Proceedings of the Institute of Acoustics

STRUCTURE BORNE SOUND TRANSMISSION BETWEEN WALLS IN FRAMED BUILDINGS

J.A. Steel

Heriot-Watt University, Department of Mechanical Engineering, Edinburgh, EH14 4AS, UK.

1. INTRODUCTION

A number of studies of structure borne sound transmission between walls in real buildings have been carried out [1,2,3,4]. Rooms and corridors are formed in framed buildings by building walls between structural columns. The effects of these columns on the transmission characteristics at joints between walls have not been considered.

The inline joint, where two walls are positioned on opposite sides of a joint column, has been investigated by Cremer *et al* [5] for a very thin connecting joint beam. Cross joints between walls and floors have been considered by Kihlman [1] and corner, cross and tee joints are considered by Gibbs and Gilford [2] for bending waves incident on a boundary between walls and allowing in-plane motion of the walls (no column). In this work a joint between connected walls is treated in the same manner as Gibbs and Gilford [2] but terms associated with rotation and deformation of a joint column are included in conditions at the joint.

2. THEORY

The joint configuration assumed in this work is shown in Fig. 1. A bending wave is assumed to be incident on the joint on wall 1. The calculations for the transmission coefficients at the joint are carried out in a similar manner to Cremer *et al* [5] and Gibbs and Gilford [2].

Any moments, M_i, applied to the column by the walls will rotate and twist the column and will be resisted by the rotational inertia in the column. The column cross section is assumed to be symmetric about the x and y axis. The total resisting moment in the column, M_c, is given by Cremer *et al* [5] as,

$$M_c = -\left(\omega^2 \rho_c J - G_c k_1 \sin^2\theta_1\right)\frac{\partial \xi_1}{\partial x} \qquad (1)$$

where ξ_i is the displacement, ρ_c is the column density in kg/m^3, J is the polar moment of inertia, k_1 is the bending wave number for wall 1 and θ_1 is the angle of incidence. G_c is the torsional stiffness which is equal to $EK_T/2(1+\mu)$ where E is the elastic modulus, K_T is a torsional stiffness constant and μ is Poisson's ratio. The total resisting force in the column, F_c, for inertia and stiffness components is given by Cremer *et al* [5] as,

$$F_c = -\left(\omega^2 \rho_{lc} - B_c k_1^4 \sin^4\theta_1\right)\xi_1 \tag{2}$$

where ρ_{lc} is the column density per unit length and B_c is the relevant bending stiffness of the column which is equal to EI_{yy} for a force in the x direction, F_{cx}, and EI_{xx} for a force in the y direction, F_{cy}.

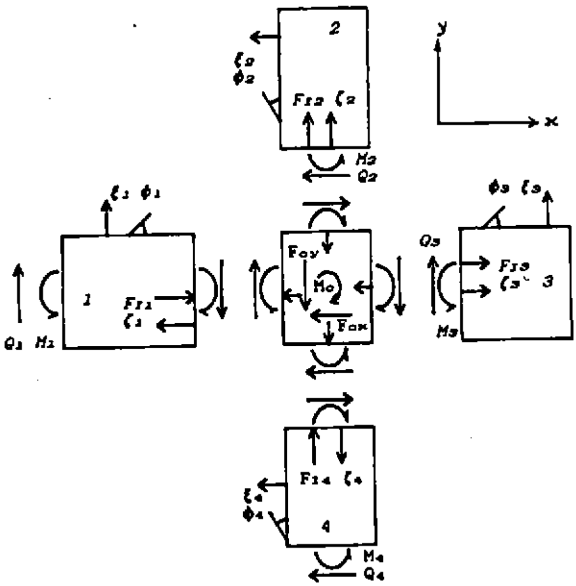


Fig 1. Joint configuration at a joint between four walls and a column.

The deformation of the column cross section can be modelled using stiffness terms in a similar manner to elastic interlayers which are studied by Cremer *et al* [5]. The deflection at the edge of the column due to shear forces is equal to $Q_i/K_{(x,y)}$ where K is the shear stiffness and Q_i is the total force in a wall [5]. For a joint column of unit length the stiffnesses are equal to $K_x=2G_ch_y/h_x$ for a force in the y direction (from wall 1 or 3) and $K_y=2G_ch_x/h_y$ for a force in the x direction (from wall 2 or 4). h_x and h_y are the column thicknesses in the x and y directions respectively.

SOUND TRANSMISSION BETWEEN WALLS IN FRAMED BUILDINGS

If the column cross section is allowed to deform due to opposing moments applied by walls 1 and 3 then the difference in slope can be calculated using a stiffness, $B'=EI_{xx}/h_x$ where $I_{xx}=h_y^3/12$ is the moment of inertia per unit length of the joint column. The shear force applied by wall 3 at the edge of the column produces a moment about the origin equal to $Q_3h_x/2$. The resulting moment applied from wall 3 at the edge of the column is equal to $M_3+Q_3h_x/2$. The difference in slope between walls 1 and 3 is equal to $(M_3+Q_3h_x/2)/B'$. The difference between the slope of walls 1 and 2 and walls 1 and 4 is equal to $(M_3+Q_3h_x/2)/(2B')$ which is half of the difference in slope between walls 1 and 3.

Conditions At The Boundary.
In this work a bending wave of unit amplitude is incident on wall 1 at the joint and bending and longitudinal waves are generated on each wall. The displacement (ξ), slope (ϕ), moment (M) and force (Q) conditions at the joint for each angle of incidence are described in a similar manner to Cremer *et al* [5]. The changes to the conditions are associated with the rotation and deformation of the column cross section and in-plane waves [6]. The subscripts 1,2,3 and 4 are used to indicate variables associated with the walls shown in Fig. 1.

The in-plane forces in the walls are given as $F_{li} = -i\omega Z_l\zeta_i$ where ζ_i is the in-plane displacement and the plate edge impedance Z_l is given by Cremer [6].

Twelve equations can be generated relating the amplitude of two bending waves (travelling and nearfield) and the in-plane wave on each wall and are given as,
<u>Displacement Conditions</u>

$$\xi_1 - Q_1/K_x + \phi_1 h_y/2 = \zeta_2 \tag{3}$$

$$\zeta_2 = \zeta_4 \tag{4}$$

$$\xi_1 - Q_1/K_x + \phi_1 h_y/2 = \xi_3 + Q_3/K_x - \phi_3 h_y/2 \tag{5}$$

$$\zeta_1 = \zeta_3 \tag{6}$$

$$\zeta_1 = \xi_2 + Q_2/K_y - \phi_2 h_y/2 \tag{7}$$

$$\zeta_1 = \xi_4 - Q_4/K_y + \phi_4 h_y/2 \tag{8}$$

Slope Conditions

$$\phi_1 - \phi_3 - (M_3+Q_3h_x/2)/B' \tag{9}$$

$$\phi_1 - \phi_2 - (M_3 + Q_3h_x/2)/(2B') \tag{10}$$

$$\phi_1 - \phi_4 - (M_3 + Q_3h_x/2)/(2B') \tag{11}$$

Moment Condition

$$M_1 - Q_1h_x/2 - M_2 - Q_2h_y/2 - M_3 - Q_3h_x/2 + M_4 - Q_4h_y/2 - M_c \tag{12}$$

Force Conditions

$$Q_1 - Q_3 - F_{l2} - F_{l4} - F_{cy} \tag{13}$$

$$Q_2 - Q_4 - F_{l1} - F_{l3} - F_{cx} \tag{14}$$

These twelve conditions can be expanded through substitution of the displacement equations for each wall and can be solved simultaneously to give the amplitude for each wave on each wall.

If terms associated with the column are omitted from the conditions then they reduce to those given by Gibbs and Gilford [2]. Similarly removing all terms associated with the column and also in-plane motion in the walls gives eight equations given by Cremer [6] describing transmission at a pinned joint.

Predicted transmission coefficients at inline joints can be obtained by removing all terms relating to in-plane waves and waves in walls 2 and 4 in the boundary conditions (Eqn's (3) to (14)). If all terms containing $h_x/2$ are also removed then the solution given by Cremer *et al* [5] for the inline joint is obtained.

The transmission coefficients τ_{ij} for transmission from a bending wave on a source wall 1 to bending or longitudinal waves on the receiving walls, j, are calculated using the same equations given by Gibbs and Gilford [2].

3. NUMERICAL RESULTS

Fig. 2 shows the transmission coefficients as a function of angle of incidence ($\sin\theta_1$) at 1000 Hz, for a cross joint. Walls 1 and 3 are 100mm thick and walls 2 and 4 are 200mm thick. The transmission coefficient for bending waves transmitted across the joint from wall 1 to wall 3, τ_{13} , has a sharp spike at 27.6° ($\sin\theta_1$=0.46) and no in-plane waves are transmitted to walls 1 or 3. On walls 2 and 4 the transmitted bending component, τ_{12} , has a small peak around 27.6° ($\sin\theta_1$=0.48) and then falls to a limiting angle of 45° ($\sin\theta_1$=0.707) above which bending waves are not transmitted. When no column is considered the results for τ_{12} are similar [2] to those shown in Fig. 2. The transmitted in-plane wave on walls 2 and 4, τ_1, has a sharp drop at 13.3° ($\sin\theta_1$=0.23) which is the limiting angle for transmission of longitudinal waves and no transverse waves are transmitted at angles greater than 22.3° ($\sin\theta_1$=0.38).

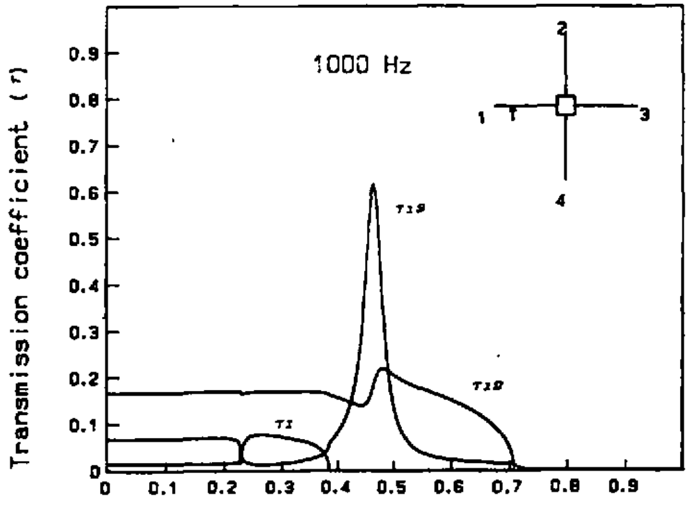


Fig. 2 Transmission coefficients for a cross joint with a 0.4m square column at 1000 Hz. $h_1=h_3$=100mm, $h_2=h_4$=200mm, ρ=2500kg/m^3, C_l=3500m/s, μ=0.3.

The results for the average transmission coefficients are similar at low frequencies to those given by Gibbs and Gilford [2]. At high frequencies the column reduces both transmitted bending and in-plane coefficients. The average transmission coefficients are reduced with increasing frequency and column thickness.

SOUND TRANSMISSION BETWEEN WALLS IN FRAMED BUILDINGS

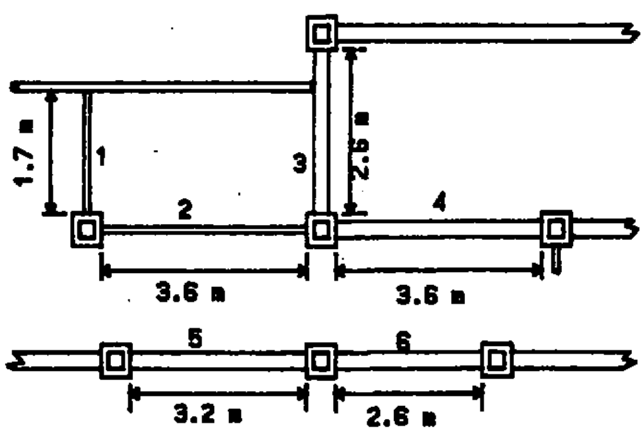
4. EXPERIMENT

An outline plan of part of the building studied is shown in Fig. 3 and typical situations for the joints that were measured are shown [7]. Walls 1 and 2 are 75mm thick and walls 3, 4, 5 and 6 are 200mm thick. The concrete blockwork walls have a density of 1425 kg/m^3 and a longitudinal wave speed of 2250 m/s. The columns are 400mm square and are hollow with a 250mm square void.

The average vibration levels of two connected walls (subsystems) were measured when one was excited using a plastic headed hammer by tapping at a rate of about 3 hits per second over the wall surface for a 15 second measuring period. The signals from accelerometers, one on each wall, were recorded for later analysis. The energy level difference (ELD) was calculated using the formula [2],

$$ELD = 10\log\frac{m_2 a_2^2}{m_1 a_1^2} \tag{15}$$

where m is the mass and a^2 is the mean square acceleration.



All walls 3.2 m high.

Fig. 3. Plan of part of the building showing typical joint configurations.

5. RESULTS

The measured and predicted ELD for transmission at a tee joint from wall 2, 75mm thick, to wall 4, 200mm thick, are shown in Fig. 4. The predicted results shown in Fig. 4 are calculated using an SEA model for the three walls at the joint [2]. For transmission from wall 2 to wall 4, flanking paths (through wall 3 shown in Fig. 3) are important. The predicted result which includes the joint column rises to -14 dB around 500 Hz, but then falls to -22 dB around 2500 Hz. The prediction for the pinned joint [6] (no joint column) is generally lower, and the difference between the two predictions is a maximum of 5 dB around 500 Hz. The measured results fluctuate at low frequencies below 250 Hz showing good agreement with the prediction for the pinned joint (no column). At higher frequencies the measured results show good agreement with the prediction which includes the column. The result shown dashed (no column but allowing in-plane motion [2]) predicts a smaller ELD around 2000 Hz but does not show good agreement with the measured results.

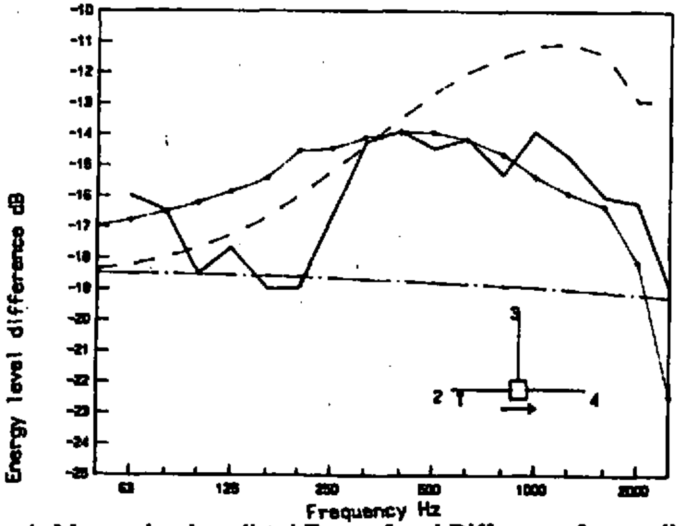


Fig. 4. Measured and predicted Energy Level Differences for coupling at a Tee joint from wall 2 to wall 4. _____, measured; -+--+-, predicted; --·--·-, predicted (no column, after Cremer [6]); - - - - , predicted (no column, after Gibbs and Gilford [2]).

6. DISCUSSION AND CONCLUSIONS

The measured transmission between walls, where a column is included in the joint, shows good agreement with predicted results. Transmission from bending waves to in-plane waves is reduced when compared to the performance of joints without columns. The transmission of bending waves across a joint at cross and tee joints is slightly increased at low frequencies and is significantly reduced at high frequencies. The transmission coefficients reduce with increasing column thickness.

For typical building structures the effects of the column are most significant in reducing transmission across a joint at high frequencies for cross and tee joints.

ACKNOWLEDGEMENTS

This work was funded by the Science and Engineering Research Council of Great Britain.

REFERENCES

1 T. Kihlman, The transmission of structure-borne sound in buildings. A theoretical and experimental investigation. *The national Swedish Institute of Building Research, Report No. 9. (1967)*

2 B. M. Gibbs and C. L. S. Gilford, The use of power flow methods for the assessment of sound transmission in building structures. *J. Sound Vib. (1976) 49 p267-286.*

3 P. G. Craven and B. M. Gibbs, Sound transmission and modal coupling at junctions of thin plates. Part 1: Representation of the problem. *J. Sound Vib. (1981) 77 p417-427.*

4 R. J. M. Craik, The prediction of sound transmission through buildings using Statistical Energy Analysis. *J. Sound Vib. 82 (1982), 505-516*

5 L. Cremer, M. Heckl and E. E. Ungar, Structure-borne sound, *Second edition, (1988) Springer Verlag.*

6 L. Cremer, The propagation of structure-borne sound. *Department of Science report No. 1. (1948) Sponsored Research, Series B.*

7 J. A. Steel, Structural vibration transmission in framed buildings using statistical energy analysis. *(1990) PhD Thesis, Heriot-Watt University.*