# SOUND INSULATION OF REINFORCED AND BRIDGED CONSTRUCTIONS

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## 1. INTRODUCTION

Diaphragm masonry walls are a modern and increasingly used external wall construction in the United Kingdom.They are used for single storey buildings such as sports centres, warehouses and supermarkets up to 10m high. The all brick construction has proved popular when compared with composite material designs since only one trade is required on-site, leading to low building costs. The wall consists of two widely spaced parallel leaves bridged with cross-ribs at regular centres. The.structural requirements of the wall have been considered in detail [1] but there has been little research into its sound insulation qualities or of that of its 'brother', the fin wall [2]. Figure 1 shows the general layout of the diaphragm and fin walls. The wide spacing of the leaves would normally result in a high sound insulation, but the strong vibrational links through the cross ribs have an adverse effect. If the sound insulation of the diaphragm wall was known and/or could be improved then there may be extended applications with respect to noise sensitive buildings as theatres and sound studios.

Existing theories concerning bridging [3,4] apply to lightweight building elements such as plasterboard and timber partitions where there is a high impedance mis-match between stud and panels. It was found that such theories do not to apply where the bridging elements are of the same material and thickness as the separated leaves, giving a low impedance mis-match, as is the case with diaphragm walls. However a modified coincidence theory is found to satisfactorily predict the Sound Reduction Index of monolithic diaphragm and fin walls. To examine the more general case of the diaphragm wall Statistical Energy Analysis(S.E.A.) was adopted which allows for sub-division of the wall into separate sub-systems and the inclusion of the effect of the cavity. S.E.A. also allows computer based parametric surveys for analysis and optimization of the wall where cross-ribs may have a different thickness, density or non-bonded coupling to the leaves. Sound intensity measurement techniques and geometric scale models of diaphragm, fin,double and single walls were used to validate prediction (See Figure 2a-2d). Models were constructed of perspex and measured in a small transmission suite.The work described was a prelude to field measurements of full scale walls, results of which will be published later.

## 2. DIAPHRAGM & FIN WALL

### 2.1 Diaphragm Masonry Walls

The primary requirement for such high walls is structural integrity which does not allow great variation in design. The leaves of the wall are widely spaced (between 0.4m-0.9m) to resist bending stresses and a strong coupling is essential between the leaves in order to resist flexural shear forces from lateral and vertical loading. The benefit in sound insulation of a wide cavity is insignificant compared with the strong vibrational coupling through the ribs. The linkage between cross rib and leaf is via bonding or tying at points (See Figure 3). Where the wall is monolithic, both cross rib and leaf are of the same material density and size - there is little impedance mis-match with the result that vibrational energy will be transmitted efficiently between the leaves. Figure 4 shows the measured vibrational level difference between the two leaves of a model diaphragm model. The models are of notional 1:8 scale, therefore values measured at 1kHz correspond with that at 125 Hz on a full scale wall. They scale only the geometry and not the material qualities of the walls, as it is the relative effect rather than the absolute effect of geometric and coupling change on the sound insulation character of the wall that is of importance in this paper.

2.2 Fin Masonry Walls
The fin wall has equal structural requirements to that of the diaphragm wall. The difference being that the cross rib is on the outside or inside of the wall and may be of a different thickness or depth. If there are two leaves, they are linked the same as a traditional double wall and for this reason the fin wall is traditionally believed to have similar sound insulation. What has not been considered is the effect of ribbing on the sound radiation characteristics of the wall.

## 3. ANALYSIS

3.1 Areas of Analysis
Three aspects of the diaphragm wall are being considered with respect to the resulting change in sound insulation.

a) The effect of cross ribs on the sound radiation of a single leaf wall.
b) The transmission hierarchy through cavities and cross ribs of the diaphragm wall.
c) The possible improvements to be gained by changes in the material qualities of the cross ribs and their coupling to the leaves.

3.2 Simple Theory
The measurement of Sound Reduction Index for a single wall clearly shows a dip in sound insulation about the coincidence frequency.For single walls good agreement, between measurement and prediction was obtained by assuming mass law up to half critical frequency according to Josse & Lamure[5] and then using the expression according to Sharp[3] above critical frequency. Measurement of the fin walls shows a plateau region below the classical critical frequency. The plateau region extends down in frequency with increasing number of ribs. This was thought due to the increased stiffness of the wall, where the wall assumes an orthotropic character. Thus for the fin wall a second critical frequency is assumed to result which is lower in frequency than that of the single panel. Simple theory was thus modified as follows; mass law was assumed up to the lower critical frequency and Sharp's expression above the original (isotropic) critical frequency of the single wall. Values are then interpolated between those at the two frequencies. Measured and predicted results for the fin models agree well using this method (See Figure 5). The detrimental effect of this plateau region is best seen by normalizing results with respect to that of a single wall of thickness equal to that of one leaf (Figures 6a and 6b). The orthotropicity of the fin is seen to result in a loss of sound insulation between the two critical frequencies. Even though the single panel has a lower effective mass than the fins, it will still give a better insulation in this region. Above and below the critical frequencies, higher insulation is predicted from Mass law and obtained.

3.2.1 Application to Diaphragm Walls. This modified theory for the fin walls was used for the monolithic diaphragm wall models. Good agreement was found in the super-critical region, but there was greater discrepancy in the sub-critical regions. Figure 7 shows the result for the 7 rib diaphragm model. Again, due to the orthotropic nature of the diaphragm wall the plateau region occurs, but it is wider than that of the fin wall because of its increased bending stiffness which results in a lower second critical frequency. It was stated earlier that the scale frequencies indicated in the figures correspond to lower frequencies in full scale structures by a factor of 8 or 10. Therefore, the dip in performance at 1 kHz shown in Figure 6 , say, corresponds to that at 100 Hz or 125 Hz. However, sound insulation in the lower frequency region is often of particular interest or most importance and it is here where improvements in the sound insulation are often desirable. Simple theory based on mass cannot predict the effect of changes in cross-rib and coupling detailing on the sound insulation of the wall, therefore a different approach is required and Statistical Energy Analysis was adopted.

## 4. STATISTICAL ENERGY ANALYSIS

### 4.1 Improvements To Sound Insulation

An increase of impedance mis-match occurs for the case of a rib is tied, rather than bonded, to one or both leaves, or where the rib may be of a different thickness or density than the leaves. Some improvement in sound insulation may thus be obtained in this way without the loss of structural integrity. If the diaphragm wall was split symmetrically into two separated fin walls it is postulated that with the increase in sound insulation due to the separation there would still result in a plateau region because both leaves would still be orthotropic in radiation character (this is presently being investigated further). If the wall is separated at a rib/leaf connection then this results in two walls, one orthotropic and one isotropic in nature. Figure 8 shows the measured diaphragm wall model separated at the rib/leaf junction with the measured diaphragm wall where ribs are bonded to both leaves and the double wall model. The large difference in sound insulation between the separated diaphragm wall and double leaf wall models over bonded diaphragm wall model illustrates the effect of the strong vibrational link of the cross ribs. It is also seen the orthotropic shape of the fin panel is lost when the diaphragm wall is separated at the rib/leaf junction. It may thus be suggested that radiation character of the isotropic leaf dominates over the plateau region and thus is not seen. Therefore a recovery of isotropicity to one of the leaves by greater decoupling of cross rib and leaf may result in increased insulation in the low frequency region.

### 4.2 Statistical Energy Analysis

Statistical Energy analysis (S.E.A.) was invoked to examine alterations to the cross-ribs in size, material density and coupling to leaves. S.E.A. is an approach to acousto-vibrational problems where transmission of sound and vibration are considered as energy flows between sub-systems. The diaphragm wall can be described as a series of repeatable vertical I-Sections which can be separated into sub-systems. The energy flows depend on the coupling loss factors between sub-systems from plate to plate, the radiation loss factors from plate to room and the modal densities of each sub-system. The radiation loss factor from the plates into the cavity and rooms was obtained from Maidanik's expression for radiation resistance as given by Crocker & Price[6] and the modal densities as given by Lyon[7]. Figure 9 shows the sub-systems of the diaphragm wall and Figure 10 is the power flow diagram in which the effect of cavity is included. Equations for each sub-system can be written as below:

Sub-system

2 $$2nE_2(\eta_{2'}+\eta_{2'1}+2n\eta_{24}+2n\eta_{25}) = E_1\eta_{12'}+2nE_4 2n\eta_{42}+nE_5 2n\eta_{52}$$

4 $$nE_4(n\eta_4+n\eta_{42}+n\eta_{45}+n\eta_{47}) = nE_2 n\eta_{24}+nE_5 n\eta_{54}+nE_7 n\eta_{74}$$

5 $$nE_5(n\eta_5+2n\eta_{52}+2n\eta_{57}+2n\eta_{54}) = 2nE_2 2n\eta_{25}+2nE_7 2n\eta_{75}+2nE_4 2n\eta_{45}$$

7 $$2nE_7(\eta_{7'}+2n\eta_{74}+2n\eta_{75}+\eta_{7'9}) = 2nE_4 2n\eta_{47}+nE_5 2n\eta_{57}+E_9\eta_{97'}$$

9 $$E_9(\eta_9+\eta_{97'}) = 2nE_7\eta_{7'9}$$

E1,E2,E4,E5,E7 & E9 are the sub-system energies relating to the source room, source-side plate, cavity, cross-rib, receiver-side plate and receiver room, respectively. $\Pi$ is the power into the system. n is the number of ribs, $\eta_{24}$ is the coupling/radiation loss factor from sub-system 2 to sub-system 4 and $\eta_2$ is the internal loss factor of sub-system 2. This set of simultaneous equations is easily solved. Without knowing the power into sub-system 1 the level difference between sub-system 1 and 9 (the two rooms) can be calculated and thus the Sound Reduction Index of the wall. Figure 11 shows the predicted Sound Reduction Index compared to that measured for the 7 Rib Diaphragm model. Results also show that the benefit of the cavity is minimal because of the strong vibrational bonding of the cross-rib. Using this approach parametric surveys are being completed on computer where the effect of variations in geometry, cross-rib detailing and rib/leaf coupling can be investigated.

## 5. MODEL & FIELD MEASUREMENT

Models of single, fin and diaphragm walls were made from 13mm perspex of area 1m x 1m and ribs of 50mm width. Fin and diaphragm models were constructed with 1, 3 or 7 ribs, evenly spaced. The Sound Reduction Index was measured, using sound intensity techniques, over the scale frequency range 400 Hz - 16kHz. Results were produced at 1/3 octaves by measuring a dual channel FFT Analyser.

## 6. CONCLUDING REMARKS

The bridging of the masonry diaphragm wall with cross ribs reduces the Sound Reduction Index of the wall. The benefits of the wide cavity are lost and the transmission of energy through the wall is dominated by the cross-rib path due to the strong impedance matching of the cross ribs and leaves. The addition of ribs to an isotropic single leaf, as seen by the fin model wall, results in the wall becoming orthotropic in character causing a plateau effect in the low frequency region This produces a loss of sound insulation in this region compared to the isotropic case. Simple modified theory fits satisfactorily for the bonded monolithic fin and diaphragm model walls. To improve the insulation of the wall some benefit is expected by increasing the impedance mis-match between cross ribs and leaves. These improvements may be gained by changes in material or by use of ties, thereby regaining in part the isotropic radiation character of the leaves.

Statistical Energy Analysis has been invoked to allow for prediction of these effects. A parametric survey is being conducted where geometry, material density, thickness and coupling can be varied. Sound intensity techniques have been used successfully for the measurement of the model walls under laboratory conditions and are being applied for full scale in-situ field measurements.

## 7. ACKNOWLEDGEMENTS

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## 8. REFERENCES

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Figure 1a: Typical cross-section of a diaphragm wall

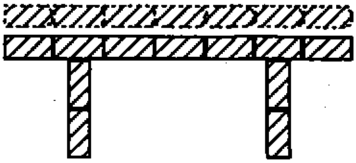

Figure 1b : Typical cross-section of a fin wall.

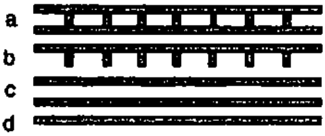


Figure 2: Model diaphragm (a) fin (b) double (b) and single wall (d) [1m$^2$ with 7 ribs]

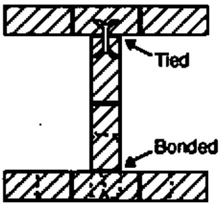


Figure 3: Connections between cross rib and leaves for diaphragm wall.

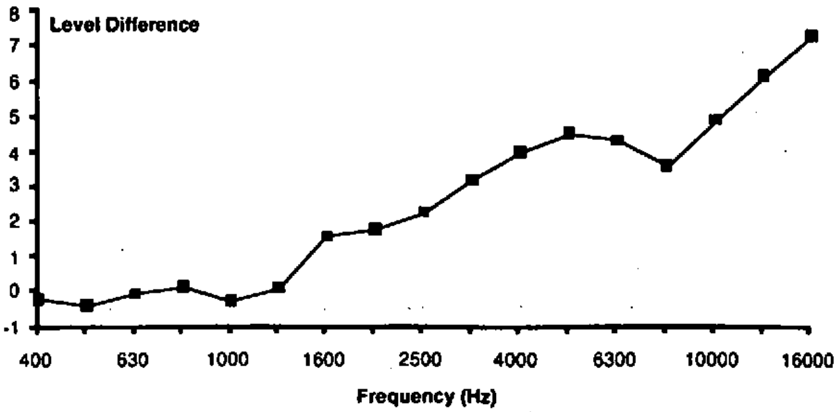


Figure 4: Level Difference between leaf faces of bonded diaphragm scale model wall.

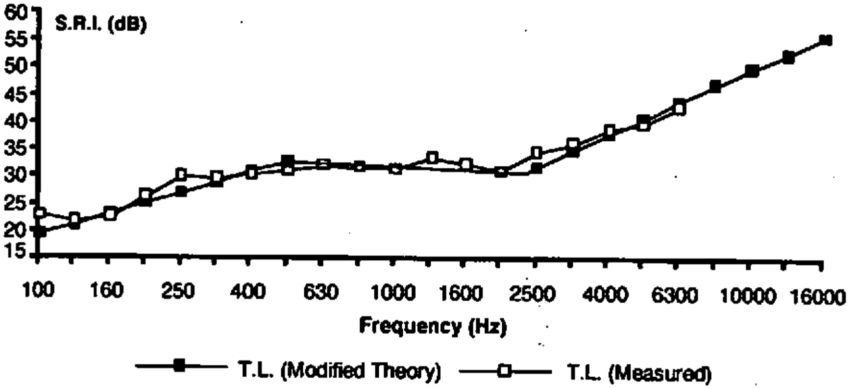


Figure 5 : 7 Rib Fin Model - Measurement & Modified Theory Prediction.

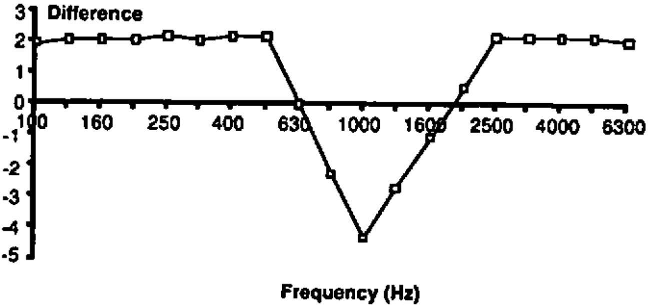


Figure 6a : Predicted results, 7 rib fin model wall S.R.I. - single model wall S.R.I.

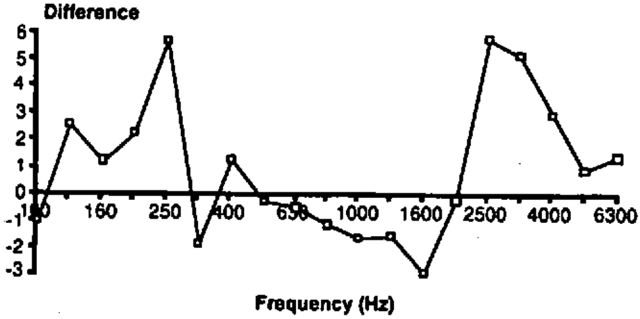


Figure 6b : Measured results, 7 rib fin model wall S.R.I. - single model wall S.R.I.

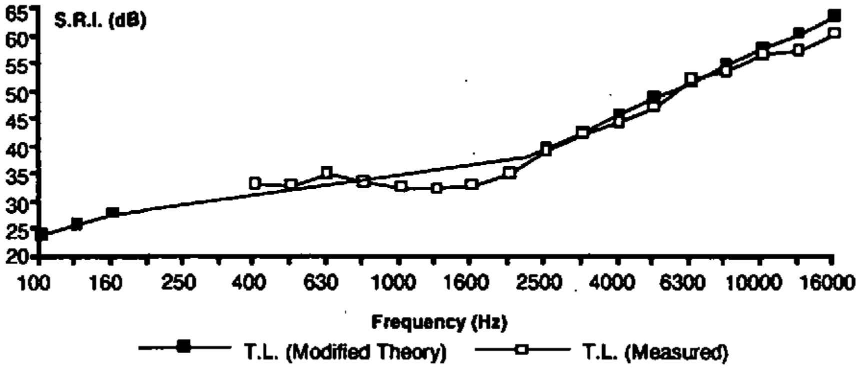


Figure 7 : S.R.I. of diaphragm model wall - measurement and predicted modified theory.

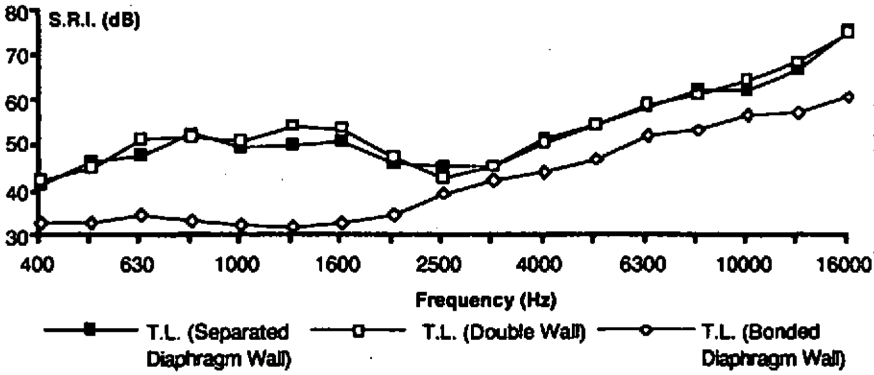


Figure 8 : Measured S.R.I.of separated & bonded diaphragm model walls and double model wall

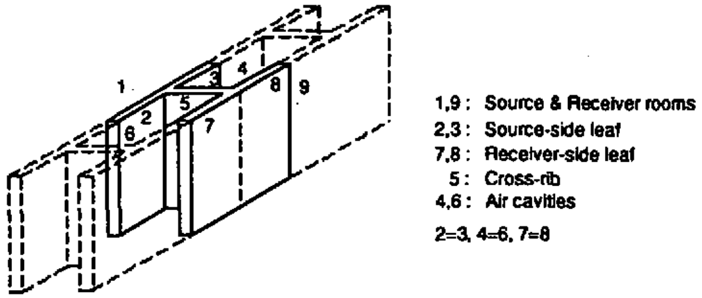


Figure 9 : S.E.A. sub-systems of diaphragm wall.

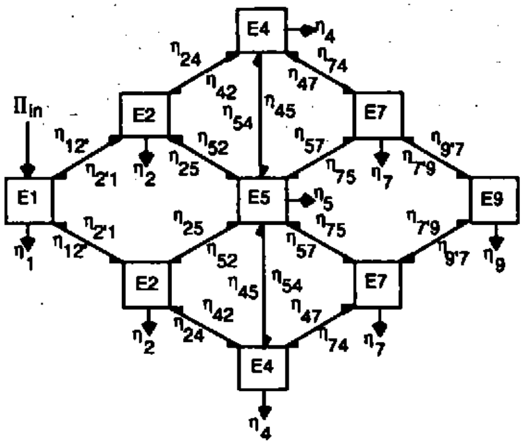


Figure 10: S.E.A. power flow diagram for diaphragm wall including air cavity path.

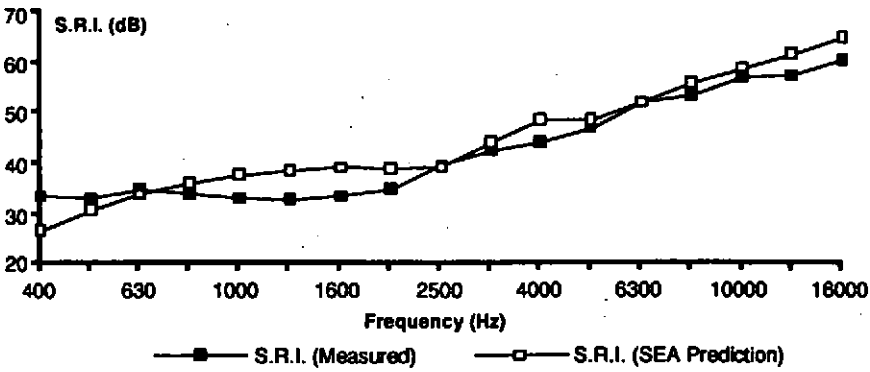


Figure 11 : S.R.I. of 7 rib diaphragm model wall - measurement & S.E.A. prediction.