 Structural transmission at a junction

When considering the frame of a timber framed building, each junction can be considered to be the intersection of up to 6 beams as shown in Figure 2. Real junctions will usually have less than 6 beams and can have any combination of 2 or more beams. A detailed model has been developed allowing vibration transmission between these beams to be predicted. The connection between the beams can be either rigid or partially pinned and appropriate offsets can also be taken into account.

This model is first used to calculate structural transmission loss between each of the beams. These values are then input into a general statistical energy analysis (SEA) model to determine the overall transmission through a framed structure and hence the actual vibration level for any specified sources.

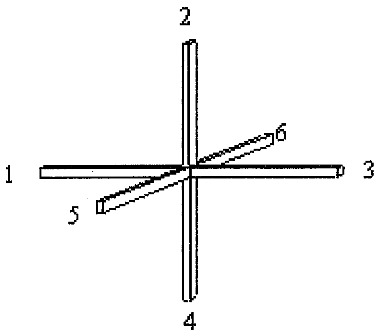
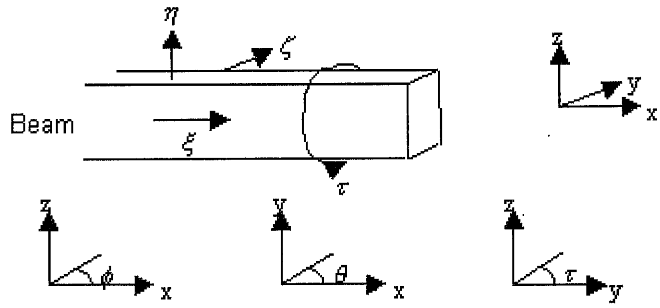


Figure 2 An idealised junction of 6 beams intersecting at a single point.



The model is based on a wave approach [8] and all types of waves are included: bending (travelling and nearfield), longitudinal and torsional. Each beam supports 2 bending waves (normal and lateral), 1 longitudinal wave, 1 torsional wave and 2 nearfield bending waves, giving a total of 6 unknown variables per beam. This in turn requires, for a junction with N beams, a set of $6N$ equations which can then be solved to give the required wave amplitudes. In order to calculate the transmission coefficients between the beams, a system of continuity and equilibrium equations is solved. For a rigid junction there is continuity of displacements (in 3 directions) continuity of slope (in 3 directions), and equilibrium of forces and moments (each in 3 directions) at the junction between the beams [9].

ξ : longitudinal displacement.
η : normal bending displacement.
ζ : lateral bending displacement.
ϕ : rotation due to normal bending.
θ : rotation due to lateral bending.
τ : rotation due to torsion.

Figure 3 Beam notation showing the displacement and rotation associated with each wave (bending, longitudinal, torsional).

Although the simplest method of modelling the joint is to assume that each beam is rigidly connected to all the other beams, in practise it is found that there is some “give” in real joints. Simple nailed or screwed joints often allow some movement of the joint. It is found that a beam that is nailed to a joint cannot be displaced linearly in any direction but that it can be rotated. This can be translated into the set of equations by stating that forces are transmitted across a nailed joint but that moments (normal bending, lateral bending and torsional moments) are not.

For a junction that comprises two beams that are pinned together in this way, a bending wave on one beam will not generate bending on the other. This is contrary to experimental evidence. However, the fastenings holding the beams together will not occur at the intersection of the centre lines of the beams and if the offset is introduced, then realistic models of real junctions are obtained.

In real junctions some moment will be transmitted across a pinned junction and therefore the two different models (rigid and pinned) provide lower and upper bounds to the expected results. Transmission cannot be stronger than rigid or weaker than pinned.

2.2 Correcting for small beam lengths

A fundamental requirement of SEA is that the response of an element or subsystem should be determined by the resonant modes. As there are few modes in beams (particularly at low frequencies), this places a limit on the frequency range over which statistical energy analysis can be used. A method of correcting the coupling loss factor between subsystems, to account for the low modal density and low modal overlap, has been proposed by Craik [10,11] as

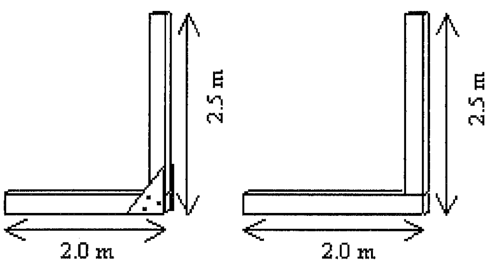
$$\eta_{12} = \eta_{12\infty} Y_2 / Y_{2\infty} \qquad (1)$$

where Y_2 and $Y_{2\infty}$ are the actual and infinite subsystem mobilities calculated according to Craik [9].

3. TEST STRUCTURES

In order to verify the theoretical models a number of experiments were undertaken. The first set of experiments were undertaken on single junctions of two beams that formed an L junction, as can be seen in Figure 4. Measurements were made on the junction firstly constructed in a typical manner by screws (as shown in Figure 4a) and secondly where additional reinforcement was added to ensure that the junction was rigid. This was achieved by adding two plywood plates glued and screwed on either side of the junction (see Figure 4b).

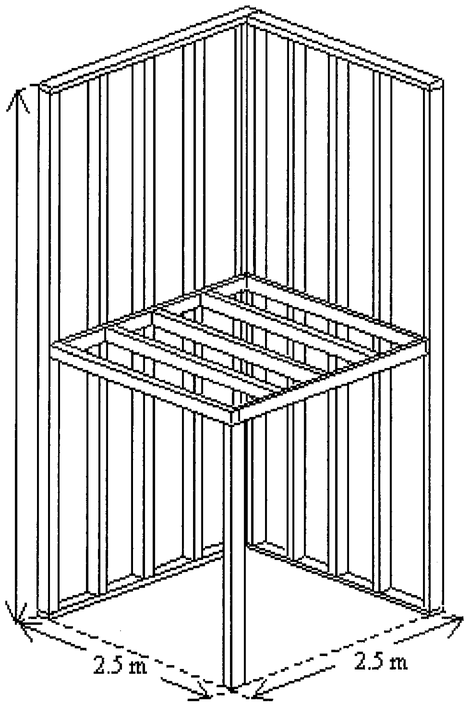
The timber beams used have a depth 0.1m, a width of 0.05m, a density of 480 kg/m^3, a Young's modulus (in the axial direction) of 9 x 10^9 N/m^2 and an internal loss factor of approximately 0.015.



a. Real junction (screwed) **b.** Reinforced junction

Figure 4 L junction of 2 timber beams attached at right angles.

4.9 m



Measurements were then made on a large timber frame (two storey height), shown in Figure 5, that allows transmission across many different types of joint and by many different wave types to be studied. The large structure was modelled as having 53 beams and 31 junctions, and was constructed from 88 x 38 mm beams.

Figure 5 Two storey timber frame structure used to represent part of a real building. Beams were screwed and nailed in the usual manner.

4. MEASURED RESULTS & PREDICTIONS

4.1 L junction

A plastic-headed hammer was used to excite the structural elements using the procedure described by Craik [12] and the vibration level difference was measured for comparison with the predicted level difference.

The results for the real and the reinforced L junctions are given in Figure 6 and it can be seen that there is a significant difference of about 10 dB between them. This result is typical of several tests and shows that real junctions (either nailed or screwed) cannot be considered as rigid.

A comparison between the measured and predicted level difference for the rigid (reinforced) case is shown in 1/3 octaves (Figure 7) and in 1/24 octaves (Figure 8). In each case the fluctuations which are most obvious at low frequencies are due to the low frequency corrections of equation (1). The 1/3 octave results are for an extended frequency range (20 Hz -10 kHz) whereas the 1/24 octave results show more detail. It can be seen that there is excellent agreement between the measured and predicted results. The beam modal frequencies used in calculating the correction of equation (1) were based of those for clamped-free boundary conditions, so there is a small error due to the peaks and dips occurring at the wrong frequencies. These results confirm [10,11] that for transmission between two subsystems, it is the modes in the receiving subsystem that affect the power flow.

The negative level difference (where the receiving acceleration is higher than the source level) occurs where there is a resonant mode in the receiving subsystem and none in the source.

A real joint has some flexibility and it is expected that the theory for rigid and pinned joints should provide lower and upper bounds for the transmission. A comparison between these bounds and the measured data for a real junction can be seen in Figure 9. At low frequencies the difference between the rigid and pinned results are large, with the measured results lying between them and tending to the upper (pinned) limit.

At high frequencies the measured level difference is higher than predicted, which may be due to the assumption that the beam is thin being no longer valid. The upper limit is often taken as being where the thickness of the element considered is no longer small compared to the wavelength [13], and this occurs at approximately 2.5 kHz for timber beams that are 0.1m thick.

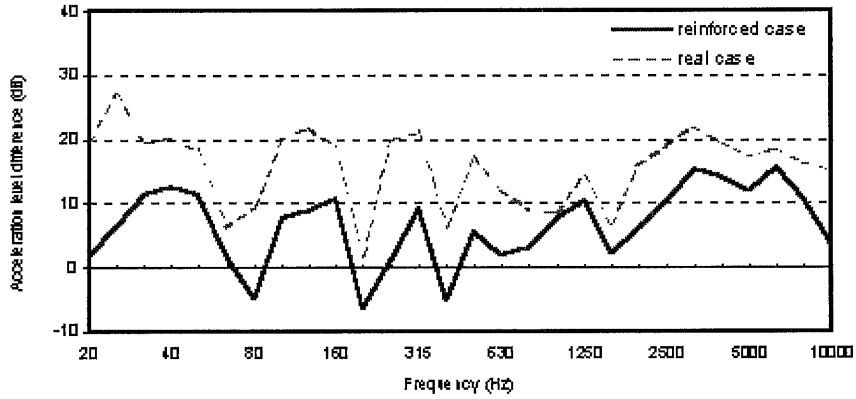


Figure 6 Measured acceleration level difference for an L junction made from two timber beams (1/3 octave). ———, reinforced case; – – – –, real case.

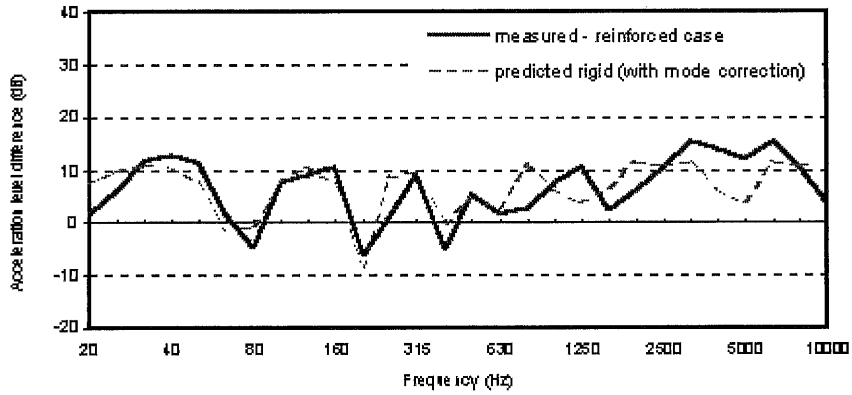


Figure 7 Measured and predicted acceleration level difference for an L junction made from two timber beams (1/3 octave). ———, measured - reinforced case; – – – –, predicted rigid (with mode correction).

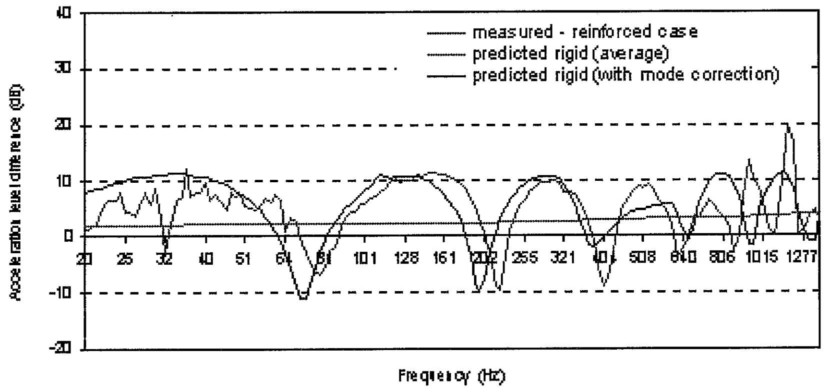


Figure 8 Measured and predicted (rigid model) acceleration level difference for an L junction made from two timber beams (1/24 octave). ———, measured - reinforced case; ——, predicted rigid (average); ——, predicted rigid (with mode correction).

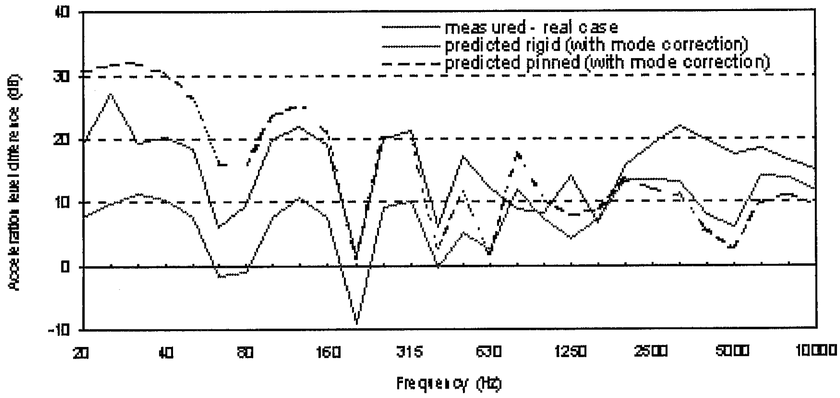


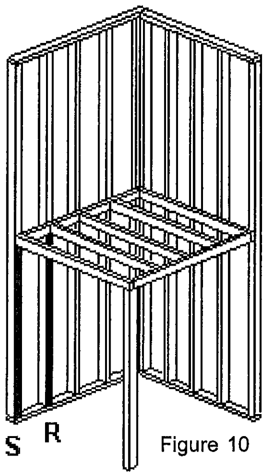
Figure 9 Measured and predicted (rigid model and pinned model) acceleration level difference for an L junction made from two timber beams (1/3 octave). ———, measured - real case; ——, predicted rigid (with mode correction); ----, predicted pinned (with mode correction).

4.2 Timber frame

The theoretical model developed and verified on the individual junctions was then used to determine the overall transmission through the large timber structure. The frame includes both rigid and flexible connections which were modelled as either rigid or pinned connections.

Measurements were again made by exciting the frame at one location and measuring the response at another. Two sets of measured and predicted results are given in Figures 10 and 11. In Figure 10 the transmission is from one frame element to the adjacent element through a minimum of two junctions. Due to the uncertainty of determining the individual mode frequencies, the low frequency correction has not been made. Instead the usual SEA theory has been used which should pass through the middle of the measured data, as the low frequency corrections are a perturbation about the mean.

It can be seen that there is excellent agreement. Results are also shown in Figure 11 for transmission over a much longer distance and again there is good agreement.



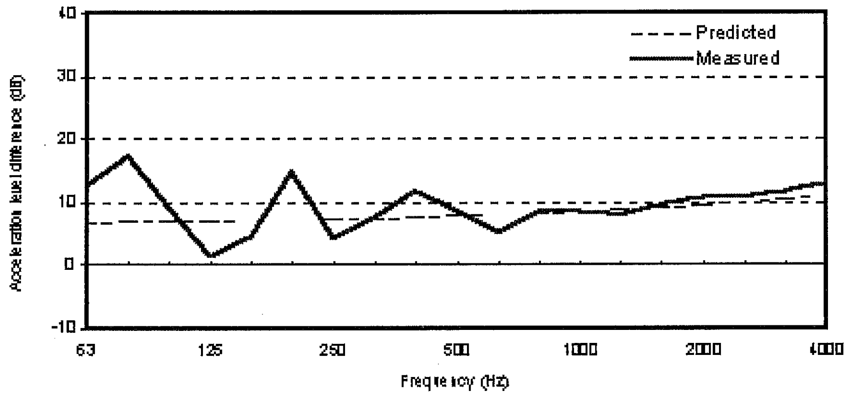
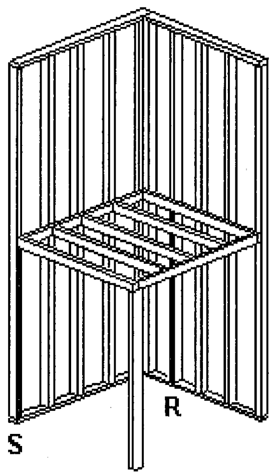


Figure 10 Flanking transmission through the timber frame. Measured and predicted acceleration level difference (**S**ource - **R**eceiver). ----, predicted; ——, measured.



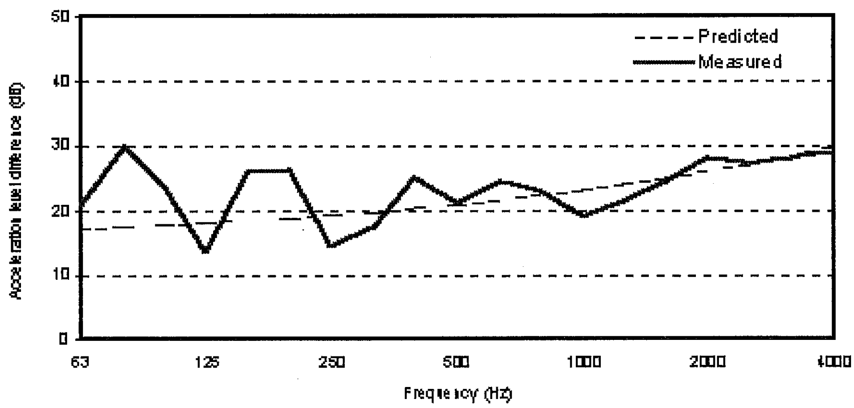


Figure 11 Flanking transmission through the timber frame. Measured and predicted acceleration level difference (**S**ource - **R**eceiver). ----, predicted; ——, measured.

5. CONCLUSIONS

A detailed model has been developed in order to predict vibration transmission through a timber frame structure. The model allows up to 6 beams to be connected together either rigidly or partially pinned and with appropriate offsets, and mode corrections can also be included. It is found that real junction of timber frame structures are normally not rigid. There is good agreement between measured and predicted result.

It has also been found that this model can be used to predict transmission through large structures composed of many beams and junctions.

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