SOUND TRANSMISSION
THROUGH DOUBLE WALLS

by

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This thesis is submitted in accordance with the requirements of Heriot-Watt University for the degree of Doctor of Philosophy.

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List of Symbols

B  Bending stiffness for a plate, per unit width. (Nm)
C  Longitudinal wavespeed. (m/s)
D  Level difference.
E  Young's modulus. (N/m²)
E_i  Energy in subsystem i. (Joules)
F  Force. (N)
K  Bulk modulus of air. (1.4 x 10^5 N/m)
L  Boundary length. (m)
L_i  Sound pressure level in subsystem i. (dB)
R  Total number of ties in a cavity wall.
S  Surface area. (m²)
T_60  Reverberation time.
V  Volume. (m³)
W_i  Total power lost from subsystem i. (W)
W_d  Power dissipated as heat in subsystem i. (W)
W_{d_i}  Power flow from subsystem i to subsystem j. (W)
Y  Mobility. (m/Ns)
Y_b  Mobility of a batten. (m/Ns)
Y_t  Mobility of a wall tie. (m/Ns)
Z  Mechanical impedance. (Ns/m)
Z_t  Impedance of a wall tie. (Ns/m)
a  Acceleration. (m/sec²)
c  Speed of sound in air. (m/s)
f  Frequency. (Hz)
f_a  Anti resonance frequency for a mass-spring-mass system. (Hz)
f_c  Critical frequency. (Hz)
f_r  Resonance frequency for a mass-spring-mass system. (Hz)
f_x  Frequency of the first cross resonance in a cavity. (Hz)
h  Thickness. (m)
i  √-1
k  Wave number. (rad/m)
k_a  Total stiffness of the air in a cavity. (N/m)
k_t  Stiffness of a rod. (N/m)
l  Cavity width. (m)
l_b  Length of a batten.
l_w  Width of a wall. (m)
l_h  Height of a wall. (m)
m  Mass. (kg)
n  Modal density.
p  Pressure. (N/m²)
r  Number of ties per square metre of cavity wall.
r_i  Reflection coefficient of subsystem i.
s  Cross sectional area of a wall tie. (m²)
v  Velocity. (m/s)
w  Width of a batten. (m)
x  Displacement. (m)
α  Absorption coefficient.
η_i  Total loss factor of subsystem i.
η_{ij}  Coupling loss factor from subsystem i to subsystem j.
η_{id}  Internal loss factor of subsystem i.
\[ \lambda \quad \text{Wavelength. (m)} \]
\[ \lambda_c \quad \text{Wavelength at critical frequency. (m)} \]
\[ \rho \quad \text{Density of air. (1.18 kg/m}^3) \]
\[ \rho_s \quad \text{Surface density. (kg/m}^3) \]
\[ \tau_{ij} \quad \text{Transmission coefficient from subsystem } i \text{ to subsystem } j. \]
\[ \omega \quad \text{Angular frequency. (rad/s)} \]
\[ \theta \quad \text{Angle of incidence.} \]
\[ \mu \quad \text{Poisson's ratio. (0.3 used throughout this report)} \]
\[ \sigma \quad \text{Radiation efficiency.} \]

**Abbreviations**

SEA  statistical energy analysis
CLF  coupling loss factor
ILF  internal loss factor
TLF  total loss factor
MSM  mass-spring-mass
B&K  Bruel and Kjaer
Acknowledgements

The author would like to extend his sincere thanks to his supervisor, Dr R.J.M. Craik, for his guidance and constant encouragement during the course of this research. One of the aims of this thesis was to provide measured data to verify theoretical work, both from his thesis and subsequently developed by him in a report for the Building Research Establishment. The theories contained therein have been reproduced in this thesis for completeness where appropriate and has been referenced appropriately. In addition the author would like to acknowledge the assistance provided in the way of computer software written by Dr Craik, which allows the potential that statistical energy analysis offers as a predictive tool to be realised.

Most of this research was carried on the behalf of the Building Research Establishment and the findings have appeared in a confidential report written for them. The author would like to thank Dr Les Fothergil of the BRE for generously funding the work and for granting permission for it’s reuse here.

The work on structural intensity was funded by the Science and Engineering Research Council whose assistance the author gratefully acknowledges.

The author would like to thank the technical staff in the Department of Building Engineering for their assistance. Notable amongst them is Tom Scott who built the numerous test walls used in this study.

Finally the author would like to extend a heartfelt thanks to his family for their tireless support during the course of this study.
Abstract

This thesis examines the transmission of sound through double walls, (walls that consist of two leaves separated by a narrow air cavity). Statistical Energy Analysis was used to assess the importance of individual transmission paths and to determine the overall performance.

An existing theory on tie coupling was examined and found to show good agreement with measured level difference data. Direct measurements of power flow across ties confirmed that the theory was accurate. This theory was modified to provide a simple means of predicting the coupling due to the stiffness of the air in the cavity. This is reasonably accurate in the region above the wall’s critical frequency. Transmission via these two paths was found to dominate the low frequency performance of masonry cavity walls, (walls where both leaves are heavy). At higher frequencies, transmission via foundations and via joints around doors and windows, was also found to be important.

For dry lined walls (walls where one leaf is heavy and the second is light), the strong structural coupling from line joints was found to be the only structural path that affected airborne transmission. This occurred as nearfield radiation from the surface of the dry lining in the vicinity of the joint. If structural coupling is weak, a path involving transmission via the air in the cavity dominates. The path involves non-resonant transmission between the cavity and the adjoining room via the dry lining and occurs as a result of its low mass and high critical frequency.

Additional transmission paths were examined and when found to be important expressions were presented which successfully predicted their performance.

This work has shown that the performance of double leaf construction can be predicted with a reasonable degree of accuracy and the theories will have applications in multiple leaf forms of construction.
Chapter 1

Introduction

1.1 General introduction

Cavity construction is widely used for providing the external envelope of buildings (external walls) and for providing separating walls between occupancies (party walls). In addition, the use of dry linings to provide the internal finish in buildings commonly takes the form of cavity construction. At its most basic this consists of two walls separated by a narrow air space.

Transmission through a party wall represents the most direct path that sound can take when travelling horizontally between two dwellings. It is important therefore that this wall possesses high sound insulation and the structural isolation provided by the cavity in a cavity wall makes this form of construction attractive.

The popularity of cavity construction for the external envelope of a building is primarily due to its ability to prevent the ingress of rain water and to control the flow of heat between the building and the external environment. External walls, however, still have an important role to play in providing sound insulation. They should possess a reasonable level of sound insulation so that noise sources emanating from outside a building do not represent a nuisance to the occupants. In addition, the external wall represents a potential flanking path between adjacent dwellings, allowing sound to bypass the party wall.

Where dry linings are used to provide the internal finish to masonry walls it is common for a small cavity to be formed behind the lining. The behaviour of this type of wall is more complicated than that of hard plastered construction and can lead to
improved performance.

The description of a cavity wall given above is very idealised. Real cavity walls have numerous structural connections between the two leaves and these serve to lower the sound insulation. Even for an idealised wall with no structural coupling, however, it is still possible for a significant amount of sound to be transmitted. The air in the cavity couples the two walls resulting in the transmission of sound from one leaf to the next. At certain frequencies this coupling can be very strong and the amount of sound transmitted can be significant. In addition, if the cavity is assumed to exhibit room-like behaviour, resonant and non-resonant transmission via the cavity will also occur. Despite these transmission mechanisms the part that the air plays in transmission tends to be important only at low frequencies. At other frequencies, very high transmission losses are predicted and can be measured.

In addition to the air coupling, which occurs over the entire area of the wall, real cavity walls commonly contain wall ties. There are usually around 2.5 per m² and they are designed to improve the structural performance of the wall by holding the two leaves together. This helps to increase the buckling resistance of tall walls and protects the external leaf of a building against suction loadings from the wind. These structural requirements are, however, at odds with the requirements for good sound insulation. The ties act as sound bridges, providing numerous transmission paths between the two leaves of the wall and this reduces the sound insulation.

In addition to wall ties, which are point acting sound bridges, there are two types of joint that result in line coupling between the two leaves of a cavity wall. Where doors and windows are present in external walls it is necessary to close the cavity at their perimeter to prevent the ingress of moisture and vermin. This is commonly achieved by returning one of the leaves of the wall to meet the second and results in the formation of a rigid joint. The second type of line joint occurs at the base of a cavity wall. The two leaves of the wall usually share a common foundation resulting in long joints that run the entire length of the wall. The coupling for both of these joints will be strong and could lead to significant transmission.
Existing theories

Before attempting to predict the performance of cavity walls that have structural sound bridges across the cavity, it is important to know how an ideal cavity wall behaves. There are many classical theories for predicting the transmission of sound through cavity walls. An assumption common to all of them is that the two leaves of the wall are identical and are coupled by the air in the cavity only. These theories are more complicated and less well developed than those for single walls because of the complex interactions that occur between the leaves of the wall and the cavity.

Once the performance of the wall can be described, it is then possible to assess the affect that introducing sound bridges has on the overall wall performance. The final part of this section examines briefly some of the approaches which allow this to be done.

Beranek and Work's theory

Beranek and Work [1] produced a theoretical model for the transmission of waves incident at the normal to a double wall. By solving the wave equation for the different regions of the wall using the continuity of acoustic impedance at each interface, they were able to obtain the ratio of pressures on any two surfaces. This allowed them to derive an expression for the difference between the incident and the transmitted sound pressure levels on the wall.

London's theory

Using a different approach, London [2] obtained a solution to the problem of sound transmission for obliquely incident waves. By assigning an impedance to the leaves of the wall and using continuity of wave potential across them, he was able to derive an expression for the transmission loss of a wave incident at an arbitrary angle of incidence. The random incidence transmission loss is obtained by integrating the expression for oblique incidence over all the possible angles of incidence. If this is done between 0° and 90°, a curve that lies below the mass law curve for an equivalent single wall (a single wall with a mass equal to the combined mass of the two leaves of a double wall) at all frequencies is obtained. London accounted for this with the
concept of an oblique mass-spring-mass resonance. At each frequency there is an angle of incidence where an oblique resonance occurred in the cavity resulting in total transmission. The transmission that occurred at this angle dominated the overall wall performance. London used an arbitrary resistance term theory to increase the transmission loss above the value for an equivalent single wall to provide good agreement with measured data. The resistance term was obtained from measurements performed on single leaf walls but no physical mechanism was given to justify it's inclusion and this severely limited the use of the theory for predicting how real partitions performed.

It is possible to predict high level differences without the use of the resistance term. This is achieved by integrating London's expression over a limited angle of incidence. Doing so sets an upper limit on the frequency of the oblique resonance and above this higher performance is predicted.

If the resistance term is set to zero and normal incident mass law transmission is assumed to occur, London's theory gives the same result as Beranek and Work's theory. An illustration of a typical transmission loss curve is shown in Fig 1.1. This is for normal incidence mass law transmission. At low frequencies the prediction closely follows the mass law value that would be obtained for a single leaf wall with the same total mass as the cavity wall. It may be deduced therefore that the air in the cavity plays little part in providing any sound reduction. Instead it behaves as if it had infinite stiffness, causing the two leaves to move as one. The first dip in the curve occurs at a frequency where a spring with a stiffness equal to that of the air in the cavity, joined at either end with two masses equal in weight to each leaf of the wall, would have it's first resonance. Some authors call this the Lower London frequency or the mass-spring-mass frequency. The transmission loss rises rapidly above this frequency until it approaches a second dip. This second dip and those that follow are caused by cross cavity resonances, standing waves that occur across the cavity.

The curve in Fig 1.1 overestimates the performance of a cavity wall because it is for normal incidence. Real walls are subjected to diffuse sound fields and as a result a lower transmission loss is obtained. When London used his theory to obtain data for
Fig. 1.1 Beranek and Work's model of a cavity wall.
random incidence the predicted data was too low, underestimating the measured performance. A modified version of these theories has however been developed by Sharp [3] who assumed that the sound field was incident over a limited angle of incidence. He obtained three approximate expressions that allow the performance of a double wall to be predicted. The results from these expressions are also shown on Fig 1.1. They have been evaluated for normal incidence so that they are directly comparable with Beranek and Work’s expressions. Below the MSM resonance, the wall’s performance is identical to an equivalent single leaf wall, rising at 6 dB per octave. Between the MSM resonance and the first cross cavity resonance the curve rises more steeply, at 18 dB per octave. The behaviour here is governed by the performance of the two single leaves of the wall and the cavity width. Sharp’s expression for this region is identical to the one given by Schiller [4]. Above the first cross cavity resonance, dependence on the cavity width is lost and performance is determined only by the behaviour of the individual leaves. The slope of the curve drops off slightly rising at 12 dB per octave. Sharp obtained good agreement between the predictions from this theory and measured data from lightweight double walls, provided the damping of the cavity was very high. For walls where the cavity was lightly damped, a severe degradation in performance occurred resulting in poor agreement with the theory.

**Mulholland, Parbrook and Cummings theory**

Mulholland, Parbrook and Cummings [5] produced an expression for the transmission loss of an infinite double wall using ray theory. They assumed that an obliquely incident wave upon entering the cavity underwent repeated reflections between the leaves of the partition, some sound being transmitted on each occasion. Absorption, positioned on the surfaces of the two leaves facing into the cavity, was introduced to the model and this attenuated the wave after repeated reflections. Their expression could be integrated over angle of incidence to give a transmission loss for a diffuse sound field. By selecting suitable values for the absorption coefficient and integrating over a limited angle of incidence they were able to obtain good agreement with measured data.

The problem with this theory was that whilst it did offer some physical mechanism
by which the theoretical results could be made to agree with measured data, the
values of the absorption coefficient were not measured, rather, the values selected
were those that produced the best fit.

In a second paper [6], Cummings and Mulholland modified their theory to allow for
the absorption to be positioned at the perimeter of the cavity of a finite double wall.
By setting the absorption coefficient to zero this model behaved as an infinite wall,
the wave in the cavity undergoing an infinite number of reflections. Increasing the
absorption at the perimeter caused a decay of the cavity wave and resulted in finite
wall behaviour. Their expression, which was integrated over a limited angle of
incidence, showed reasonable agreement with measured data from lightweight walls,
without the need to select arbitrary values for the absorption in the cavity. The theory
only applies to resonant transmission however, and their approach has been criticised
by Sewell [7], who disputes the use of ray theory in a narrow cavity at frequencies
where the wavelength is much larger than the cavity width.

**Sewell's theory**

Sewell [7] developed a two dimensional solution for the transmission of reverberant
sound through a finite double wall based on wave theory. He modelled the wall as
two simply supported panels, each set in it's own infinite rigid baffle. The cavity was
also assumed to be infinite to prevent the return of sound travelling past the edges of
the wall. This assumption eased the modelling of the boundary condition for the air
at the perimeter of the cavity. The solution provides expressions for transmission
above and below critical frequency, for both resonant and non-resonant transmission.
By varying the value for the internal loss factor of the panels, Sewell managed to
obtain reasonable agreement with published measured data.

**Donato's theory**

By using an electrical analogue of the two leaves and the cavity of a cavity wall, with
the appropriate expressions for the impedances of these, below and above, critical
frequency, Donato [8] obtained an equation to predict the performance of an infinite
double wall. For transmission below critical frequency an approximation was made
that accounted for the finite size of a real wall.

**Structural coupling models**

The theories for predicting the effect of point or line joints between the leaves of a cavity wall are even less well developed than those for transmission across the air in the cavity. Sharp [3] gives expressions based on impedance models for the effect that rigid tie or line coupling has on the airborne performance of a cavity wall. These however, do not allow the effect of this coupling on structural performance to be examined and are limited to bending waves incident normally on the joint. Bhattacharya, Mulholland and Crocker [9] have examined the same problem using a wave model of two parallel plates coupled along their centres by a tie plate. Their model, however, assumed that the tie plate exhibits modal behaviour and this limits the usefulness of the theory. Sound bridges in typical cavity walls will not display modal behaviour until very high frequencies are reached, higher than the building acoustics range. Coupling at the base of a cavity wall, similar to that on a strip foundation, has been examined by Vinokur [10] who gave approximate expressions for it’s impact on the airborne performance of a wall.

**Discussion**

These theories are all of limited use for predicting the performance of real cavity walls. They consider specific aspects of transmission and are in forms that do not allow the different transmission mechanisms to be gathered together to provide a comprehensive description of the wall’s performance. In addition, they consider the cavity wall in isolation and are therefore unable to account for the interaction that would occur between a real wall and any connected structures. This means that it is not possible to assess the impact of flanking transmission on the wall’s performance.

1.3 **Statistical energy analysis**

Statistical energy analysis (SEA) is a more flexible approach to modelling the behaviour of complex systems and it is able to overcome most of the failings of the classical theories.
Brief outline of SEA

The background to SEA and the concepts behind it, along with the general theory necessary to use it are described by Lyon [11]. SEA is a technique that was developed in the 60's to allow complex structures to be modelled with relative ease. This is done by breaking the structure (system) down into smaller more manageable pieces called subsystems. Each has it’s own identifiable energy which is assumed to be stored it’s resonant modes. The subsystems are coupled to each other and energy flows through the system from subsystems with high modal energy to subsystems that have low modal energy. This allows the macro behaviour of a structure to be examined, eg the velocity level difference between two plates. This is all that many users of the technique are interested in, however, one of the real attractions of SEA is that it allows specific aspects of transmission to be examined. In complex structures there are numerous different transmission paths that sound can take when travelling between two subsystems. SEA allows the transmission that occurs along a specific path to be examined in isolation, despite the presence of all the other paths in the model. This is of great use at the design stage of a project since identifying dominant transmission paths allows attention to be concentrated at the specific parts of the structure that are responsible for transmission. SEA is also useful for describing the complex behaviour that some structures exhibit. This can usually be explained by changes in the dominance of different transmission paths. Identifying these and observing when they are dominant provides a clearer understanding of the important mechanisms involved in transmission. In addition, it is relatively easy to model the whole of a system using SEA, not just the specific parts that are of prime interest. If this is done, the affects of flanking transmission are modelled automatically and by using a paths approach to examine the behaviour of the system, the strengths of these paths, relative to any paths of interest, may be assessed.

The initial uses of SEA were for analysing the behaviour of space vehicles and aircraft, however, the principles of the technique are general and can be applied to any type of structure. SEA is merely a means of representing a structure and describing it’s behaviour in a simple manner. SEA draws heavily on other disciplines for describing the properties of the subsystems and the coupling that occurs between them.
Application of SEA to Building structures

The technique started to be applied to building structures at the end of the 60's. In applying it, many of the existing classical theories used to predict the performance of building structures are used to describe the behaviour of the subsystems and the strength of the coupling between them. For rooms, energy is assumed to be stored in the room resonant modes and the theory of room acoustics is used to describe the properties of these subsystems. For walls and floors etc, the energy is usually assumed to be stored in the resonant bending modes. To describe the properties of these structural subsystems, bending wave theory is used. Maidanik's [12] theory of radiation efficiency allows the coupling that occurs between structures and rooms to be modelled and classical mass law theory is used to model the non-resonant coupling that occurs between rooms via walls. These theories allow relatively simple systems to be modelled using SEA, eg. Crocker and Price's model for a single wall separating two rooms [13].

To be able to model more complex building structures, it is necessary to be able to describe the coupling that occurs between structural subsystems. This is obtained from transmission coefficients which can be derived using wave models of structural joints. The basic techniques for obtaining these are given in Cremer et al [14] and the work of Kihlman [15], Gibbs [16] and Craik [17] allow many of the joints commonly encountered in buildings, to be modelled. Gibbs and Guilford [18] applied these to examine the performance of joints in scale models of building joints using SEA and Craik [17] applied them to successfully model the overall performance of a real building.

Application of SEA to cavity wall construction

Some work has been done to apply SEA to cavity walls. White and Powell [19] produced the first SEA work on cavity walls, however, this has been criticised by Sewell [7] and Donato [8] for dealing only with resonant transmission and, more seriously, for an error in an assumption made in one of their equations. Price and Crocker [20] provided all the expressions necessary to model a cavity wall using SEA, however, their theory too has been criticised. Both Donato [8] and Brekke [21] point out that the change in performance observed for real walls when the cavity
width is varied, is not predicted by the theory. Brekke attributed this to the omission of an expression accounting for the stiffness of the air in the cavity and gives an empirical term that can be used when calculating the airborne performance. It is not however of any use if the structural behaviour of the wall is of interest. Brekke has also extended the use of SEA to model transmission through triple walls, walls that have three leaves and two cavities. A discussion of the application of SEA to cavity wall construction and a comparison with classical theories is given by Elmallawany [22].

Craik [17] presented an expression that allows coupling across wall ties to be included in a SEA model of a cavity wall. Measured data from a real wall was provided for comparison with the SEA prediction, however, the agreement was poor. This work was extended in work carried out on behalf of the BRE [23]. A simple expression was presented for predicting the transmission between two rooms separated by a cavity wall with wall ties. In addition the theoretical behaviour of rooms separated by a party wall was studied and the effect of flanking transmission due to the presence of external cavity walls was assessed along with the affects that building defects have on performance. Lee [24] used an SEA approach to examine the behaviour of double walls built in the laboratory. The agreement between the measured and predicted results was good, however, existing theories for the coupling across structural sound bridges in the cavity were found to be unsuitable and an empirical approach was adopted.

The important transmission paths through a cavity wall

One of the advantages cited earlier for using SEA to model complex systems was that it is possible to take a paths-based approach to analysing the behaviour.

One of the simplest models encountered in applying SEA to building structures is of two rooms separated by a single leaf wall. This is the model that Crocker and Price [13] examined and a block diagram showing the subsystems and the transmission paths is given in Fig 1.2. It can be seen that there are only a few simple transmission paths in this model.
Fig 1.2. SEA model of a single leaf wall.

Fig 1.3a. SEA model of a single leaf wall showing the resonant path. Path 1-2-3.

Fig 1.3b. SEA model of a single leaf wall showing the non-resonant path. Path 1-[2]-3.
As with the classical models, placing a second wall next to the first, and thereby creating a cavity between them results in the behaviour of the wall becoming more complicated. The number and complexity of the paths through the system increases and it is this that makes it so difficult to model the system using classical techniques. If, however, the performance of each path is examined in turn, as may be done using SEA, the task of describing of the wall’s behaviour is made simpler.

Before examining the paths through a cavity wall, it is important to distinguish between two different types of transmission that can be encountered when modelling systems. These are resonant paths and non-resonant paths. They arise because structures can exhibit two different types of wave motion. Free bending waves on a structure, described by the bending wave equation [14], undergo reflections at the boundaries and produce standing wave fields. These are called resonant modes and it is these that are assumed to contain the subsystem energy in SEA. The rate at which the energy is dissipated in the subsystem is governed by it's damping, which is the sum of the losses due to coupling to other subsystems plus internal losses within the subsystem such as heat dissipation.

The second type of wave that occurs on structures are forced waves. These are different from bending waves and are caused by pressure fluctuations from the sound field in adjoining rooms. These waves have a small amplitude and their behaviour is not governed by the bending wave equation. The energy that is transmitted by this mechanism can not therefore be described using the properties of the resonant subsystem. The amplitude and hence the energy of these waves is different and the rate at which they lose energy is not determined by the resonant subsystem damping. The way in which this mechanism is usually represented in SEA is shown in the model of a single wall in Fig 1.2. Path 1-2-3 represents the resonant path through the wall from the source room to the receiving room. Transmission occurs via the resonant modes on the wall and the arrows on the figure are shown connecting the subsystem that represents the wall to those representing the two rooms. The non-resonant path due to the forced waves on the wall is given by path 1-3 where the structural subsystem (which represents the resonant behaviour only) has been bypassed. This is because the non-resonant path does not involve the resonant modes.
on the wall. For transmission via this path the only property of the wall that
determines the strength of the coupling is it's mass, the coupling being obtained using
the classical mass law expression.

For describing the paths in a cavity wall, this representation is a little limiting. It does
not allow the non-resonant transmission to be attributed to any specific structure and
where there are numerous non-resonant mechanisms the actual path the sound takes
can not be identified. Figure 1.3 shows the same model as Fig 1.2 but using a
convention for describing the paths that occur due to resonant and non-resonant
mechanisms. The rooms are represented by single subsystems as they only have
resonant modes. The wall is represented by two subsystems, one that models the
resonant behaviour which is the same as subsystem 2 in Fig 1.2. In addition,
however, the wall also has a "shadow" subsystem for modelling the non-resonant
transmission. This represents the mass of the wall only and identifies that the path
passes through subsystem 2 and not through some other subsystem that may be
coupled non-resonantly to the two rooms. Part a of the figure shows the resonant
path, path 1-2-3. Part b shows the non-resonant path, which is represented by, path
1-[2]-3, the square brackets denoting that the transmission is non-resonant.

In addition to walls, there are other subsystems that exhibit both resonant and non-
resonant behaviour. The air in the cavity behaves like a special type of room whose
behaviour differs from that of a normal room. The cavity is very narrow in
comparison with it's remaining two dimensions and for this reason it exhibits two
dimensional resonant behaviour over a wide range of frequencies. Sound can be
transmitted via these modes (in which the particle motion is parallel to the wall),
however, the stiffness of the air (in which the particle motion is normal to the wall
surface), also plays an important role in transmission at these frequencies. This is a
non-resonant mechanism and needs to be considered if the behaviour of the cavity is
to be modelled correctly. At high frequencies, cross cavity modes occur and the
cavity can be treated as a normal room.

Another important mechanism that can exhibit resonant and non-resonant behaviour
is a wall tie. These tend to be fairly short and as a result it is not until frequencies
in the order of 30 kHz are reached that they begin to undergo resonant behaviour (for wall ties force transmission is important and energy would be stored in longitudinal modes). For the building acoustics range of frequencies the behaviour of this subsystem is non-resonant, characterised by the tie stiffness. Coupling at foundation level and line joints between the leaves of a cavity wall will display the same type of behaviour, non-resonant transmission at the frequencies of interest in building acoustics.

A knowledge of the important paths and a method for describing them allows the behaviour of a cavity wall to be examined using a paths-based approach. Figure 1.4 shows a section through a cavity wall separating two rooms. The wall is built on a strip foundation and it’s leaves are coupled by the air in the cavity, by wall ties and by a line connection. The two rooms (subsystems 1 and 4), are purely resonant subsystems. The leaves of the wall (subsystems 2 and 3), exhibit both resonant and non-resonant behaviour over most of the frequency range of interest. The air in the cavity (subsystem 5), exhibits both resonant and non-resonant behaviour. The wall ties (subsystem 6), line connections (subsystem 7) and foundation (subsystem 8) are all non-resonant at the frequencies of interest. The SEA representation of the wall, is given at the bottom of Fig 1.4.

Only simple paths will be considered in this section, these travel directly from the source room to the receiving room without travelling back upon themselves. They are considered in two groups, paths across the air in the cavity and structural paths across the cavity.

Paths via the air in the cavity
These paths are illustrated on Fig 1.5.

path 1-2-5-3-4  This path involves: resonant transmission from the source room to the first leaf of the wall; resonant transmission from this leaf to the cavity; resonant transmission from the cavity to the second leaf of the wall; and finally, resonant transmission from this to the receiving room.
Section through a cavity wall

SEA model of a cavity wall

Fig. 1.4 SEA model of a typical cavity wall.
Fig. 1.5 Paths via the cavity for airborne transmission through a cavity wall.
This is the path that is modelled by Mulholland, Parbrook and Cummings [5]. It is one of the paths that Price and Crocker [20] model. Donato [8] gives expressions for this path above critical frequency of the wall and Sewell [7] models it above and below critical frequency.

**path 1-2-[5]-3-4** This path involves: resonant coupling from the source room to the wall. There is then resonant coupling between the two leaves of the wall due to the non-resonant stiffness path through the air in the cavity. The second leaf of the wall is then coupled resonantly with the receiving room.

It is this path that Brekke [21] and Donato [8] identified as being missing from Price and Crocker's [20] SEA model of a cavity wall.

**path 1-[2]-5-[3]-4** This path involves non-resonant transmission from the source room to the cavity via the first leaf of the wall. There is then non-resonant coupling from the cavity to the receiving room via the second leaf of the wall.

Price and Crocker's [20] theory contains an expression for modelling this path and Sewell's model contains expressions for this path below critical frequency of the wall.

**path 1-[2]-[5]-[3]-4** This path involves transmission from the source room to the receiving room, bypassing all the resonant modes in the wall. In this path the two leaves of the wall are modelled by their mass and the air by its stiffness. The wall behaves as a mass-spring-mass system and the transmission is characterised by a dip at the frequency where the system exhibits a resonance. At this frequency, transmission via this path is very strong and a dip is usually observed in the airborne level difference.

Price and Crocker's [20] model did not include this path. However, both the theories of Beranek and Work [1] and London [2], model it correctly.

**path 1-2-5-[3]-4** This path involves resonant transmission from the room to the first leaf of the wall and then resonant transmission from the wall into the cavity.
There is then non-resonant transmission from the cavity to the receiving room via the second leaf.

This path is important for walls where one leaf is heavy (subsystem 2) and the other is much lighter and more flexible (subsystem 3). A dry lined concrete wall would be a typical example of this type of construction. Sharp's [3] theory predicts the performance of this path provided that the cavity is highly absorbent.

Paths via structural sound bridges across the cavity

If the two leaves of a cavity wall are coupled by structural sound bridges, as shown in Fig 1.4, then paths in addition to those across the cavity are formed. These paths are illustrated on Fig 1.6.

path 1-2-[6]-3-4  This is the path via the wall ties. Over the building acoustics range of frequencies, the behaviour of the tie is non-resonant and it is characterised by its stiffness. The path involves resonant transmission from the source room to the first leaf of the cavity wall. There is then resonant transmission between the two leaves of the cavity wall via the stiffness of the tie. The second leaf of the wall is then coupled resonantly with the receiving room.

This transmission path has been studied by Craik [17] who produced an expression for the structural part of the path, part 2-[6]-3. Using this coupling he arrived at an expression for the performance of the whole path [23]. Crocker [25] produced an expression for the transmission of bending moments via the structural part of the path, however, according to Cremer et al [14] it is the transmission of forces that dominates the performance of a joint of this type.

path 1-2-[7]-3-4  Transmission via this path occurs around the perimeters of windows and doors where the two leaves of the wall are coupled by a stiff line acting structural bridge. This path involves resonant transmission from the source room to the first leaf of the wall. There is then resonant coupling between the two leaves of the wall via the non-resonant behaviour of the sound bridge. There is then resonant coupling between the second leaf of the wall and the receiving room.
Fig. 1.6  Paths via structural sound bridges across the cavity for airborne transmission through a cavity wall.
This is the path for transmission via the foundation. As with the previous two paths it is very unlikely that the strip foundation would exhibit any resonant behaviour at building acoustics frequencies. The path therefore involves resonant transmission from the source room to the first leaf of the test wall followed by resonant coupling between the two leaves of the test wall due to the non-resonant behaviour of the strip foundation. There is then resonant coupling between the second leaf of the wall and the receiving room.

Vinokur [10] has an approximate theory that will predict the performance of a joint of this type.

These paths would probably not be encountered in a normal cavity wall at building acoustics frequencies. This is because they involve resonant behaviour of the tie or line connection. It is, however, included for completeness. The path involves resonant coupling from the source room to the first leaf of the test wall, resonant coupling from this wall to the tie and then resonant coupling from the tie to the second leaf of the test wall. There is then resonant coupling between the second leaf of the wall and the resonant modes in the receiving room.

The theory necessary to predict the coupling between the leaves of the wall and the tie or line connection has been examined by Bhattacharya, Mulholland and Crocker [9].

Discussion

From the brief consideration of the paths presented here it can be seen that even for a cavity wall where the only thing coupling the two leaves is the air in the cavity, the behaviour is far more complicated than that of a single leaf wall. The introduction of structural bridges into the cavity further complicates this behaviour. To predict the performance of the wall using classical methods would be extremely difficult and still would not account for the interaction of the wall with the rest of the structure it forms a part of. This means that flanking transmission around a cavity wall in a real building can not be assessed.
SEA models have the required flexibility to cope with modelling complex structures. Although the construction of a cavity wall does not appear to be complex, its behaviour is complicated. The ability to predict the performance of individual paths is of enormous benefit when attempting to explain this behaviour. It allows important paths to be identified and eases the understanding of the mechanisms involved.

1.2 Aims of the thesis

In his PhD, Craik [17] developed a theory for predicting the transmission of sound across the wall ties in a cavity wall. In later work funded by the BRE [23], he extended his theory to examine the predicted effect of ties on the performance of cavity party walls and associated external walls. In addition, he developed an expression for the airborne level difference between two rooms separated by a cavity wall.

This thesis aims to develop this work, to expand and build on it. The aims were to provide measured data to compare with the existing theory for transmission across ties and to investigate some of the other important transmission mechanisms that exist in cavity walls. The final goal was to combine these individual theories within an SEA framework, to predict transmission of sound through all the types of cavity walls commonly found in buildings.

The approach adopted was to identify and examine each transmission path in turn to produce and then verify, theoretical models to predict their performance. Where possible existing theoretical models were used, new theories being developed when existing theories were found to be inappropriate or non-existent. The predicted results were then verified using measured data obtained from test walls designed so that the relevant path of interest dominated transmission. Finally, by combining the transmission from each of the mechanisms in a statistical energy analysis (SEA) framework, predicted data was obtained that included the effects of all the paths and the interactions between them.
Each chapter in this thesis deals with a separate subject and has been written, as far as possible, to be self contained. This is necessary for clarity as there are many transmission mechanisms to consider. Some chapters therefore contain theory sections to provide a clearer understanding of the work they cover. Inevitably, this has led to some duplication between chapters. To keep this to a minimum, chapter 2 gives a review of the existing theories used to predict the performance of buildings and building elements. Gathering them together in a single chapter is not only a convenient way of preventing repetition where numerous references are made to the same expression, it also helps to show how the individual theories are combined in SEA. An SEA model of the test walls and the transmission suite in which they were built was used to provide the predicted data throughout this thesis. A brief description of how to model a system using SEA is presented in chapter 2 along with all the theory, drawn from numerous references, necessary to calculate the coupling in the model. This again helps to concentrate all the theory that is common to most of the thesis in one chapter.

Some of the theories are specific to cavity construction and so have been examined in more detail to provide a greater understanding of the mechanisms involved in transmission. When this has been done, the theories have been reproduced in their entirety from other references, eg the section on tie coupling by Craik [17].

Chapter 3 describes the experimental facilities, experimental techniques and measurement accuracy. In addition, the details of the measurement of material properties and tie stiffness are given. Techniques for the direct measurement of power flow are also examined.

Chapter 4 examines the importance of the transmission path via the air in the cavity and compares the predictions made using an SEA model with predictions from classical theories. The existing theory of Price and Crocker [20] is used in the SEA model along with a new expression, given in chapter 2, for modelling the stiffness of the air in the cavity. Two different walls were built to examine the behaviour of the cavity and both were designed so that the non-resonant path, path 1-[2]-5-[3]-4 and the resonant path, path 1-2-5-3-4 were unimportant. For both of the different
walls the path via the stiffness of the air in the cavity, path 1-2-[5]-3-4 was the most important.

Chapters 5 and 6 describe the effect of tie stiffness and the number of ties on wall performance and include a comparison of measured and predicted results. In these chapters the resonant path via the tie stiffness, path 1-2-[6]-3-4 was designed to be dominant and the affect varying number and stiffness of ties is examined theoretically and experimentally.

Chapter 7 gives a theoretical model that allows transmission across double walls, where the coupling occurs along lines, to be predicted. The predicted results from the model are compared with measured data from a test wall where path 1-2-[7]-3-4 dominated transmission.

Chapter 8 gives the results for dry lined walls where one leaf is much lighter than the other. The results from this wall are a little different from those for the masonry walls in the other chapters. The difference in the properties and hence behaviour of the two leaves means that the dominant paths are not symmetrical about the cavity as with masonry cavity walls. The most important path for this wall was, path 1-2-5-[3]-4 where 2 is the masonry wall and 3 is the dry lining. The results from tests with ties and battens are also presented, these examining transmission via paths 1-2-[6]-3-4 and 1-2-[7]-3-4.

Chapter 9 describes experiments to measure, directly, the power flow across individual ties (path 2-[6]-3). Two measurement techniques are used, one uses instrumentation similar to that found in an impedance head. The other is a structural intensity technique using two accelerometers mounted side by side on the test object.

Chapter 10 describes theories for predicting transmission at mass-spring-mass resonance and an expression radiation efficiency which improves the predicted performance of masonry walls at critical frequency. The mass-spring-mass mechanism allows the behaviour of path 1-[2]-[5]-[3]-4 to be predicted. Studying the radiation efficiency allows more accurate predictions to be made at critical frequency for any
path that involves the interaction between the test wall and the room, ie paths that contain 1-2, 3-4, 2-5, 5-3 or the reverse. In addition, the measurement of sound transmission across foundations, path 1-2-[8]-3-4, is described and an existing theory for joints containing beams is used to predict the transmission via this path.

Chapter 11 brings together all the findings from previous chapters and discusses some of the consequences they have on different types of construction.

Chapter 12 contains a summary of the conclusions and gives some suggestions for further work.
2.1 Introduction

Statistical energy analysis (SEA) is a technique which can be used to model the behaviour of complex systems [11]. The analysis technique breaks the system down into subsystems, parts of the structure which have their own identifiable acoustical or vibratory energy e.g., walls, rooms, floors etc. The dynamic parameter, energy, is used in place of pressure or velocity as this keeps the calculations simple. However the results can be converted back into velocity or pressure at any time. The energy in a subsystem is assumed to be stored in the modes and within a given frequency band, equipartition of energy between the modes is assumed to exist i.e. each mode holds the same amount of energy. Power flows through the system from subsystems which have high modal energy to subsystems which have low modal energy. The extent to which power is transmitted between two subsystems is dependent upon the difference in the energy stored in the subsystems and upon the strength of the coupling between them. This framework of analysis is the only one which is general enough to enable all aspects of transmission to be considered. It can incorporate resonant and non-resonant transmission and can, more or less, describe all structures. It can also be used for flanking transmission.

2.2 Basic SEA models

Two subsystem SEA model

Fig 2.1 shows an SEA model of a simple system consisting of two subsystems. There is a source of power input into subsystem 1.
Power in

Figure 2.1. Two subsystem SEA model.

Figure 2.2. Three subsystem SEA model.

Figure 2.3. Four subsystem SEA model.
The power entering any subsystem is equal to the power that leaves it. Part of the power leaves the subsystem through coupling to other subsystems. The quantity which describes the amount of power that is transmitted between subsystems is the coupling loss factor (CLF), \( \eta_{ij} \), and is defined as the fraction of energy transmitted from subsystem \( i \) to subsystem \( j \) per radian cycle. The power flowing from subsystem 1 to subsystem 2 in Fig 2.1 can therefore be defined as,

\[
W_{12} = E_1 \omega \eta_{12}
\]

(2.1)

where \( E_1 \) is the energy in subsystem 1.

In addition to power being lost from the subsystem by transmission to other subsystems, some of the energy is dissipated as heat within the subsystem. The internal loss factor (ILF), \( \eta_{ii} \), is defined as the fraction of energy which is dissipated as heat within subsystem \( i \) per radian cycle. The power dissipated in the subsystem 1 (Fig 2.1) is therefore given by,

\[
W_{1d} = E_1 \omega \eta_{1d}
\]

(2.2)

The total power lost from a subsystem is equal to the sum of the power lost by transmission and the power lost by dissipation. For any given subsystem, the CLFs and the ILF can be summed to give a single loss factor called the total loss factor (TLF), \( \eta_i \). This is the fraction of the energy which is lost from that subsystem in one radian cycle and is either dissipated within the subsystem or transmitted to other subsystems. The total power lost from subsystem 1 in Fig 2.1 can therefore be given by,
Thus, for subsystems 1 and 2, the power balance equations are,

\[ W_1 + E_2 \omega \eta_{12} = E_1 \omega \eta_1 \]

and

\[ E_1 \omega \eta_{12} = E_2 \omega \eta_2 \]

The two resulting equations can then be solved to determine the energy in each subsystem for a power input \( W_I \).

**Three subsystem SEA model**

Fig 2.2 shows a model for a system with three subsystems and is the model that would be used to model transmission between two rooms through a single wall, where subsystems 1 and 3 represent two rooms and subsystem 2 represents the wall. The direct coupling that occurs between the two rooms represents the non-resonant transmission. This is similar to the model proposed by Crocker and Price [13]. Their model considered only the power flow in the direction from the source room to the receiving room. Power flowing back into the wall from the receiving room and power flowing back into the source room from the receiving room and the wall were neglected. The omission of these paths leads to only a small error. For this model the energy ratio due to the direct resonant transmission path can be given as [23],
\[ \frac{E_1}{E_3} = \frac{\eta_2 \eta_3 V_3}{\eta_{12} \eta_{23} V_1} \]

(2.5)

giving the level difference, \( D \), as [23],

\[ D = L_1 - L_2 - 10 \log \frac{\eta_2 \eta_3 V_3}{\eta_{12} \eta_{23} V_1} \]

(2.6)

where \( L \) is the sound pressure level difference and is found by using eqn(2.10) to give the relation between the energy and the pressure.

**Four Subsystem SEA model**

Fig 2.3 shows a four subsystem SEA model with only resonant transmission paths shown. This can be used to represent two rooms separated by a cavity wall where each room and each leaf of the wall are separate subsystems. If the two walls are coupled by stiff ties then the power flowing from the source room to the receiving room via the cavity would be negligible compared with the power crossing the cavity via the ties. In such cases the cavity can be omitted from the SEA model. The level difference for the four subsystem model is more complex due to the multiple transmission paths that are present across the cavity. The most important of these is the direct path, which from Fig 2.3 can be represented as path 1-2-3-4. This is the shortest path, the sound taking the most direct route and always travelling towards the receiving subsystem. It can be shown that the level difference for the sum of the direct path and all paths that involve transmission back and forth across the cavity (eg 1-2-3-2-3-4, 1-2-3-2-3-2-3-4,.....), is [23],
The first term in the equation represents the level difference that would be obtained from a single wall and the second term gives the increase in level difference that would be obtained from the addition of the second leaf. In this equation $\eta'$ represents the damping of a single wall in the absence of coupling by the wall ties.

At low frequencies where the ties are very stiff, equipartition of energy occurs between the two leaves of the wall. The level difference between the two leaves is 0 dB and the cavity wall is best modelled as a single subsystem. If a slip plane is assumed to occur between the leaves of the wall, the wall can be modelled as a single leaf wall which has a bending stiffness and surface density equal to the sum of the single wall values. The results from a single subsystem model would be equal to the level difference of a single leaf of the cavity wall plus 6 dB for the doubling of the surface density [23]. Fig 2.4 shows the level difference that would be obtained from this single subsystem model.

When using eqn(2.7), at low frequencies $\eta_{23}$ is much greater than $\eta_2'$ and the term for the additional insulation afforded to a single wall by the addition of the second leaf tends to 3 dB. It can be seen in Fig 2.4 that the answer given by eqn(2.7) is 3 dB lower than the answer for a single wall. By changing the constant 2 to a 4 in this equation, the two models can be made to agree at low frequencies without affecting the answer at high frequencies [23].

There is some evidence in chapter 5, (from the change in impedance at the mass-spring-mass resonance frequency) that no slip plane occurs and that at low frequencies the wall is stiffer than the sum of the stiffnesses. For this case the performance of the wall is more complicated and can not be corrected using the correction presented above. This correction was not made in any calculations presented in this thesis and there is therefore a little uncertainty in the results at very low frequencies.
Fig. 2.4 Predicted airborne transmission loss for a cavity wall.
Five subsystem SEA model

Price and Crocker [20] suggested a five subsystem SEA model to represent two rooms separated by a cavity wall as shown in Fig 2.5. Transmission between the two leaves of the wall was assumed to occur via the air in the cavity only. This model was used in this thesis for modelling dry linings. As the cavity width, \( l \), is small relative to its two other dimensions, the cavity supports only axial and tangential modes over a wide frequency range. It is therefore inappropriate to model it as a room at lower frequencies. It is not until the first cross cavity mode \( f_x \) which occurs at,

\[
f_x = \frac{c}{2l}
\]

(2.8)

that it is possible to model the cavity as a true room.

SEA models with \( n \) subsystems

For general systems with \( n \) subsystems the power balance equations can be written in matrix form. For a system comprising \( n \) subsystems the power balance matrix is

\[
\begin{bmatrix}
-\eta_1 & \eta_{21} & \eta_{31} & \cdots & \eta_{n1} \\
\eta_{12} & -\eta_2 & \eta_{32} & \cdots & \eta_{n2} \\
\eta_{13} & \eta_{23} & -\eta_3 & \cdots & \eta_{n3} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\eta_{1n} & \eta_{2n} & \eta_{3n} & \cdots & -\eta_n
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
\vdots \\
E_n
\end{bmatrix}
= \begin{bmatrix}
-W_1/\omega \\
-W_2/\omega \\
-W_3/\omega \\
\vdots \\
-W_n/\omega
\end{bmatrix}
\]

(2.9)

This can be solved numerically to obtain the energy in each subsystem for given loss factors and power inputs.
Fig. 2.5 Five subsystem SEA model.
2.3 Subsystem energy

Room energy
The energy in a room, $E_r$, of volume $V$, is related to the spatial and temporal average of the mean square sound pressure, $p^2$, through [11],

$$E_r = \frac{p^2 V}{\rho c^2}$$

(2.10)

Structural energy
The energy in a structure, $E_s$, is stored as both kinetic and potential energy. The total energy is divided equally between the two forms so the total energy can be obtained from twice the kinetic energy obtained from the measured spatial and temporal mean square velocity, $v^2$, on a structure of mass, $m$, through,

$$E_s = m v^2$$

(2.11)

2.4 Modal density

Room modal density
The modal density of a room, $n_r$, of volume $V$ is given by Kuttruff [26] as,

$$n_r = \frac{4 \pi f^2 V}{c^3} + \frac{\pi f S}{2c^2} + \frac{L}{8c}$$

(2.12)

where $S$ is the total surface area of the room and $L$ is the total length of all the edges in the room. $n_r$ is the modal density in modes/Hz.
A special case of room is the cavity in a cavity wall. As the cavity width is small compared with the remaining two dimensions, modal behaviour occurs in only two directions for a wide frequency range and it is not correct to use eqn(2.12) to determine the modal density. Price and Crocker [20] suggested an expression for the modal density of a cavity, \( n_c \), below the first cross cavity resonance \( f_c \),

\[
n_c = \frac{S_c f}{c^2}
\]  

(2.13)

where \( S_c \) is the cross sectional area of the cavity which normally equals the area of the wall. Above the frequency of the first cross cavity resonance the modal density can be given by eqn(2.12).

**Structural modal density**

The modal density of a plate of surface area \( S \), thickness \( h \) and with a longitudinal wavespeed \( C_l \), is given by Lyon [11] as,

\[
n_w = \frac{\sqrt{3}S}{C_l h}
\]  

(2.14)

2.5 **Structural impedance**

Impedance is defined as the ratio of the force, \( F \), at a point to the resulting velocity, \( v \), it produces. For an infinite plate of thickness \( h \), surface density, \( \rho_s \), and longitudinal wavespeed, \( C_l \), Cremer et al [14] give the impedance as,
\[ Z = \frac{F}{v} = 2.3 \rho_s h C_l \]

(2.15)

Mobility, \( Y \), is the inverse of impedance and for a plate is given as,

\[ Y = \frac{1}{Z} = \frac{1}{2.3 \rho_s h C_l} \]

(2.16)

### 2.6 Tie properties

The stiffness of a rod, \( k_r \) (N/m) which is short compared to the wavelength, is given by,

\[ k_r = \frac{E s}{l} \]

(2.17)

where \( E \) is the Young’s modulus of the material the tie is made from, \( s \) is the cross sectional area and \( l \) is it’s length. These properties can easily be measured and the stiffness of a rod-like tie can be determined. Wall ties however are rarely rod-like structures. They are fabricated in such a way as to prevent water from running across them. This usually involves forming twists or kinks at the mid point to form a drip. Accounting for these features theoretically would be difficult.

In addition to the departure from a rod-like structure, the bonding between the tie and the wall may also have an effect on the stiffness of very stiff ties. Twists, cuts or loops are commonly formed at the end of the tie to form a mechanical bond when they are bedded or cast into the wall. In addition to the mechanical bond, there is also
a bond formed between the surface of the tie and the cement in the mortar or concrete. It is possible that movement taking place in this region could also effect the stiffness of very stiff ties.

For these reasons eqn(2.17) does not predict tie stiffness accurately.

In order to determine the stiffness of wall ties an alternative method can be used to measure the stiffness. If two masses are joined by a spring, the system will display a resonance when excited. The resonance frequency is dependent on the size of the masses and the stiffness of the spring. This can be used as a basis for measuring the tie stiffness. By casting the tie into two blocks of concrete, one at each end, the tie forms a spring connecting two masses. Since the tie is cast into the concrete the possible effect of the tie/wall bond is accounted for. By exciting the system and measuring the resonance it is possible to determine the stiffness.

The system can be modelled as two masses of mass \( m_1 \) and \( m_2 \), connected by a spring of stiffness \( k \), as shown in Fig 2.6. A force, \( F \), is assumed to act on the mass, \( m_1 \), and this produces displacements \( x_1 \) and \( x_2 \) on block 1 and 2 respectively.

From Newton's second law, for block 1 [27],

\[
m_1 a_1 = F_1 - k_1 x_1 + k_2 x_2
\]

(2.18)

and for block 2 [27],

\[
m_2 a_2 = -k_2 x_2 + k_1 x_1
\]

(2.19)

This can be solved for \( a_1 \) and \( a_2 \) to give the frequency response for the system, the ratio of the acceleration to the exciting force. This ratio is equivalent to the inverse
Fig. 2.6  Model of two masses coupled by a spring.
of the dynamic mass, a quantity which is easy to work with.

The ratios are [27],

\[
\frac{a_1}{F_1} = -\frac{(k_t - m_2\omega^2)}{\omega^2 m_1 m_2 - k_t (m_1 + m_2)}
\]

(2.20)

and [27],

\[
\frac{a_2}{F_1} = -\frac{k_t}{\omega^2 m_1 m_2 - k_t (m_1 + m_2)}
\]

(2.21)

From eqn(2.20) it can be seen that the response of the source mass displays an anti resonance when the numerator is zero, when \(k_t\) is equal to \(\omega^2 m_2\). This occurs at a frequency \(f_a\) given by,

\[
f_a = \frac{1}{2\pi} \sqrt{\frac{k_t}{m_2}}
\]

(2.22)

For both the eqn(2.20) and eqn(2.21) a resonance occurs when the denominator is zero, when \(m_1 m_2 \omega^2 = k_t(m_1 + m_2)\). This occurs at,

\[
f_0 = \frac{1}{2\pi} \sqrt{k_t \left(\frac{1}{m_1} + \frac{1}{m_2}\right)}
\]

(2.23)
Fig 2.7 shows a typical response obtained when eqn(2.20) and eqn(2.21) were evaluated for a system where the two masses were the same, 10 Kg, and where the spring had a stiffness of $10^6$ N/m.

At low frequencies both equations can be approximated by,

$$\frac{a}{F} = \frac{1}{m_1 + m_2}$$

(2.24)

This is the reciprocal of the sum of the mass of the two blocks and implies that the spring behaves as an infinite stiffness and whole body motion occurs. The dip in the response of the source block can be seen at 50 Hz, the frequency given by eqn(2.22) and the peak predicted by eqn(2.23) at 71 Hz can be seen on both curves.

At high frequencies eqn(2.20) can be approximated by

$$\frac{a_1}{F} = \frac{1}{m_1}$$

(2.25)

This is the inverse of the dynamic mass of the source block. This implies that the spring is behaving as an isolator and reduces the influence on the receiving block has on the source block. At high frequencies eqn(2.21) approximates to,

$$\frac{a_2}{F} = \frac{f_2^2}{f^2} \cdot \frac{1}{(m_1 + m_2)}$$

(2.26)

The ratio decreases above the mass-spring-mass resonance as the receiving mass is
Fig. 2.7  Typical frequency response curves for a mass-spring-mass system.
isolated from the source mass by the spring.

2.7 Coupling loss factors

A coupling loss factor, CLF, is defined as the fraction of energy transmitted from one subsystem to another subsystem per radian cycle.

Wall to Room Coupling Loss Factor
The wall to room CLF, $\eta_{wr}$, can be given as [11],

$$\eta_{wr} = \frac{\rho c \sigma}{\omega \rho_s}$$

(2.27)

where $\sigma$ is the radiation efficiency. The equation for $\sigma$ depends on the frequency range of interest. There are three equations for frequencies below the critical frequency, at the critical frequency and above the critical frequency. The critical frequency is the frequency at which the wave speed in the structure and the wave speed in the air are equal. This is given by,

$$f_c = \frac{c^2 \sqrt{\frac{3}{\pi h C_l}}}{\pi h C_l}$$

(2.28)

The radiation efficiency of a plate is given as [28],
\[ \sigma = \frac{\lambda_c^2}{S} g_1(\alpha) + \frac{P \lambda_c}{S} g_2(\alpha) \]

\[ f < f_c \]

\[ \sigma = \left( \frac{I_x}{\lambda_c} \right)^{1/2} + \left( \frac{I_y}{\lambda_c} \right)^{1/2} \]

\[ f = f_c \]

\[ \sigma = \left( 1 - \frac{f_c}{f} \right)^{1/2} \]

\[ f > f_c \]

where \( P \) is the perimeter length of the wall, usually equal to twice the length \( I_x \) plus twice the height \( I_y \), \( \lambda_c \) is the wavelength at critical frequency, \( S \), is the area of the wall and where [28],

\[ g_1(\gamma) = \frac{8}{\pi^4} \frac{(1-2\gamma^2)}{\gamma(1-\gamma^2)^{0.5}} \quad f < f_c/2 \]

\[ g_1(\gamma) = 0 \quad f > f_c/2 \]

\[ g_2(\gamma) = \frac{1}{4\pi^2} \left[ \frac{(1-\gamma^2) \ln\left( \frac{1+\gamma}{1-\gamma} \right) + 2\gamma}{(1-\gamma^2)^{3/2}} \right] \]
Price and Crocker [20] have suggested that when the frequency is below the critical frequency the radiation efficiency should be doubled for radiation into a cavity as the wall radiates into a quarter space rather than a half space.

The expressions in eqn(2.29) provide accurate predictions of the radiation efficiency above and below critical frequency. The expression at \( f = f_c \), however, predicts large values of radiation efficiency which causes a large dip in the predicted level difference. These are never measured on masonry walls and the agreement between the measured and predicted data is usually poor in this frequency region. Radiation efficiency is examined in more detail in chapter 10 to arrive at a more accurate expression for this frequency region.

**Room to Wall Coupling Loss Factor**

The CLF from a room to a wall, can be found by using the consistency relationship [11],

\[
\eta_1 \eta_{12} - \eta_2 \eta_{21}
\]

(2.31)

where \( \eta \) is the subsystem modal density. This equation is valid for all coupling loss factors.

Taking the first term for the modal density of a room (eqn(2.12)) and that for a wall (eqn(2.14)) gives the CLF from a room to a wall as,
The eLF for transmission from a cavity to a wall can be found by using the consistency relationship \[11\],

\[
\eta_{cw} = \eta_{wc} \frac{n_w}{n_e}
\]

(2.33)

where \(n_w\) is the modal density of the wall, given by eqn(2.14) and \(n_e\) is the modal density of the cavity. The small width of the cavity compared with the remaining two dimensions means that for a large part of the frequency range of interest, modal behaviour occurs in only two dimensions. This affects the modal density of the cavity and an expression for the reduced modal density is given in eqn(2.13). Above \(f_c\) the modal density of the cavity is the same as a room and \(n_e\) is given by eqn(2.12). The CLF for coupling from the wall to the cavity \(\eta_{wc}\) is obtained by using eqn(2.27), with the appropriate correction below critical frequency.

**Room to Room Coupling Loss Factor**

Direct coupling takes place between rooms which are separated by a wall due to non-resonant or mass law coupling. Pressure fluctuations from the sound field on the source side result in motion on the wall which produces pressure fluctuations in the room on the other side. As the free bending waves on the wall play no part in this transmission (the assumption in the SEA model is that these modes store the subsystems energy), the structural subsystem is, in effect, bypassed and the two rooms are coupled directly. The transmission coefficient for non-resonant transmission between two rooms separated by a single wall is [28],

\[
\eta_{rw} = \frac{\rho c^4 S / \sqrt{3} \alpha}{8 \pi f^3 \rho \sigma CI h V}
\]

(2.32)
\[ \tau_{rr} = \frac{1}{1 + \left(\frac{\omega \rho_s}{2pc}\right)^2 \frac{1}{\pi}} \]  

(2.34)

which is related to the CLF for the non-resonant path from a room of volume, \( V \), through a wall with surface area, \( S \), by [11],

\[ \eta_{rr} = \frac{cS\tau_{rr}}{8\pi fV} \]  

(2.35)

A special case of room to room coupling is the coupling that occurs between a room and a cavity in a double wall. The CLF for transmission from the room to the cavity is given by eqn(2.34). The CLF, \( \eta_{rr} \), for transmission in the opposite direction is obtained using the consistency relationship in eqn(2.33), with the room modal density, from eqn(2.12) substituted for the wall modal density [20].

**Structure to Structure Coupling Loss Factor along a structural line**

Fig 2.8 shows a cross joint formed by the connection of four plates along their edges. The CLF for transmission between two walls, eg. from subsystem 1 to subsystem 2, is related to the transmission coefficient, \( \tau_{12} \), which is defined as,

\[ \tau_{12} = \frac{\text{Power transmitted}}{\text{Power incident}} \]  

(2.36)

The relationship between \( \tau_{12} \) and the CLF, \( \eta_{12} \), is given by Lyon [11] as,
Fig. 2.8 Structural coupling along an edge.

\[ h_1 = h_3 \]
\[ h_2 = h_4 \]
\[ Cl_1 = Cl_3 \]
\[ Cl_2 = Cl_4 \]
\[ \rho_1 = \rho_3 \]
\[ \rho_2 = \rho_4 \]
\[
\eta_{12} = 0.1365 \frac{L_{12}}{S_1} \left[ \frac{h_1 C_{II}}{f} \right]^{1/2} \tau_{12}
\]

(2.37)

where \( h_1, S_1 \) and \( C_{II} \) are the thickness, surface area and longitudinal wavespeed of the source subsystem and \( L_{12} \) is the common boundary length of the joint between them. The structural joints considered in this thesis are corner joints, tee joints and cross joints. Waves can be incident at a structural joint at many angles of incidence and to account for this expressions for \( \tau(\theta) \), the transmission coefficient of a wave incident at an angle of incidence, \( \theta \), are used. The average transmission coefficient for waves incident on the joint at angles between 0° and 90° given by [14],

\[
\tau_{av} = \int_0^{\pi/2} \tau(\theta) \cos \theta \, d\theta
\]

(2.38)

is used in eqn(2.37) to obtain the CLF.

Equations of differing complexity can be used to predict the transmission coefficients. In each case a wave is assumed incident on the joint and the amplitude of the reflected and transmitted waves are computed. If the joint is assumed to be pinned, so that no motion takes place, then relatively simple expressions can be used for the transmission coefficients. These are given below. If motion of the joint is permitted then the calculations are more complex. Such procedures are given by Craven and Gibbs [29].

**Coupling at a corner joint**

If plates 3 and 4 are omitted from the construction shown on Fig 2.8, the remaining two plates form a corner joint. The transmission coefficient for a joint of this type (where there is no motion of the joint), is given in [14] as,
\[
\tau_{12}(\theta) = \frac{2 \psi \sqrt{\chi^2 - \sin^2 \theta_1} \cos \theta_1}{\sqrt{\chi^2 + \sin^2 \theta_1} \sqrt{1 + \sin^2 \theta_1} + \sqrt{\chi^2 - \sin^2 \theta_1} \sqrt{1 - \sin^2 \theta_1}} + \chi^2
\]

(2.39)

where \( \theta_i \) is the angle of incidence of the wave on the source plate.

**Coupling at a cross joint**

A cross joint is shown in Fig 2.8 and for calculation purposes it is assumed that plates 1 and 3 have the same thickness and material properties and similarly that plates 2 and 4 have the same thickness and material properties.

For transmission from plate 1 to plate 2 (or 4) the transmission coefficient is given by [30],

\[
\tau_{12}(\theta) = \frac{0.5 \psi \sqrt{\chi^2 - \sin^2 \theta_1} \cos \theta_1}{\sqrt{\chi^2 + \sin^2 \theta_1} \sqrt{1 + \sin^2 \theta_1} + \sqrt{\chi^2 - \sin^2 \theta_1} \sqrt{1 - \sin^2 \theta_1}} + \chi^2
\]

(2.40)

which is 1/4 of the value for a corner joint.

For transmission from plate 1 to plate 3 the transmission coefficient is dependent upon the value of \( \chi^2 \) relative to the value of \( \sin^2 \theta \). When \( \chi^2 > \sin^2 \theta \) then \( \tau_{13} \) is given [30] as,

\[
\tau_{13}(\theta) = \frac{0.5 \chi^2 \cos^2 \theta_1}{\sqrt{\chi^2 + \sin^2 \theta_1} \sqrt{1 + \sin^2 \theta_1} + \sqrt{\chi^2 - \sin^2 \theta_1} \sqrt{1 - \sin^2 \theta_1}} + \chi^2
\]

(2.41)

When \( \chi^2 < \sin^2 \theta \) the wave on plates 2 and 4 become imaginary and there is no
power transmitted so that \( \tau_{12} \) is zero. For \( \tau_{13} \), the transmission is given by [30],

\[
\tau_{13}(\theta) = \frac{\cos^2 \theta_1}{R + \frac{\psi^2 R^2}{\chi^4}}
\]

(2.42)

where,

\[
R = \sqrt{\chi^2 + \sin^2 \theta_1} + \sqrt{\sin^2 \theta_1 - \chi^2}
\]

(2.43)

**Coupling at a tee joint**

For a tee joint in which plate 3 is missing from Fig 2.8, the transmission coefficient from plate 1 to plate 2 (or 4) is given by [17],

\[
\tau_{12}(\theta) = \frac{2 \psi \sqrt{\chi^2 - \sin^2 \theta_1} \cos \theta_1}{4\psi^2 + 2\psi(\sqrt{\chi^2 + \sin^2 \theta_1} + \sqrt{\chi^2 - \sin^2 \theta_1}) + \chi^2}
\]

(2.44)

For a tee joint where plate 4 is missing the equation for \( \tau_{12} \) is [17],

\[
\tau_{12}(\theta) = \frac{\psi \sqrt{\chi^2 - \sin^2 \theta_1} \cos \theta_1}{\psi^2 + \psi(\sqrt{\chi^2 + \sin^2 \theta_1} + \sqrt{\chi^2 - \sin^2 \theta_1}) + 2\chi^2}
\]

(2.45)

and \( \tau_{13} \) is given by [17],
\[ \tau_{13}(\theta) = \frac{0.5\chi^2 \cos^2 \theta_1}{\frac{\Psi^2}{4} + \frac{\Psi}{2}(\sqrt{\chi^2 + \sin^2 \theta_1} \sqrt{1 + \sin^2 \theta_1} + \sqrt{\chi^2 - \sin^2 \theta_1} \sqrt{1 - \sin^2 \theta_1}) + \chi^2} \]  

(2.46)

when \( \chi^2 > \sin^2 \theta \) and [11],

\[ \tau_{13}(\theta) = \frac{\cos^2 \theta_1}{2 + \frac{\Psi}{\chi^2} \sqrt{1 + \sin^2 \theta_1} R + \frac{\chi^2 R^2}{4\chi^4}} \]  

(2.47)

when \( \chi^2 < \sin^2 \theta \).

The quantities \( \chi \) and \( \Psi \) are given by [14],

\[ \chi = \frac{k_2}{k_1} \]  

(2.48)

and,

\[ \Psi = \frac{B_2 \frac{k_2^2}{k_1^2}}{B_1 \frac{k_2^2}{k_1^2}} \]  

(2.49)

Where \( B \) is the bending stiffness (per unit width) of the plates given by [14],
where $E$ is the Young's modulus of the material the plate is made from, $h$ is the plate thickness and $\mu$ is Poisson's ratio. $k$ is the wavenumber for bending waves given by [14],

\[ k = \sqrt{\frac{\rho_s}{B} \omega^2} \]  

(2.51)

where $\rho_s$ is the surface density of the plate.

Structure to structure coupling of parallel plates at a point

The CLF for two plates connected by a wall tie can be found by considering the impedances using electrical analogues [17]. The system being considered is shown in Fig 2.9. The force $F$ acting on the tie from the source plate is related to the difference between the velocity at a point distant from the tie, $v_o$, and the velocity at the tie, $v_t$, by [14],

\[ F = \frac{v_o - v_t}{Y_1} \]  

(2.52)

where $Y_1$ is the mobility of the source plate given by eqn(2.16).

If the tie has a stiffness $k_t$, then the force acting on it, $F$ is related to the velocity at each end through the expression [17],
Figure 2.9  Two walls coupled by a wall tie.

Figure 2.10  Electrical analogue for two walls coupled by a wall tie.
This gives the mobility of the tie, $Y_n$, as [17],

$$Y_n = \frac{v_2 - v_1}{F} - \frac{i\omega}{k_t}$$  \hspace{1cm} (2.54)

The system in Fig 2.9 can be represented by the electrical analogue shown in Fig 2.10 where velocity is the "across" and force is the "through" quantity. From this the force can be found as [17],

$$F = \nu_o \frac{1}{Y_1 + Y_2 + Y_t}$$  \hspace{1cm} (2.55)

The velocity on the receiving plate at the point of excitation is [17],

$$v_2 = \nu_o \frac{Y_2}{Y_1 + Y_2 + Y_t}$$  \hspace{1cm} (2.56)

The power transmitted by the tie to the receiving plate, $W_{12}$, is given by [14],

$$W_{12} = Re(Fv^*)$$  \hspace{1cm} (2.57)
where \( Re \) denotes the real part and \( v^* \) is the complex conjugate of \( v \). Substituting the expressions for force and velocity given in eqn(2.55) and eqn(2.56) the power transmitted by the tie is [17],

\[
W_{12} = v_e^2 \frac{Re(Y_2)}{|Y_1 + Y_2 + Y_1|^2}
\]

(2.58)

If the two walls are coupled by \( R \) ties the power flowing across the cavity would be \( R \) times the value given by eqn(2.58), provided that the power transmitted by each tie was uncorrelated with the power transmitted by every other tie.

In SEA models the power flow between two plates is defined as,

\[
W_{12} = E_1 \omega \eta_{12}
\]

(2.59)

where the energy on the plate is given by eqn(2.11).

Equating eqn(2.58) and eqn(2.59) gives the CLF for transmission between two plates coupled by a wall ties as [17],

\[
\eta_{12} = \frac{r Y_2}{\omega \rho_{sl} \left[ (Y_1 + Y_2)^2 + \left( \frac{\omega l}{E_s} \right)^2 \right]}
\]

(2.60)

where \( r \) is the number of ties per square metre of wall \( (r=R/S) \).

Fig 2.11 shows a typical CLF obtained for a wall connected by wall ties. It can be
Fig. 2.11  A typical coupling loss factor for a steel wall tie.
seen that the tie exhibits two types of behaviour. At low frequencies the tie stiffness term in the denominator of eqn(2.60) is insignificant and the coupling can be approximated by [17],

$$\eta_{\text{low}} = \frac{rY_2}{\omega \rho_{sl}(Y_1 + Y_2)^2}$$

(2.61)

The curve produced by this equation is also shown on the figure. At these frequencies the tie is behaving as if it possessed infinite stiffness and the coupling is determined only by the number of ties present in the wall and the physical properties of the two leaves of the wall. The CLF at low frequencies is very high and drops at 3 dB per octave.

At high frequencies,

$$\left(\frac{\omega l}{E_s}\right)^2 \gg (Y_1 + Y_2)^2$$

(2.62)

and the CLF can be approximated by [17],

$$\eta_{\text{high}} = \frac{rY_2}{\omega \rho_{sl} \left(\frac{\omega l}{E_s}\right)^2}$$

(2.63)

The curve produced by this equation is also is shown on Fig 2.11. It can be seen that at high frequencies the CLF reduces at 9 dB per octave. The point where the change occurs can be found by equating eqn(2.61) and eqn(2.63) and is [17],
\[ f = \frac{1}{2\pi} \frac{E_s}{l} (Y_1 + Y_2) \]  

(2.64)

**Discussion**

Cremer *et al* [14] have shown that, for two parallel plates with a uniformly distributed stiffness, the two plates will act as a single plate at low frequencies. The transition frequency, where the plates change from acting as a single plate to two separate plates, is the same as the mass-spring-mass resonance frequency though is due to wave coupling. It is given by [14],

\[ f_0 = \frac{1}{2\pi} \sqrt{(k_a + k)(\frac{1}{\rho_{s1}} + \frac{1}{\rho_{s2}})} \]

(2.65)

where \( k_a \) is the stiffness of the air and is given by eqn(2.74) multiplied by the area of the cavity and \( k \) is given by eqn(2.17). It is assumed that the total tie stiffness can be considered as a uniformly distributed stiffness. Below this frequency the velocity level difference of the two structural plates is 0 dB.

For the SEA model, where the two plates, (plates 2 and 3), have the same material and thickness the level difference is given by [23],

\[ \frac{E_2}{E_3} = 1 + \frac{\eta_2'}{\eta_{23}} \]

(2.66)

As \( \eta_{23} \) is large at low frequencies, this equation also gives a level difference of 0 dB at low frequencies. If the two walls do not have the same material and thickness then the SEA model has coupling \( \eta_{23} \) that is different from \( \eta_{32} \) as well as having two
subsystems with different surface densities.

The power balance for subsystem 3 is,

\[ \frac{E_2}{E_3} = \frac{\eta_3}{\eta_{23}} \]

(2.67)

and as \( \eta_{32} \) is large, \( \eta_3 \) is approximately \( \eta_{32} \). This gives the ratio of the energies as the ratio of CLFs which from the consistency relationship eqn(2.31) is equal to the ratio of the modal densities.

\[ \frac{E_2}{E_3} = \frac{\eta_{32}}{\eta_{23}} \frac{n_2}{n_3} \]

(2.68)

This gives the velocity ratio as,

\[ \frac{v_2^2}{v_3^2} = \frac{Y_2}{Y_3} \]

(2.69)

For walls that have two different leaves, the SEA model predicts a level difference that will be greater or less than 0 dB, depending on the direction of transmission. The SEA model can be made to agree with Cremer's model using eqn(2.69) at frequencies below the MSM resonance.

**Structure to structure coupling of parallel plates along a line**

In addition to the coupling that can occur between parallel plates at points it is also
possible to get coupling along lines. Examples of this are the battens that are used to fix dry linings to walls or the studwork in a plasterboard partition. As with the coupling at a point the CLF can be found by considering impedances using electrical analogues [31].

The batten connecting the two plates is assumed to possess a stiffness (per unit length), $k_b$.

$$k_b = \frac{Ew}{l}$$

(2.70)

where $l$ is the depth of the batten, equal to the cavity width and $w$ is the width of the batten. If there is a wave normally incident on the batten then the relationship between the stiffness of the batten and the mobility of the batten, $Y_b$, is given by eqn(2.54). The power flowing across the batten (per unit length) is given by eqn(2.58) and equating this with eqn(2.59) gives the CLF for a batten of length, $l_b$, as [31],

$$\eta_{23} = \frac{l_b \text{Re}(Y_2)}{\rho_2 S_2 \omega |Y_2 + Y_3 + Y_b|^2}$$

(2.71)

Since the batten is continuous and the contact is continuous this is equivalent to modelling the plates as a beams of unit width. The mobility of an infinite beam is used for $Y_2$ and $Y_3$ in eqn(2.71).

The equation for the mobility of an infinite beam is given by Cremer et al [14] as,
\[ Y_{\text{beam}} = \frac{1}{2.67 \rho_i S \sqrt{C/\rho f} (1+i)} \]  

(2.72)

where \( \rho_i \) is the mass per unit length of the beam which for a beam of unit width is the same as the surface density of the plate, \( h \) is the thickness and \( S \) is the cross sectional area which for a beam of unit width is the same as the plate thickness. Eqn(2.71) will only give approximate CLFs as only the contribution from waves on the wall which are normally incident on the batten are correctly modelled.

This coupling is similar to the coupling, described in chapter 7, for parallel plates coupled along lines. A wave model was used in chapter 7, which accounted for the effects of moments and forces and which could be integrated to obtain transmission coefficients for random wavefields. The normal incidence solution from the wave model is close but not identical to the impedance model. The impedance model considers only forces and so some difference would be expected. For the walls examined, the two models agree to within about 1.5 dB.

**Coupling across the air in a cavity**

In addition to coupling of the walls by the wall ties, the air in the cavity also couples the two leaves.

**Cremer et al [14]** examined the problem of transmission through floating floors. The floor was modelled as two parallel infinite plates coupled by an air layer. The model is appropriate for frequencies well below any cross cavity resonances. From the coupled bending wave equation two pairs of bending waves were identified. For the first type, the two plates moved together in phase with equal amplitude and in the second type they vibrated out of phase and became more decoupled with increasing frequency. The velocity level difference in the second region is given by,
\[ \Delta L = 40 \log \frac{f}{f_o} \]  

(2.73)

where the frequency, \( f_o \), is the cross-over region between the dominant wave types and is given by eqn(2.65).

This equation is not in a form that can be used in an SEA model but provides some insight into the mechanisms of transmission.

In order to model the air in a manner suitable for an SEA model it is possible to consider the stiffness due to the air connecting the two leaves of the wall as acting at a single point. This then allows the CLF equation developed for metal ties (which are point connections) to be used.

The stiffness of the air per unit area of cavity, \( k_a \), is given by [14],

\[ k_a = \frac{K}{l} \]  

(2.74)

where \( K \) is the bulk modulus of air and \( l \) is the cavity width. If the air compression is isothermal (which is most likely at low frequencies [14]) then the bulk modulus is approximately \( 10^4 \) N/m\(^2\). If the compression is adiabatic (as is more likely at high frequencies) then this increases to \( 1.4 \times 10^5 \) N/m\(^2\).

The total stiffness of the cavity is then \( k_a \) times the area of the wall, \( S \). If it is assumed to be concentrated at a single point, as an "airtie", the coupling loss factor can be obtained by substituting \( k_a S \) in place of,
\[ \frac{E_s}{l} \]

(2.75)

in eqn(2.60), to give [31],

\[ \eta_{23} = \frac{Y_3}{\omega \rho_s \left[ (Y_2 + Y_3)^2 + \left( \frac{\omega}{SK} \right)^2 \right]} \]

(2.76)

This approach is somewhat arbitrary but gives an approximate value for the importance of the airborne path across the cavity. By using the stiffness of the air in the expression for the coupling across the steel ties it is possible to classify the air as being equivalent to a given number of ties. If the air is equivalent to a large number of steel ties compared with the actual number present it may be concluded that airborne path is important and a more accurate prediction of it's contribution may be necessary.

The total coupling across the cavity can be obtained by summing the CLF for the ties and the CLF for the "airtie". For walls with a large number of very stiff ties it is fair to assume that the structural path across the cavity would be more important than the airborne path.

The above expression for the coupling holds only so long as there are no longitudinal modes on the wall ties or for the air in the cavity. For steel wall ties in a wall with a typical cavity width, the first longitudinal mode on the tie occurs at around 30 KHz, a frequency which is of little interest in building acoustics. Air is much less stiff than steel and the frequency at which cross cavity modes occur, given by eqn(2.8) is much lower. At these frequencies the air in the cavity becomes much stiffer and the
expression given by eqn(2.76) is no longer correct.

There are several methods of accounting for this increased stiffness however it would be desirable to be able to account, also, for any absorption that may take place at the wall surface. An approach that allows this to be done is one based on the behaviour of waves on beams of finite length. The stiffness of a spring $k_i$ can be related to the force, $F$, that acts on it and the velocities at it's ends, $v_1$ and $v_2$, by [17],

$$k_i = \frac{i\omega F}{v_2 - v_1}$$  \hspace{1cm} (2.77)

The mobility of the spring $Y$, can therefore be given by,

$$Y = \frac{v_2 - v_1}{F}$$  \hspace{1cm} (2.78)

Cremer et al [14] have shown that the velocity, $v_x$, at a given position, $x$, on a beam of finite length, $l$, which is clamped at one end and free at the other, when it is excited at one end by a force, $F$, can be given by,

$$v_x = \frac{F}{Z} \frac{e^{-ikx} + r_2 e^{-ik(2l-x)}}{1 - r_1 r_2 e^{-2ikl}}$$  \hspace{1cm} (2.79)

where $k$ is the wave number, $r_1$ and $r_2$ are the reflection coefficients at the ends of the beam and $Z$ is the impedance of the beam. The reflection coefficient is related to the absorption coefficient since $\alpha = (1 - r)$. If one end of the beam is positioned at $x = 0$ then the velocities at $x = 0$ and $x = l$ can be found. Substituting for $v_1$ and $v_2$ in
eqn(2.78) gives the mobility of the beam as,

\[ Y = \frac{1}{Z} \frac{-1 + e^{-ikl} - r_2 e^{-2ikl} + r_2 e^{-2ikl}}{1 + r_1 r_2 e^{-2ikl}} \]

(2.80)

For the air in the cavity the wave number is given by [14],

\[ k = \frac{\omega}{c} \]

(2.81)

and the impedance \( Z \) is equal to \( \rho c \). The CLF for the air in the cavity can then be determined by substituting the value for the mobility of the air, \( Y_a \), obtained from eqn(2.80), for \( Y \), eqn(2.58) to give,

\[ \eta_{23} = \frac{Y_3}{\omega \rho \omega S_2 |Y_2 + Y_3 + Y_a|^2} \]

(2.82)

Fig 2.12 shows a comparison between the CLF for a wall with dense concrete leaves and an 85 mm cavity, obtained using the mobility from eqn(2.80), and the CLF for the same wall obtained using eqn(2.76), where the cavity was modelled as a single tie of equivalent stiffness to the air. It can be seen that, at low frequencies where there is no cross cavity modal behaviour, the two results are the same. At higher frequencies, where the cross cavity modes occur, the two curves start to deviate from one another. The peaks in the CLF occur at the frequencies where the modes would be expected to occur, at these frequencies the air in the cavity is very stiff and a large amount of power would be transmitted across the cavity. The dips in the CLF occur at frequencies where half the wavelength is equal to odd multiples of the cavity width,
Fig. 2.12  Coupling loss factor for transmission across the air in an 85 mm wide cavity.
this suggests that at these frequencies the air in the cavity becomes very soft and that little power would be transmitted across it.

An alternative theory is the four pole theory given by Cremer et al [14]. This is based on a more exact analysis of beam motion but does not allow damping to be readily introduced. The CLF from this calculation is also shown in the figure. The results from this are almost identical to those obtained using eqn(2.82) except for the dips in the CLF.

The use of eqn(2.82) allows the effect of the absorption of the surfaces of the walls to be included and prevents the coupling from going to infinity at resonance. Fig 2.13 shows the effect on the CLF of varying the absorption coefficient of the wall surfaces facing into the cavity. The absorption has it’s greatest effect in the high frequency regions where the cross cavity modes occur. It can be seen that all the anti-resonances are damped, this having the effect of stiffening the air in the cavity and resulting in more power being transmitted across the cavity. The absorption only appears to damp the resonances which have wavelengths equal to odd multiples of the cavity width. Resonances which have wavelengths equal to even multiples of the cavity width are unaffected and would transmit a large amount of power across the cavity. This is probably a result of the assumption that one end of the beam was clamped which means that absorption at one end is effective. At the low frequencies increasing the absorption results in a slight lowering of the CLF which would result in a slight reduction in the power flowing across the cavity.

**Radiation by nearfield bending waves**

In addition to radiation from freely travelling bending waves, radiation can also occur due to nearfield waves generated by a point or a line excitation of a wall. If a plate has a high critical frequency (below which radiation from the free bending wavefield is low), radiation from the nearfield may be important.

**Radiation arising from point excitation**

The power, W, radiated into a room by the bending nearfield generated by a point connection is given by Cremer et al [14] as,
Fig. 2.13 The effect of the absorption coefficient of the wall surfaces facing into the cavity, on the cavity CLF.
where $R$ is the total number of point connections, $\lambda_c$ is the wavelength of bending waves on the panel at critical frequency, $v$ is the velocity at the point connection and $\rho$ and $c$ are the density of air and the speed of sound waves in air respectively.

For walls such as dry lined walls, like the one shown in Fig 2.14, where there is a large difference in the physical properties of the two leaves and where the tie that produces the point connection is very stiff, the velocity of the dry lining at the connecting point will be approximately equal to the velocity of the heavier core wall. In effect this directly couples the core wall to the room by-passing the dry lining. This power flow can be expressed as a CLF from the core wall to the room by relating the energy in the core wall to the power radiated by the nearfield. The power radiated from the core wall to the receiving room, $W_{24}$, is by definition,

$$W_{24} = E_2 \omega \eta_{24}$$

(2.84)

where $\eta_{24}$ is the CLF from the core wall to the room. By equating the two expressions for the radiated power it is possible to obtain the CLF, $\eta_{24}$, as

$$\eta_{24} = \frac{8 \rho c R \lambda_c^2}{\omega \rho_2 S_2 \pi^3}$$

(2.85)

As with non-resonant transmission (eqns(2.34) and (2.35)), the coupling is determined by the material properties of a subsystem which is neither the source subsystem or
For a dry lined wall with stiff ties it is assumed $v_2 = v_3$ at the tie location.
the receiving subsystem.

**Radiation arising from line excitation**

If the bending nearfield is generated by a line of length $L_b$, the power radiated is given in [14] as,

$$W = \frac{2 \rho c L_b \lambda_c y^2}{\pi}$$

(2.86)

where $\lambda_c$ is the wavelength of the panel at critical frequency. Again for walls such as dry lined walls, the velocity of the panel can be assumed to be the same as the core wall.

Relating the power radiated by the panel to the power flow from the core wall (equating eqn(2.86) with eqn(2.84)), gives,

$$\eta_{24} = \frac{2 \rho c L_b \lambda_c \epsilon_0}{\rho \epsilon \sigma S_2 \omega \pi}$$

(2.87)

### 2.8 Total loss factor

For all subsystems the TLF is equal to the sum of the coupling loss factors plus an internal loss factor. The ILF represents the rate at which energy is dissipated as heat or to parts of the structure not included in the model. For building type structures, the value is generally assumed to be independent of frequency and a typical value is 0.015. For rooms, it is difficult to separate the total loss factor from the internal loss factor and measured data is usually used. For all subsystems the total loss factor is related to the reverberation time $T_{60}$ by,
\[ \eta = \frac{2.2}{f \ T_{60}} \]  

(2.88)

**Rooms**

For all rooms the TLF was measured. However, the \( T_{60} \) can be predicted from [26],

\[ T_{60} = \frac{0.161V}{\sum S \alpha} \]  

(2.89)

where \( S \) is the surface area of a given material present in the room, \( \alpha \) is the absorption coefficient of that material and \( V \) is the volume of the room.

**Cavity**

A special case of room is the cavity in a double wall. Over a wide range of frequencies waves travel parallel to the faces of the wall. If it is assumed that absorption only occurs at the cavity perimeter, then the TLF of a cavity can be determined from the absorption coefficient \( \alpha \) of material positioned there, using [20],

\[ \eta_c = \frac{0.375 \ Ac \alpha}{V_e \omega} \]  

(2.90)

where \( A \) is the surface area of the edges of the cavity equal to twice the length plus the twice the height of the cavity multiplied by the width.

If there is absorption throughout the cavity then the waves would travel through it and it's effective area would be greater.
Structures
For all structures the TLFs were, where possible, predicted from the sum of the CLFs plus the ILF. Where these could not be predicted as in the case of some of the chamber walls and floors the approximation [30],

\[ \eta = \frac{1}{\sqrt{f}} + 0.015 \]

(2.91)

was used.

2.9 Conclusions
This chapter presented the basic concepts behind the SEA approach of modelling structures. The theory necessary to calculate all the coupling loss factors for a general model were presented and in addition some of the coupling loss factors specific to cavity construction were examined. The last section of this chapter showed how the total loss factors of structures and rooms can be predicted.
Chapter 3
Experimental facilities and measurement techniques

3.1 Introduction

This chapter describes the equipment used and the procedures adopted to carry out the measurements in this study. It begins with the measurement of the material properties made on the concrete blocks from which the test wall was built. It then deals with the calibration of force transducers, accelerometers and microphones. Finally the measurement of reverberation time, level difference, and tie stiffness is described along with the accuracy of the results.

3.2 The measurement facilities

Most of the measurements performed in this study were made on test walls built in a transmission suite. The transmission suite, shown in Fig 3.1 and Fig 3.2, consisted of two rooms that were structurally isolated from each other. Both rooms shared a common opening measuring 4.0 x 3.0 m where the test walls were built. The smaller of the two rooms measured 6.7 x 4.0 x 3.0 m and was used as the source room for airborne level difference measurements. The second room was larger measuring 7.0 x 6.0 x 5.0 m and this was used as the receiving room for airborne level difference measurements. The floors and ceilings of the chambers were made from 0.2 m thick in-situ concrete. The measured longitudinal wavespeed of the concrete was 3250 m/s and the design density was 2400 Kg/m³. The walls of the chambers were built from 0.22 m thick brickwork that had a measured longitudinal wavespeed of 2130 m/s and a design density of 1685 Kg/m³. The walls and ceilings were painted to reduce the absorption in the room. Part of the way through the measurement programme, the
Fig. 3.1  Vertical section through the test chambers.
Fig. 3.2  Horizontal section through the test chambers.
floors were also painted.

The two chambers were structurally isolated from each other. This was done by building the larger of the two chambers on springs. A 10 mm gap between the walls of the two chambers maintained the isolation at the perimeter of the common opening. The gap was sealed with a flexible silicone mastic joint. The isolation between the test chambers prevents flanking transmission from the structure of one room to the structure of the next. This helps to ensure the dominance of the direct transmission path, which is the one of prime interest. For practical reasons it is necessary to build the test wall in such a way that there are some structural joints formed between it and the test chambers. This means that the structure of the test suite will still affect the performance of the wall. Some of these effects are discussed in reference [32].

To account for the interaction that occurs between the test wall and chambers, the chamber structure was included in the SEA models that were used to compute test wall performance. These included all the walls, floors, ceilings and rooms of the transmission suite giving about 25 subsystems. Only the key subsystems are described in detail in each chapter. The measured dimensions and longitudinal wavespeed along with the design material densities were used for calculating the additional coupling loss factors. The damping of the structural subsystems was assumed to be equal to the sum of the CLFs plus an ILF. The internal loss factor for the brickwork was assumed to be the same as that for the concrete and a value of 0.015 was used. Results from damping measurements made on the test walls suggested they possessed a lower ILF of 0.008. Measured reverberation time data was used with eqn(2.88) to obtain measured values of TLF for the rooms.

Where flanking transmission through the structure was important, the effect that it has on the overall performance of the test wall is discussed with the results.
3.3 The test walls

In this thesis the behaviour of several different types of wall tie was studied and to do this, it was necessary to construct a new wall each time a different type of tie was tested. To enable the results for the different types of tie to be compared, the design of the basic wall and the materials from which it was constructed were kept constant. Where any changes to this design were made, the details are given in the relevant chapter.

A section through a typical test wall is shown in Fig 3.3. It consists of two leaves of masonry, each 100 mm thick, separated by an 85 mm wide cavity. The concrete blocks from which it was built had a longitudinal wave speed of 2200 m/s, (giving the critical frequency for the walls as 297 Hz), and a density of 2010 Kg/m³. Poisson's ratio was assumed to be 0.3. One leaf of the wall was built in each room so that they were structurally isolated from each other. This ensured that the only transmission paths across the double wall were either via the air in the cavity or via any wall ties that were present.

The cavity was a little wider than those commonly found in domestic construction due to a limitation imposed by the construction of the transmission suite. The silicone mastic sealed gap between the two floor slabs at the common opening between the two chambers was not in line with the gap between the chamber walls. An offset occurred at the junction between the floor and the walls making the absolute minimum cavity width approximately 50 mm. To prevent a structural flanking path, caused by mortar bridging the gap during the construction of the test walls, it was necessary to increase the width further. As a result the narrowest cavity that could be obtained was approximately 85 mm wide.

The wall that was built in the smaller of the two rooms was butt-jointed around all four edges to the structure of the chamber. The wall in the reverberant room (receiving room) was built free standing and was connected to the chamber only along it's base. A small gap was left between the chamber structure and the sides and top edge of the wall to prevent further coupling. This was done to minimise flanking
Fig. 3.3 Section through a concrete block cavity wall.
transmission. This gap was packed with closed cell foamed plastic and sealed with a silicone mastic joint. The faces of both the walls were sealed with cement paint to eliminate sound transmission through the pore structure of the blocks.

Three blocks on the bottom course of one leaf were bedded in sand during construction. This allowed access to be gained, after construction, to clear the cavity of mortar droppings. These droppings built up to a depth of several centimetres and could have resulted in a flanking path around the edge of the wall. After clearing the cavity of the mortar droppings, the blocks were fixed securely back in place with mortar.

3.4 Measurement of density

Determining the density of the materials used to construct test walls was a straightforward task of measuring the volume of sample blocks and then weighing them on electronic scales to find the mass. When built into a wall, errors arise due to neglecting the effect of the mortar on the overall density of the wall. For concrete blockwork the mortar joints represent only about 10% of the area of a wall. Any slight variations between the density of the mortar and the density of the blockwork would result in an error in the measured mass of less than 5%.

For structures other than the test walls (the walls, floors and ceilings of the test chambers), the design density, obtained from architects drawings, was used. These do not give a completely reliable measure of the density of the materials used but it should be accurate to within about 10%. The design values of density were used for parts of the test chamber which formed flanking paths. These tended to be less important than the direct path through the test wall so the error in any predicted results due to the variations in the density would be small.
3.5 Measurement of longitudinal wavespeed

The longitudinal wavespeed, \( C_l \), of a beam is related to the Young's modulus, \( E \), and density, \( \rho \), by \([14]\),

\[
C_l = \sqrt{\frac{E}{\rho}}
\]

(3.1)

For a plate the relationship is,

\[
C_l = \sqrt{\frac{E}{\rho(1-\mu^2)}}
\]

(3.2)

where \( \mu \) is Poisson's ratio (taken as 0.3 for all materials). The technique for measuring longitudinal wavespeed is described by Craik [33]. It is a convenient and non-destructive method for determining the Young's modulus of a structure in-situ. This allows bending stiffness to be obtained for use in further calculations.

The simplest way to excite a longitudinal wave on a structure is to strike it on an edge with a plastic-headed hammer. Unfortunately the edges of walls are rarely exposed and it is necessary to excite the waves indirectly. Fig 3.4 shows how this is achieved. If the wall under test is part of a corner, tee or cross joint, the excitation of the perpendicular plate, close to the edge of the wall under test, will cause longitudinal waves to be generated.

A plastic-headed hammer was used to excite the walls and a force transducer mounted at the hammer tip provided a pulse to show when the waves were generated. An accelerometer (mounted so that it's axis of greatest sensitivity lay in the same
Figure 3.4 Measurement of longitudinal wavespeed.

Figure 3.5 Measurement of structural damping.
direction as the wave motion) was used to detect the arrival of the waves at the opposite side of the wall. The signals from both transducers were fed into a storage oscilloscope which allowed the transit time to be found. The distance between the point on the edge of the wall where the waves were excited and the point where the waves were detected was measured. From this data the wavespeed was determined.

3.6 Measurement of damping

The total loss factor, $\eta$, was obtained from measurements of reverberation time, $T_{60}$, using the equation,

$$\eta = \frac{2.2}{f T_{60}}$$

(3.3)

For rooms, the reverberation time was measured in third octaves using a Nortronics Type 823 analyser. This produces band-limited noise which it cuts off and then records the decay of the sound pressure in the room. From this it calculates the reverberation time based on the first 30 dB of usable decay, normalised to a 60 dB range. Measurements were made between 25 Hz and 5 KHz over at least six positions.

For structures, an accelerometer is used instead of a microphone to detect the decay. As the decay can be as short as 40 milliseconds the equipment shown in Fig 3.5 was used, following the procedure given by Craik [30]. A single blow from a plastic-headed hammer was used to excite the subsystem and the decay was detected by an accelerometer attached to the wall with beeswax. Care was taken not to strike the wall too close to the accelerometer to prevent nearfield effects. The signal from the accelerometer was fed into a measuring amplifier and passed through a set of third octave filters. It was then squared and converted into a logarithmic signal. This gives a straight line decay curve that was displayed on the screen of a storage oscilloscope,
calibrated in dB along its vertical axis. By measuring the slope of the decay and knowing the time base on the oscilloscope, it was possible to find the reverberation time for the wall and then determine the TLF. Measurements were made at six positions between 40 Hz and 5 KHz on each leaf of the test wall. This procedure gave a 95% confidence interval of less than 1 dB over this frequency range.

The reverberation time of the cavity in a concrete blockwork cavity wall was also measured using this set up. A loudspeaker was built into the cavity and fed with band-limited noise. A two-pole switch was used to simultaneously cut off the sound to the loudspeaker and trigger the oscilloscope to capture the decay. The measurement was performed at six positions using a microphone inserted through holes drilled in the wall. Data was obtained between 63 Hz and 3.15 KHz.

3.7 Calibration

Microphones
The airborne measurements were made using half inch B&K Type 4134 condenser microphones connected to B&K Type 2639 pre amplifiers. These were calibrated before and after each measurement using a B&K Type 4230 sound level calibrator. This generates a SPL of 93.8 dB at 1 KHz for a half inch microphone and calibrates to an accuracy of ± 0.3 dB.

Accelerometers
Most of the structural measurements performed in this study were made using B&K Type 4369 accelerometers with B&K Type 2635 charge amplifiers. These were calibrated using a B&K Type 4294 calibration exciter that produces an acceleration of 10 m/s² at 159.2 Hz. It calibrates to an accuracy of approximately ± 0.2 dB.

Force transducer
Force was measured using Kistler Type 9011 force transducers. They were used primarily for the measurement of power flow across a specially instrumented wall tie.
The force transducer, mounted on the wall tie, was screwed into one end of a solid 53 Kg steel cylinder and secured with a lock nut as shown in Fig 3.6. An accelerometer was fixed to the other end of the cylinder with beeswax. The outputs from both the accelerometer and the force transducer were fed via charge amplifiers into a dual channel FFT analyser (B&K Type 2032). Calibration was performed by connecting the acceleration signal to channel A and the force signal to channel B. The transfer function gives the ratio of the force to the acceleration, which is equal to the dynamic mass (from Newton’s law $F = m \times a$). The sensitivity of the force channel was adjusted until the dynamic mass was equal to the mass of the cylinder.

3.8 Level difference measurements

Most of the level difference measurements performed in this study were made in third octaves using two real time digital frequency analysers. The remainder were made using an FFT analyser that produced an 801 line narrowband spectrum. Several types of measurements were performed but in the main they consisted of airborne level differences, (the sound pressure level difference between two rooms) and structural level differences, (the difference between the acceleration levels measured on two structures). For the airborne level differences a loudspeaker fed with pink noise was used as a sound source and for the structural level differences a plastic-headed hammer was used to excite the leaves of the test wall using the procedure described by Craik [34]. Calibration of the equipment was carried out before each test and for the structural measurements the charge amplifiers and the analysers were checked to ensure that they were not overloaded by the hammer blows. During the measurements the analysers were watched constantly to ensure they were not being overloaded. At the end of a measurement the calibration of the transducers was rechecked.

Third octave measurements

The experimental set up for making the third octave measurements is shown on Fig 3.7. The measurements were made using two third octave, real time analysers (B&K Type 2131) connected to a desk top computer via an IEEE bus. This allowed the two signals to be measured simultaneously for all third octave bands.
Figure 3.6 Calibration of the force transducer on the instrumented wall tie

Figure 3.7 Experimental set up for 1/3 octave measurement of sound pressure and surface acceleration
Sixteen seconds of linear averaging was carried out at each measurement position, at the end of which the computer automatically read and stored the data from both the analysers. The computer calculated the mean, standard deviation and 95% confidence interval for the level difference at each frequency band. The microphone or accelerometer positions were then changed and the procedure repeated until the 95% confidence interval was less than 1 dB between 100 Hz and 3.15 KHz.

**Accuracy of third octave measurements**

In SEA it is important that the standard deviation, which is a property of a subsystem, is known. This allows the spread of possible values about the predicted mean to be determined. Equations exist for predicting the standard deviation and these were found to be successful for rooms but showed poor agreement with the measured standard deviation for structures [17].

For the work in this thesis the greatest interest lies in determining how accurate the mean of a set of measurements is and for this reason the emphasis has been on the 95% confidence interval. As the changes made to the construction of the test wall resulted in only small changes in the walls performance it was necessary to work to a high level of accuracy. This ensured that any changes measured were due to the change in construction and not statistical variations arising from the measurement procedure. In order to determine the accuracy it is necessary to know the statistical distribution of the data. Craik [17], examined this problem and concluded that the standard deviation and the 95% confidence interval for structural and airborne data, when in dB, could be assumed to follow a normal distribution. The standard expressions for determining accuracy, given below, can therefore be used.

After a measurement was completed, the mean was recomputed to account for the effects of background noise. If the measured level was within 8 dB of background noise the data was disallowed. The number of measurement positions at that frequency was then reduced by 1 for calculating the mean level.

To calculate the mean the measured data was converted from dB into absolute units. The mean was then calculated and converted back into dB. For a single variable
measurement the mean, \( m \), of a set of, \( n \), measurements is given by [35],

\[
m = \frac{\Sigma x}{n}
\]

(3.4)

It is not necessary to convert the measured data into absolute units when calculating
the standard deviation, \( sd \), and the 95\% confidence interval, as these can be obtained
directly from the dB values [17]. The standard deviation is given by,

\[
sd = \sqrt{\frac{\Sigma x^2 - (\Sigma x)^2}{n}}
\]

n - 1

(3.5)

and the 95\% confidence interval is obtained using,

\[
95\% CC = \frac{s(dB)}{\sqrt{n}} \times t_{v,0.975}
\]

(3.6)

t_{v,0.975} is the value taken from the students t-distribution for a 95\% confidence interval
for a measurement with \( v \) degrees of freedom, where \( v \) is equal to \( n-1 \).

Typical 95\% confidence intervals for the third octave measurements performed in this
thesis are given in Figs 3.8 and 3.9. Over most of the frequency range this was less
than 1 dB. Some exceptions to this occurred at low frequencies but these were
generally less than 2 dB. This is sufficiently accurate for the differences measured
between the performance of the walls studied to be significant. Should the standard
deviations be required they can be obtained from the 95\% confidence intervals,
provided, \( n \), the number of measurements is known. For structural measurements this
Fig. 3.8 95% confidence intervals for the airborne level difference and structural level difference for a cavity wall where the number of ties is varied.
Fig. 3.9 95% confidence intervals for the airborne level difference and structural level difference for cavity walls with different wall ties.
was normally 40 and for airborne measurements it was 30.

**Narrowband measurements**

The narrowband level difference measurements were made between 20 Hz and 1.6 KHz using a dual channel FFT analyser (B&K Type 2032). At each position a linear average of one hundred time samples was taken. As it is not a real time analyser, only part of the signal fed into the analyser by the transducers is processed. To prevent the discontinuities between the samples of data from affecting the resulting spectra, a Hanning window was used. The data was again transferred to a desk-top computer via an IEEE bus and stored. For the narrowband measurements twenty positions were measured for each test. This usually gave a 95% confidence interval of around 1.5 dB, a higher value than obtained for an equivalent number of third octave results. Where it was greater, the accuracy is discussed in the relevant section of the thesis.

**3.9 Measurement of tie stiffness**

For the theory of sound transmission across a cavity wall it is necessary to know the stiffness of the wall ties. Simple ties can be modelled as rods and predicting the stiffness is straightforward. However real ties have a complex structure and this means that the simple theory cannot be used to predict their stiffness. It was therefore necessary to use measured tie stiffness to make the predictions.

**Measurement procedure**

To measure the stiffness a concrete cube was cast onto each end of a wall tie; the centre was left free for a distance equal to the width of the cavity.

The test samples were prepared in moulds used for making concrete cubes for compressive strength tests. Concrete was poured into the mould and tamped to remove air bubbles. The end of the tie was then pushed into the concrete and a trowel was used to produce a flush surface on the top of the cube. When the first cube had set it was removed from the mould, which was then refilled. The free end of the tie
was then pushed into the fresh concrete. To ensure that the correct spacing was obtained between the cubes and to support the first cube, two timber spacers were used. These were placed on top of the cube mould. The surface of the second cube was trowelled to produce a smooth finish and to ensure that the correct tie length was obtained. After setting, the second cube was removed from the mould and the test piece was left to strengthen. Before testing the blocks were weighed.

The measurement was performed with the blocks supported on two wooden trays that were suspended from a steel pole as shown in Fig 3.10. To perform the measurement one of the blocks (the source block), was excited with a hammer that was instrumented with a force transducer. The response of this block or the second block (the receiving block), was measured with an accelerometer. The outputs from both the transducers were fed via charge amplifiers into a dual channel FFT analyser. By inputting the acceleration signal to channel B and the force signal into channel A, the frequency response function on the analyser provided data to compare with the predicted responses obtained using eqn(2.20) and eqn(2.21). The measurement was performed with the accelerometer mounted on the source block and then was repeated for the accelerometer on the receiving block.

A typical pair of measured frequency response curves are shown in Fig 3.11. From the mass of the two concrete cubes and the measured resonance frequency of the system, the stiffness of the tie can be determined using eqn(2.23). This can then be used to predict the entire frequency response using eqn(2.20) and eqn(2.21). The results shown in Fig 3.11 are for a hook tie, (stiffness = 2.1 x 10⁶ N/m). There is very close agreement between the measured and predicted frequency responses.

An alternative technique for measuring the stiffness involves the use of two accelerometers, one mounted on each block, and a hammer to excite the system. The level difference can be obtained from the output of the two accelerometer signals. Dividing eqn(2.20) by eqn(2.21) gives the predicted curve for this measurement. A measured level difference is shown in the top part of Fig 3.12 and the two frequency responses for the system are shown in the centre for comparison. It can be seen that the dip in the level difference occurs at the frequency of the anti-resonance given by
Fig. 3.10  Experimental set-up for the measurement of tie stiffness.
Fig. 3.11 Measured and predicted frequency responses for a mass-spring-mass system.
Different techniques for determining the stiffness of a tie using a mass-spring-mass system.
eqn(2.22). At the resonance frequency of the system the two frequency responses are the same and the level difference crosses the $y = 0$ line. If the position of the dip in a level difference measurement is used for determining the tie stiffness, eqn(2.22) should be used.

The simplest way to find the mass-spring-mass resonance is to measure the response of one block with a single accelerometer, whilst using a plastic-headed hammer (which has a fairly flat force spectrum) to excite the system. As both blocks share the same mass-spring-mass resonance frequency it does not matter whether the accelerometer is mounted on the source or the receiving block. The lower part of Fig 3.12 shows the response of both blocks and the resonance can be seen clearly. This technique is suitable for ties that display a simple response, which was the case for several of those tested. Unfortunately, the other ties displayed more complicated responses and the greater detail offered by the frequency response technique was necessary to measure the stiffness.

**Verification of the measurement technique**

To check that the stiffness measured using the resonance technique gave reliable results, a controlled set of measurements were performed to find the stiffness of a length of threaded steel rod. Steel masses were fixed to the ends of the rod and secured with lock nuts. They were made from 15 mm thick steel plates that could be bolted together to vary the mass. Measurements were performed with masses at either end of the rod of 1.25 Kg, 3.4 Kg, 5.25 Kg and 6.95 Kg, over a variety of tie lengths, this being taken as the distance between the two lock nuts. From the measured resonance frequencies the stiffness was obtained using eqn(2.23).

The measured tie stiffnesses (shown as $20 \log (\text{stiffness})$) are compared, in Fig 3.13, with a predicted stiffness obtained from eqn(2.17). The measured data is within 1 dB of the predicted stiffness for most of the tie lengths. For very short tie lengths (and therefore very high stiffnesses) the measured stiffness is slightly lower than the prediction. This is possibly caused by the joint between the end of the tie and the masses not being perfectly rigid. There may be some play in this region which would make the tie appear less stiff, in much the same manner as suggested for the joint
Fig. 3.13  The variation in measured tie stiffness for a system where the length of the tie and the mass of the blocks is varied.
between the wall ties and the concrete blocks. The mass of the blocks does not affect the measured stiffness, there being a random spread of results around the prediction.

Shown below the measured stiffness is the standard deviation for the measurement. If this is similar to the uncertainty expected for the measured stiffness of wall ties, the uncertainty in the predicted performance can be found. The CLF for a wall tie, given by eqn(2.60), is related to \( k^2 \), which results in an uncertainty of about ± 0.5 dB in the predicted data.

Results for wall ties

Measurements were performed on six different types of wall tie. Five of the ties were used in test walls that are described in chapters 5 and 6. The value of stiffness obtained from these measurements was used in eqn(2.60) to determine the standard CLF across the cavity which was used in the predictions. The sixth tie was included for interest. It is a tie that contains a rubber isolator at it's centre. It was designed by the BBC to reduce sound transmission.

The results from the measurements are given below. An illustration of the ties is shown in Fig 3.14.

Hook ties

Figure 3.11 shows the measured and predicted frequency responses for the hook ties. The tie responses are very smooth for measurements performed on both the source and receiving blocks. The resonance occurred at the same frequency on both responses, 216 Hz. The mass of both blocks together was 4.55 Kg, this was assumed to be divided equally between the two blocks. After the tests to determine the tie stiffness were completed, the mass of several test specimens was measured. The ties were cut off and each block was weighed individually. It was found that the difference in block masses from the same specimen tended to be less than 10 g, the error involved in assuming the mass to be distributed equally is negligible.

Using the resonance frequency of 216 Hz and assuming that the mass of the blocks was the same, \( m_1 = m_2 = 2.27 \text{ Kg} \), the stiffness of the tie was found to be \( 2.1 \times 10^6 \).
Fig. 3.14 The wall ties studied in chapter 3.
N/m for a free tie length of 85 mm.

**Bar ties**
The frequency responses for the bar ties were of a similar quality to those of the hook ties and so have not been shown. To keep the resonance at a relatively low frequency, the tie was cast into larger concrete cubes (150 mm instead of 100 mm). The resonance frequency was 629 Hz and the mass of the blocks was $m_1 = m_2 = 7.79$ Kg. Using eqn(2.23) the stiffness for a free tie length of 85 mm was $60 \times 10^6$ N/m.

**Double triangle ties**
The responses for the double triangle ties, on Fig 3.15, were not as clear as those for the hook and bar ties. Although the curves are not as smooth, they do follow the same general shape as the predicted frequency response. The resonance occurs at the same frequency on both curves but they are less sharp than those of the bar and hook ties. This suggests that the ties are quite heavily damped at this frequency. It also leads to a little uncertainty in deciding where the resonance peak is. With the resonance occurring at 301 Hz and $m_1 = m_2 = 2.392$ Kg, the stiffness from eqn(2.23), is $4.3 \times 10^6$ N/m, for a free tie length of 85 mm.

**BBC wall tie**
The BBC tie proved to be the least stiff of all the ties tested and had a frequency response similar to that of the double triangle tie. The behaviour of the system is the same as two masses coupled by a spring. For this tie, however, the spring was very heavily damped so the response at resonance was very low and the peaks were very rounded. The damping is probably provided by the rubber block at the centre of the tie. The source block resonance occurred at 113 Hz and the receiving block resonance at 105 Hz. An average of the two values was used in eqn(2.23) with $m_1 = m_2 = 2.46$ Kg giving the stiffness as $0.6 \times 10^6$ N/m. The distance between the two blocks was 85 mm but, for this type of tie the length probably has very little effect on the stiffness as the rubber centre section provides most of the resilience.

**Replacement wall ties**
Replacement wall ties are intended for use in situations where the existing ties on a
The frequency response of the system used to measure the stiffness of double triangle ties.
building are too few or have failed. They are designed to be inserted through a hole drilled in a cavity wall and use expanding bolts at each end to couple the two leaves. The ties tested were identical to the one shown in Fig 3.14. It consists of a 7 mm diameter stainless steel rod which is turned at it's centre to provide a drip and has expanding bolts at each end. To enable the effect of the expanding bolts to be measured it was inappropriate to cast the ties into the concrete cubes. Instead two cubes were cast with 10 mm diameter holes formed through their centres. The ties were then inserted into the blocks and fixed using the expending bolt mechanisms. This ensured that the ties were fixed correctly. Again, as with the bar ties, because the tie was expected to be quite stiff, 150 mm concrete cubes were used to keep the resonance at a low frequency.

The measured frequency responses were very smooth and the resonance occurred at the same frequency on both, 443 Hz. The mass of the blocks, \( m_1 = m_2 = 7.57 \text{ Kg} \) gave the stiffness of the tie is \( 30 \times 10^6 \text{ N/m} \). Because of the way that the tie is fixed into the wall it's length is always the same, it is independent of the width of the cavity. The effective length is the distance between the two points where the expanding bolts bear on the masonry, which was approximately 170 mm regardless of cavity width.

This tie was also used on tests performed on an external test wall, a wall with one dense concrete leaf and an aerated concrete leaf. To test whether the coupling between the tie and the aerated concrete affected the measured stiffness, a second measurement was carried out.

Two concrete cubes were cast, one with a 10 mm hole formed through it and one had a small aerated concrete block with a 10 mm diameter hole drilled in it, cast in. The resulting cubes had approximately the same mass and had the correct physical properties in the region where the tie was fixed. A wall tie was fixed into the blocks and the frequency response of the system was measured. From the measured MSM resonance, the stiffness of the tie was \( 20 \times 10^6 \text{ N/m} \), softer than the same tie used in the dense concrete blocks.
**Butterfly ties**

The behaviour of butterfly ties when cast into the concrete blocks was complicated and the measurements to find their stiffness proved to be the most difficult to perform. From Fig 3.14 it can be seen that the tie is fundamentally different from the other ties. The other ties are basically rods that are fixed perpendicularly between the faces of the two leaves of a double wall. The butterfly tie consists of two strands of wire which form an X-shaped connection between the two leaves of the wall. Unlike the other ties the strands of wire in a butterfly tie are not subjected to axial forces and so are likely to be less stiff. One of the two wire strands that cross the cavity is cut and twisted together to form a drip. This would be expected to reduce the stiffness further.

A difficulty arose when measuring the stiffness of the butterfly wall ties. It was caused by the many degrees of freedom that the measurements using the test blocks allow. In a wall, the dominant motion is where the walls move towards and away from each other. This type of motion occurs on the concrete blocks, however, the force from the hammer blow is invariably exerted eccentrically and several other resonances are also excited. The three most important are shown in Fig 3.16.

The twisting mode occurred on all the ties studied. It had a large amplitude but occurred at very low frequencies. The axial mode was the mode that was used in determining the tie stiffness as this is the type of motion that occurs in a cavity wall. The oblique mode was unique to the butterfly tie as it possesses strands of wire that are incident on the block surfaces at angles other than normal.

Fig 3.17 shows the measured frequency responses for a butterfly tie. Two dominant resonances can be clearly seen at 157 Hz and 367 Hz. To help identify the resonances, two calibrated accelerometers were fixed onto the receiving block as shown in the lower part of Fig 3.17. The phase difference between the outputs from the two accelerometers is also shown on the figure. At 157 Hz the phase difference is 0°. This means that the block is vibrating to and forth along the common axis of the two blocks suggesting that this is the axial mode, the one of interest. At 367 Hz the phase difference is 180°. This suggests that the block is twisting about it’s vertical
Fig. 3.16  Modes excited when measuring the stiffness of wall ties.
Source block frequency response.

Receiving block frequency response.

Fig. 3.17 Measured frequency response and phase for butterfly ties.
axis which is the type of motion that the oblique mode would be expected to generate. This mode would also be expected at a higher frequency because the wire is vibrating along its longitudinal axis which is stiff and contains no kinks or twists which would serve to soften it.

Using the resonance at 157 Hz to determine the stiffness with the block mass $m_1 = m_2 = 2.23$ kg, the tie stiffness was found from eqn(2.23) to be $1.1 \times 10^6$ N/m.

Summary of tie stiffness

The table below provides a summary of the measured tie stiffness. For all, except the BBC and the replacement ties, the measurements relate to a tie length of 85 mm. The replacement tie, because of the way in which it is inserted into a wall, has a stiffness that is independent of the cavity width. The BBC tie, because it consists of what is essentially a very stiff metal tie with a soft isolator at its centre, also has a stiffness that is independent of cavity width.

<table>
<thead>
<tr>
<th>Tie type</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBC tie</td>
<td>$0.6 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Butterfly tie</td>
<td>$1.1 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Hook tie</td>
<td>$2.1 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Double triangle tie</td>
<td>$4.3 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Replacement tie</td>
<td></td>
</tr>
<tr>
<td>In a cavity wall</td>
<td>$30 \times 10^6$ N/m</td>
</tr>
<tr>
<td>In an external wall</td>
<td>$20 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Bar tie</td>
<td>$60 \times 10^6$ N/m</td>
</tr>
</tbody>
</table>

Table 3.1 Measured wall tie stiffness

Discussion

Wall ties have a complicated shape so that it is not possible to assume that they behave like simple rods and use their length, cross sectional area and Young’s
modulus to calculate their stiffness. The twists and kinks present on real ties (and the possible effect that the bond between the tie and the wall) means that predictions based on idealised rods overestimate the true stiffness. For bar ties the measured stiffness was $60 \times 10^6$ N/m and the stiffness based in the calculation is $150 \times 10^6$ N/m an overestimate of 2.5 times. For the hook ties the calculation resulted in a value which was six times stiffer than the measured value.

Using the proposed measurement procedures the tie stiffness was easily determined for most of the ties tested. There were however two exceptions to this. The first was the BBC tie which possessed heavy damping and the second was the butterfly tie because many resonances were excited.

3.10 Conclusions

In this chapter the test facilities and the test walls built inside them were described. The cavity test walls were designed so that structural flanking via the test chambers was minimised. This was achieved by leaving a small gap around the perimeter of one of the two leaves. This helped to increase the dominance of the direct transmission path through the wall.

The techniques used to perform structural and airborne measurements on the test walls were described. Third octave measurements were made to a 95% confidence interval of $\pm 1$ dB in the frequency range between 100 and 3.15 KHz. This allowed subtle changes in wall performance to be observed.

A technique for measuring the stiffness of wall ties was presented. This involved casting concrete blocks onto the two ends of a tie and measuring the mass-spring-mass resonance of the system. From this and the mass of the two blocks, the tie stiffness can be determined. The measured stiffnesses are used in later chapters to predict the performance of the test walls. The results from this chapter indicate that the measured stiffnesses result in an uncertainty of approximately $\pm 1$ dB in these predictions.
Chapter 4
The performance of double walls with no ties

4.1 Introduction

This chapter describes work carried out on masonry cavity walls where the two leaves
of the wall were structurally isolated from each other. The walls were built to study
the behaviour of sound transmission across the air in the cavity in the absence of any
structural transmission paths. A dry lined wall was also tested in this thesis but it's
behaviour was fundamentally different from the masonry walls' and for the sake of
clarity the results have been grouped together in a separate chapter. The walls in this
chapter had both leaves made from 0.1 m thick masonry. The first was similar to a
cavity party wall, consisting of two identical leaves of dense concrete blocks. The
second type of test wall was similar to an external cavity wall, comprising of one leaf
of dense of concrete blocks (identical to the blocks used in the party wall) and one
leaf of lightweight aerated concrete blocks.

The measured data obtained from these walls allowed the theory of "airtie" coupling,
presented in chapter 2, to be examined. It is used in conjunction with the expressions
given by Price and Crocker [20] for cavity coupling and is intended to remedy the
criticisms levelled at their theory by Brekke [21]. Brekke noted that Price and
Crocker's theory failed to predict, correctly, the change in performance expected
when the cavity width was varied. This was attributed to the omission of an
expression for the stiffness of the air in the cavity. The "airtie" coupling is intended
to solve this problem.

In addition to studying transmission in the absence of structural coupling, the results
from this chapter are also useful for understanding some of the results obtained in
other chapters. In chapters 5 and 6 the behaviour of cavity walls with various different types of wall ties is examined. Each time a different type of tie was tested it was necessary to build a new wall. The results from this chapter provided some indication of the variability that could be expected in the performance of the basic wall without ties. In chapter 7 the results from an external wall, where the two leaves were coupled at their centres along a line, are presented. Measurements made in this chapter allow a comparison to be made between the performance of the wall before and after the two leaves were coupled.

4.2 Performance of cavity party walls

The common form of construction used in party walls is to build two identical leaves of dense masonry separated by a narrow cavity. This provides the benefits that mass imparts on the sound insulation properties of a wall plus the added benefit of structural isolation between the two leaves. In real walls however, this isolation is not complete. Wall ties provide paths for structural transmission across the cavity and the two leaves commonly share the same foundation. In order to fully understand the behaviour of real walls, which possess these extra transmission paths, it is necessary to know how much sound is transmitted by the air contained in the cavity between two structurally isolated leaves of a cavity wall.

Construction of the test walls

Measurements were performed on two similar test walls. These were walls built primarily to study the performance of wall ties. At some point in the measurement procedure, however, it proved possible to perform tests with the ties absent.

The first wall was built to examine the effect that increasing the number of wall ties had on wall performance. This was done using replacement wall ties which were inserted into the wall after it had been built. It was therefore possible to test the wall before any ties were inserted. The construction of this wall differed from all the other walls in that the mastic joint, which sealed the gap at the common opening between
the two chambers, was absent. This meant that the cavity was not sealed and may have resulted in a reduction of the stiffness of the air contained within it.

The second wall was used to test the behaviour of hook ties. These ties were relatively soft and since they had very small heads it was easy to remove them after the wall had been tested. The location of the ties was known and a drill was used to clear the mortar from the bed and expose the head of the tie. A steel bar was then used to force the tie into the cavity clear of the wall and the hole was sealed with mortar.

In addition to providing data to study the performance of walls without ties, the results were also useful for determining whether or not there was any variation in the performance of the basic test wall (ie the wall without ties). This was important for the measurements described in chapter 6 where walls with different ties are examined. It was not possible to test all the different types of ties on the same wall and a new wall had to be built each time a different tie was tested. The concrete blocks used to build the walls were obtained from the same source but not at the same time. Checks were made on the material properties of the blocks, the density and longitudinal wavespeed, and these showed a variation which was less than the measurement accuracy. All the walls were built by the same person to the same design, which should have reduced variations caused by workmanship. A detailed description of the basic test wall is given in chapter 3.

**Predicted performance**

Three sets of predicted data were obtained to compare with the measured results. The main prediction was made using an SEA model of the test wall and transmission suite. The remaining two predictions were obtained from classical theories and are included to provide a comparison for the results from the SEA model.

**SEA model**

The predicted performance was obtained using the full SEA model of the test chambers described in chapter 3. The important subsystems in the model are shown
in Fig 4.1. The CLFs for resonant and non-resonant coupling between a cavity and a room or wall were obtained using Price and Crocker's expressions [20]. The coupling between the two leaves of the test wall due to the stiffness of the air in the cavity was modelled as an "airtie" using eqn(2.82). Close to the cross cavity resonances the predicted CLF varies considerably and so an average across the third octave band was taken. A cavity width of 85 mm was used in the predictions and the blockwork facing into the cavity was assumed to have an absorption coefficient of 0.4. This is a typical value for open textured blockwork and is close to the values obtained from reverberation times measured in the reverberant chamber, prior to painting the external faces of the wall. The value of absorption selected is only important at high frequencies where cross cavity modes occur.

TLFs for the structure of the test chamber and the two leaves of the test wall were assumed to equal the sum of the CLFs plus an ILF. For the chamber walls the ILF was assumed to be 0.015 and for the test walls measurements of the TLF at high frequencies indicated a value of 0.008 should be used. The measured reverberation times for the receiving room were used to obtain the room TLF.

For the cavity, the measurement procedure described in chapter 3 was used to obtain the cavity reverberation time, from which the TLF was obtained. The measured cavity TLF is shown in Fig 4.2. The value of $T_{60}$ at 63 Hz was used to provide an extrapolation for the TLF at low frequencies where it could not be measured. This may lead to some errors in the prediction at these frequencies. The jumps in the curves at 125 and 315 Hz occur where the time base on the oscilloscope was changed during the measurement. This suggests a bias in reading the slope of the curves has occurred at these frequencies.

Classical theories
The classical theories discussed in chapter 1 are only suitable for predicting the airborne level difference of the direct path between two rooms separated by a cavity wall. For the walls tested in this theses, the direct path was only dominant above the critical frequency of the test walls. Below this frequency the floor of the receiving room was the dominant radiating surface. It is only sensible, therefore, to compare
Fig. 4.1  SEA model for a cavity wall with no sound bridges.
Fig. 4.2 Measured total loss factor for the cavities of a cavity party wall and an external cavity wall.
expressions for transmission in the region above critical frequency with the measured data. Two of the theories discussed in chapter 1 were used to provide data for comparison with the SEA model and the measured data. The performance of the SEA model is dominated by the "airtie" at these frequencies therefore the results from this section allow the behaviour of the "airtie" mechanism to be compared with more conventional theories.

Donato [8], produced an infinite plate theory based on the impedances of the leaves of the wall and the cavity. Above critical frequency, $f_c$, the transmission coefficient, $\tau$, is given by,

$$\tau = \frac{4\pi \sqrt{\beta^{-1}} \sqrt{1 - \beta^{-1}} (1 - \beta^{-1})}{A^3B}$$

(4.1)

In this equation,

$$A = 1 + \frac{\omega \rho_s \eta}{\rho_o c_o} \sqrt{1 - \beta^{-1}}$$

(4.2)

and,

$$B = \frac{4\omega \rho_s}{\rho_o c_o} (\beta - 1) \sqrt{\beta^{-1}}$$

(4.3)

where,

$$\beta = \frac{f}{f_c}$$

(4.4)
\( \rho_z \) is the surface density of the leaves of the wall and \( \eta \) is the structural damping.

Sewell’s [7] theory was used to provide the second classical prediction. This uses wave theory to predict the performance of a finite wall. Above critical frequency Sewell gives the transmission coefficient as,

\[
\tau = \frac{2 \rho_o c_o}{\eta'' \rho_o \omega \sqrt{\beta^2 - \beta}} \int_0^\pi \frac{(\eta'' + C)(C^2 + D^2)}{(\eta'' + 2C)[(\eta'' + C)^2 + D^2]} \, d\phi
\]

(4.5)

where,

\[
C = \frac{\alpha \sin^2 \theta}{\theta^2}
\]

(4.6)

and,

\[
D - \cosec \phi - \frac{\alpha \sin 2\theta}{2\theta^2}
\]

(4.7)

In these equations,

\[
\eta'' = \frac{1 + \eta \rho_s \sqrt{4\pi^2 f (f - f_c)}}{\rho_o c_o}
\]

(4.8)

and,
\[ \alpha = \frac{\sqrt{\beta} - 1}{h'} \]  

(4.9)

where \( h' \) is equal to the width of the cavity divided by half the width of the wall and \( \theta \) is the angle at which the sound wave is incident on the wall. This is given by,

\[ \theta = \phi \alpha \]  

(4.10)

Results for party walls with no ties

The measured structural level difference for the two walls is shown in Fig 4.3. Above 125 Hz the data for the second test wall is about 5 dB higher than the data for the first wall. Below this frequency the difference is reversed, the data from the first test wall being around 5 dB higher than that for the second. At the highest frequencies both curves show signs of levelling off, the data for the second wall, however, starts to display this behaviour two third octave bands before the data for the second wall. The levelling off in the data implies that the stiffness of the cavity has increased, probably as a result of the first cross cavity mode at 2 KHz. The data for the two walls starts to level off at different frequencies because the level differences are not the same. As might be expected the wall with the highest level difference is more sensitive to the effect of the cross cavity resonance and displays evidence of it at a lower frequency than the wall with the lower level difference.

Three predicted level difference curves, obtained from the SEA model, are also shown on the figure. One is for the resonant path via the cavity, one is for transmission via the "airtie" and the third is the sum of these two paths. Above the critical frequency of the test wall, the "airtie" prediction shows good agreement with
Fig. 4.3 Measured and predicted structural level difference for two similar cavity party walls with no wall ties (prediction made using SEA model).
the measured data from the first wall. The second test wall, however, has a higher level difference, suggesting that it's cavity was less stiff. The predicted dip at 2 KHz is caused by the first cross cavity resonance and the agreement with the measured data is good, in so far as predicting it's position. The agreement between the level differences in this region is not as good however.

At low frequencies the measured data for both of the test walls lies between the predicted curves for the resonant and "airtie" paths. At these frequencies the agreement between the data from the first wall shows very poor agreement with the "airtie" prediction, being 15 dB lower in places. The results from the second wall show better agreement with the "airtie" prediction, they are still however 5 dB higher than the predicted level difference. For the first test wall there is a possible explanation for the large discrepancy. The gap between the two chambers was unsealed and as this runs around the perimeter of the cavity, the air contained within it would have been free to move in and out, reducing it's stiffness. It is possible that the high level differences measured at low frequencies for this wall occurred as a result of this mechanism. In addition it is possible that the hydrodynamic short circuit, which occurs on the surfaces of both leaves of the wall below critical frequency, prevents any build up of pressure in the cavity. This would have the effect of reducing the stiffness of the air and result in increased attenuation.

Fig 4.4 shows the airborne results for the same walls. These follow the results from the structural data quite closely. The data for the second test wall is between 3 dB and 4 dB higher than that for the first wall at frequencies above 125 Hz. Below this frequency the agreement between the curves is quite good except below 80 Hz where the data for the second wall drops about 8 dB below the data for the first wall. There was no data measured at the very high frequencies (in the region of the cross cavity resonances) where the levelling off was observed in the structural data.

The predicted level differences from the SEA model are also shown on this figure. There are four predicted curves, one for the non-resonant path from the source room to the receiving room via the cavity, one for the resonant path via the cavity, one for transmission across the "airtie" and the final predicted curve, which is the sum of
Fig. 4.4  Measured and predicted normalised airborne level difference for two similar cavity party walls with no wall ties. (prediction made using SEA model).
these three paths. The non-resonant path via the cavity has a very high transmission loss and is unimportant for this wall. The resonant path is also less important, being around 9 dB higher than the "airtie" path. The "airtie" path is the most important path though the agreement with the measured data is not always good. In the vicinity of the critical frequency both the resonant and "airtie" predictions overestimate the strength of the transmission. This is caused by the expression used to predict radiation efficiency, eqn(2.29). For masonry walls it overestimates the radiation efficiency at critical frequency and this results in the overestimate in transmission. This problem is considered in more detail in chapter 10.

The two predictions obtained using classical theories are shown on Figures 4.5 and 4.6. Each of the theories has structural damping as a variable. There are two possible values of damping that can be used in making the predictions. One is the internal damping, obtained from the ILF and the other is the sum of the ILF and the boundary losses, obtained from the TLF. For each of the theories two predictions were made, one for each of the damping values. The ILF used was 0.008, the value suggested by the measured TLF data for the test walls. In the prediction the TLF was assumed to be given by eqn(2.91) with the measured ILF used in place of 0.015.

The predicted results obtained using Donato's expression for an infinite double wall are shown in Fig 4.5. Shown for comparison purposes are the measured data for the two test walls and the prediction made using the "airtie". Both of the predicted curves share the same slope as the "airtie" prediction, however, the prediction made with the damping estimated using eqn(2.91) is much higher than the measured results. Better agreement is obtained with the prediction made using the ILF. The reason for this is possibly because the model on which the prediction is based is for an infinite wall and so boundary losses are not assumed to occur. Donato compared measured and predicted results in his paper and for these he used the internal damping. The walls he examined were, however, of lightweight construction. These would probably have had weak coupling to the transmission suite in which they were tested and as a result the boundary absorption would have been small in comparison with the ILF. It is therefore probable that for his walls the ILF and the TLF may have been very similar making the choice of damping unimportant.

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Fig. 4.5 Comparison between the normalised level difference for a cavity party wall with no wall ties, predicted using an "airtie" and the normalised level difference from Donato's [8] theory.
Sewell's prediction with coupling plus internal losses.
Sewell's prediction with internal damping only.
Prediction for the airtie.
Measured data for the first test wall.
Measured data for the second test wall.

**Fig. 4.6** Comparison between the normalised level difference for a cavity party wall with no wall ties, predicted using an "airtie" and the normalised level difference from Sewell's [7] theory.
Fig 4.6 shows the prediction made using Sewell's expression for transmission above critical frequency. The predicted result obtained using the TLF of the wall is almost identical to the "airtie" prediction and shows reasonable agreement with the results from the second test wall. The prediction made using the ILF is about 10 dB too low. This theory is for a finite wall and the damping is modelled more correctly by the TLF. Sewell compared his predicted data with published measured data and found good agreement. The published results however did not give details of the structural damping and Sewell had to assume values.

The results from the classical theories compare favourably with the predictions made using the "airtie". They share the same slope and predict approximately the same level difference.

The final prediction was based on the measured coupling between the leaves of the test wall. By rearranging eqn(2.4) it is possible to obtain the CLF in terms of the measured energy level difference between the two subsystems and the damping of the receiving subsystem. Two measured "airtie" CLFs were obtained from the measured structural level difference for the test walls and these were used in the SEA model in place of the predicted "airtie". This is a retrospective method of obtaining predicted data and so it is not ideal. It does, however, allow the airborne performance of the wall to be studied in the absence of any errors in the coupling across the cavity. Any difference between the measured and predicted airborne level difference therefore arises out of errors elsewhere in the model.

The measured and predicted data is shown in Fig 4.7. The general agreement between the data is poor considering the cavity coupling is modelled correctly. The exception occurs over a narrow range of frequencies above 80 Hz. At the critical frequency of the test wall the poor agreement is due to an overestimate of the strength of the coupling between the test wall and the rooms. This is due to the use of eqn(2.29) which overestimates the radiation efficiency at this frequency. Above the critical frequency the radiation efficiency is predicted accurately; the poor agreement between the measured and the predicted data is therefore a result of some other mechanism. The most likely cause is flanking transmission which would force the measured level
Comparison between the measured normalised airborne level difference for a cavity party wall with no wall ties and the predicted normalised airborne level difference based on the measured cavity coupling.

Fig. 4.7
difference down below the prediction as shown in the figure.

The agreement between the results obtained using the measured "airties" and the predicted "airtie" is encouraging. Below the critical frequency of the test wall it would appear that the predicted "airtie" overestimated the stiffness of the air in the cavity, the level difference being lower than that for the measured "airtie" predictions. Above the critical frequency, however, the predicted curves all have the same slope and the level difference for the predicted "airtie" is almost identical to that obtained using the measured "airtie" from the first test wall.

Discussion

Using the SEA model to predict the performance of party walls allowed the relative performance of the transmission paths to be examined. The non-resonant and resonant paths were modelled using Price and Crocker's expressions.

For a party wall the non-resonant path was found to be insignificant and the resonant path, though stronger, was unimportant except at critical frequency. The strong transmission predicted in this region, however, was not observed in the measured results and stems from an overestimate in the radiation efficiency.

The dominant transmission path was found to be due to the stiffness of the air in the cavity. This was modelled as an "airtie", where the stiffness of the air was assumed to be concentrated at a single point allowing the expression for structural tie coupling to be used to provide the CLF.

The agreement between the "airtie" prediction and the measured data was reasonable. Above critical frequency the measured structural results had the same slope as the prediction and displayed what was probably the first cross cavity resonance at the same frequency as the prediction. There was however a difference of about 5 dB in the measured performance of the two test walls and the prediction lay along the lower limit of the measured data. For the airborne results in the same frequency region the "airtie" predicted the correct general airborne level difference but the slope of the curve was steeper than the measured results, the agreement worsening with increasing
frequency. The predictions made using the measured "airtie" suggested that the drop off in the measured data was probably caused by flanking transmission. The results from the external cavity wall, discussed next, suggest that this may have occurred via the mastic joint at the perimeter of the free standing leaf of the wall.

Below critical frequency the agreement between the prediction and both the airborne and structural results was poor. The measured level difference was far higher than the predicted data suggesting that the stiffness of the cavity had been overestimated by the "airtie". There are several possible explanations for this.

For the first test wall the gap between the two test chambers was unsealed. This would have allowed air to flow in and out of the cavity, resulting in a reduction of it's stiffness and an increased transmission loss. This wall had a higher level difference than the second test wall (which had a sealed cavity) and it is likely that this freedom of air movement is the reason for the improved performance.

The results from the second test wall below critical frequency were also higher than the prediction. The cavity on this wall was, however, sealed and an additional explanation for the apparent reduction in cavity stiffness is required. The hydrodynamic short circuit that occurs on the surface of the walls below critical frequency provides a possible explanation. The freedom of the air to undergo lateral motion, from regions where the wall is compressing the air to regions where it is stretching it, would reduce the build up of pressure in the cavity making the air appear less stiff. This would increase the attenuation across the cavity, resulting in the observed increase in level difference.

Two classical theories were used to provide data for comparison with the SEA model. The quality of the agreement obtained depended on the value of damping used. One was an infinite plate theory and this showed best agreement when only internal losses were considered. The second theory was for a finite wall and this worked best when the TLF for the wall was used. The agreement between these theories and the SEA model was encouraging. They shared the same slope, predicted approximately the same level difference and the agreement they showed with the measured results was
no better than that of the SEA model. If the measured data was affected by flanking transmission, however, the apparent overestimate in predicted performance would be expected.

In addition to comparing the prediction obtained using the predicted "airtie" with theoretical predictions, predicted airborne data was also obtained using the measured cavity coupling. Above the critical frequency of the test wall, the agreement between the model with the predicted "airtie" and the model with the measured "airtie" from the first test wall was good. The second test wall had a slightly softer cavity and so predicted a higher level difference.

Finally it was found that there was some variation in the performance of the basic test wall. Variations of at least 5 dB in the structural performance and 3 dB in the airborne performance can be expected for walls that share the same basic design. The omission of the mastic joint from the gap between the two chambers for the first test wall appeared to affect it's performance below critical frequency. Above this frequency, however, the measured data indicates it's cavity was stiffer than that of the second test wall which had a sealed cavity. This suggests that the omission of the joint did not affect performance in this region and may have been caused by a variation in the porosity of the concrete blocks. The variation in performance between the walls is not a problem for comparing the results from walls with many stiff ties as these form the dominant transmission path. However, for walls where the stiffness of the ties is close to that of the air in the cavity, it may result in some uncertainty in the results.

4.3 Performance of external cavity walls

External walls represent another important group of cavity walls. They normally consist of an inner leaf of lightweight masonry and an outer leaf of dense masonry. They therefore represent a more general form of construction than the party wall which has both leaves the same. The ability to predict the performance of an external wall is important because it provides a flanking path for sound to travel around the
edge of a party wall.

**Construction of the test wall**

The test wall used to study external cavity wall behaviour was built in a transmission suite. Structural isolation between the two leaves of the wall was obtained by building one leaf on either side of the gap in the common opening between the two chambers. This ensured that the dominant transmission path through the wall was via the cavity. Both walls were 4.0 x 3.0 x 0.1 m. The dense leaf had a surface density of 201 Kg/m² and a longitudinal wavespeed of 2200 m/s ($f_c = 297$ Hz). This is the same type of concrete block that was used for building the party test walls. Aerated concrete blocks were used for the lightweight leaf. These had a surface density of 75.6 Kg/m² and a longitudinal wavespeed of 1700 m/s ($f_c = 384$ Hz).

The dense concrete leaf was butt-jointed, around all four sides, to the perimeter of the opening between the two chambers. The lightweight leaf was built free standing, connected to the structure of the test chamber only along its base. Closed cell foam (6 mm thick) was used to isolate the remaining three sides of the wall from the chamber and the gap was sealed with a mastic joint. After construction, three blocks were removed from the bottom course of the dense concrete leaf and the cavity was cleared of mortar droppings to ensure that the structural isolation of the two leaves was maintained.

Cement paint was used to seal the faces of both leaves to prevent airborne transmission through the pore structure of the blocks. In addition, the surface of the dense leaf that faced into the cavity was sealed. This was done by building the dense leaf first and painting both faces before building the lightweight leaf. The reason for doing this was to reduce any uncertainty in the cavity width. The dense blocks were made from porous concrete and it is possible that the air in the pores of the blocks increased the effective width of the cavity causing its stiffness to be reduced. The closed cell structure of the aerated blocks meant that air was unable to penetrate to any significant depth, making it unnecessary to seal them. The width of the cavity, as measured between the faces of the two leaves, was 80 mm.
Predicted performance

The external wall was initially tested without any wall ties. The only coupling between the leaves was via the air in the cavity.

The predicted data for the wall was obtained using the same basic SEA model that was used to predict the performance of the party wall, shown in Fig 4.1. It accounted for the coupling between the test wall and the test chambers and included the paths via the cavity using the equations given by Price and Crocker [20].

Measured values of reverberation time were used to obtain the TLFs of rooms. The cavity TLF was also obtained from measured reverberation times, the measurement technique being the same as that used for the party wall. For all other subsystems the sum of coupling loss factors plus an internal loss factor was used to obtain the TLF. The dense leaf of the test wall was assumed to have an ILF of 0.008, a value suggested from measured TLF data. All the other structural subsystems were assumed to have an ILF of 0.015. The air in the cavity was assumed to have a bulk modulus of $1.4 \times 10^5 \text{ N/m}^2$ when calculating the CLF for transmission across the cavity.

The SEA model is the only source of predicted data available to compare with the measured results for this wall. This is because it is not possible to use the theories of Donato or Sewell to predict the performance of walls where the leaves have different physical or material properties.

Results for external walls with no ties

The measured and predicted airborne-level differences are shown in Fig 4.8. Although the "airtie" is the most important transmission mechanism, the resonant path assumes more importance than it did in the party wall. Above critical frequency it is only about 2.5 dB higher than the "airtie" path and this results in the sum for all the paths being about 1.5 dB below the path across the "airtie".

Above the critical frequency of the lightweight leaf, the measured results and the
Fig. 4.8 Measured and predicted normalised airborne level difference for an external cavity wall with no wall ties. (prediction made using SEA model).
predicted curve for the sum of the paths show reasonable agreement. Cross cavity resonances are predicted in the 2 and 4 KHz bands and the measured curve shows some evidence of this mechanism at the lower of these two frequencies. Above this frequency very high level differences are predicted and it is possible that transmission paths not included in the model may have affected the measurements in this region. Around the critical frequency of the two leaves, which extends over two third octaves, the predicted level difference is lower than the measured results. This is because eqn(2.29) was used in the prediction and this overestimates coupling between rooms and masonry structures in this region. In the frequency region between critical frequency and the MSM resonance (predicted at 28 Hz), the measured level difference is up to 15 dB higher than the prediction. This is similar to the behaviour of the party wall tested without ties and may be due to an overestimate of the stiffness of the air in the cavity below critical frequency. As with the party wall this is probably caused by the hydrodynamic short circuit that occurs on the surfaces of the test wall. This may prevent the pressure in the cavity from increasing and would have the effect of making the cavity appear less stiff.

Figure 4.9 shows the measured and predicted structural level difference. In the mid frequency region the agreement between the two curves is good. There is poorer agreement above 800 Hz, the measured results being higher than the prediction. A dip occurs in the measured level difference in the 2 KHz band, the same band as the first predicted cross cavity resonance. In the low frequency region, as with the airborne data, the measured level difference is higher than the predicted curve. This is again consistent with the air in the cavity being less stiff than predicted in this region.

Besides performing level difference measurements, the sound pressure level (SPL) in the cavity was also measured. Six holes were drilled through the lightweight leaf and sealed with plasticine. The microphone was inserted into each hole in turn so that it was positioned approximately at the centre of the cavity. As this leaf was built in the receiving room, the transmission of sound through the sealed holes into the cavity would have been insignificant. The measurement was performed using narrow band analysis (with a bandwidth of 8 Hz) and the SPL is shown in Fig 4.10. There are
Fig. 4.9 Measured and predicted structural level difference for an external cavity wall with no wall ties. (prediction made using SEA model).
Fig 4.10 Measured narrowband sound pressure level in the cavity of an external cavity wall, plotted with the measured and predicted third octave sound pressure level for the same measurement.
peaks in the level at the frequencies of the first two cross cavity resonances at 2 KHz and 4 KHz.

The measured cavity TLF shown in Fig 4.2 was used along with Price and Crocker’s expressions to predict the third octave SPL in the cavity. The narrowband SPL was converted into third octaves by summing between the upper and lower cut-off frequencies for the bands. These are plotted on Fig 4.10 with the third octave predicted data. The agreement between the measured and predicted values is quite good, the largest difference occurring in the region of the anti-resonances between the cross cavity resonances. This would be expected as the discrete effects of the anti-resonances are not accounted for by Price and Crocker’s CLFs.

Discussion
The measurements performed on an external cavity wall without wall ties showed reasonable agreement with the results from an SEA model. In the model the paths via the cavity were accounted for using an "airtie" for the air stiffness and Price and Crocker’s expressions for cavity coupling. The transmission path due to the air stiffness was found to be the most important, though for this wall the resonant path via the cavity was also important. The increased importance of the resonant path was caused by an increase in the CLF between the cavity and the aerated leaf of the wall.

Good agreement was obtained between the measured and predicted cavity SPL. This suggests that Price and Crocker’s expressions for predicting transmission into the cavity work reasonably well and implies that the relative strengths of the paths through the wall were predicted correctly by the SEA model.

The measured airborne results for this wall showed much better agreement with the predicted data at high frequencies than was obtained for the party walls. This may have been due to an improvement in the mastic joint detail between the free standing wall and the transmission suite. Mortar was introduced between the edge of this leaf and the foamed plastic packing, resulting in a much tighter joint. If this design change was the cause of the improved performance, it implies that the transmission of sound
from the cavity, past this joint, caused the levelling off observed in the airborne level difference of the party walls at high frequencies.

In addition to the change in the mastic joint, this wall differed from the party test walls in several other respects. The most obvious difference was the fact that it had an aerated concrete leaf. This had a higher critical frequency than the dense concrete leaf and as a result the region where critical frequency affected the predicted data extends over two third octaves. Although the measured data does not display the sharp dips that are predicted at these frequencies, the results for this wall do remain fairly flat over a wide range of frequencies in this region. The second major difference between this wall and the party wall was that the surface of the dense concrete leaf facing into the cavity was sealed. This resulted in the cross cavity resonances being more pronounced, possibly because the damping provided by the porous structure of the dense blocks was reduced.

Sealing the blocks did not, however, appear to increase the stiffness of the cavity in the region between critical frequency and the MSM resonance. The results for the external wall were similar to those for the party wall in this frequency region, up to 15 dB higher than the predicted data. This tends to suggest that the open pore structure of the dense concrete blocks was not responsible for the apparent reduction of the cavity stiffness. Also, for this wall the gap between the two chambers, which runs around the perimeter of the cavity, was sealed, so the flow of air in and out of the cavity was not possible. This leaves the hydrodynamic short circuit of the pressure within the cavity as the only remaining explanation for the observed behaviour in this frequency region.

4.4 Conclusions

In this chapter the transmission of sound across the air in the cavity of two different types of cavity wall was examined. The first wall was a cavity party wall with two identical leaves of dense concrete masonry. The second type of wall was an external cavity wall with one dense leaf and one leaf of aerated concrete.
An SEA model was used to provide predicted data for the walls. In the model three mechanisms were found to be responsible for transmission across the cavity, a non-resonant and a resonant mechanism modelled using Price and Crocker's [20] expressions and a mechanism due to the stiffness of the air in the cavity modelled using an "airtie". Non-resonant coupling between the two rooms via the cavity was found to be the least important of these, having no observable effect on overall performance. Resonant coupling between the leaves of the test wall and the cavity was found to a stronger mechanism, however, it had only a negligible effect on the performance of the party wall and only a small effect on the external wall performance. Of the three mechanisms the "airtie" was found to be the most important. It dominated transmission through the party wall and was the major transmission path through the external wall.

Price and Crocker's expressions were used to predict the cavity sound pressure level for the external wall. This showed good agreement with the measured levels and it may be concluded that their expressions correctly predict the strengths of the resonant and non-resonant paths through masonry cavity walls.

Above critical frequency the "airtie" prediction for the airborne performance of the party wall was compared with two classical predictions and a prediction based on measured coupling between the leaves of the test wall. It was found to show good agreement with the classical predictions provided the appropriate value of damping was used. For the infinite theory internal damping was used and for the finite theory a TLF was used. The agreement between the data from the SEA model with the measured "airtie" and the model with the predicted "airtie" was also good.

The predictions obtained using the "airties" and the classical theories showed poor agreement with the measured results, however it is highly likely that this was the result of flanking transmission. Evidence of flanking came from the predictions made using the measured cavity coupling in the SEA model which showed poor agreement with the measured airborne data. The results from the external cavity wall indicated that the flanking probably occurred via the mastic joint at the perimeter of the free standing leaf. The "airtie" prediction for the external wall (which was constructed
with a modified mastic joint around the free standing leaf) showed good agreement with the measured data above critical frequency.

It may be concluded that, above critical frequency, modelling the air in the cavity as a point stiffness, using an "airtie", is reasonably accurate technique for obtaining a simple prediction of the strength of transmission via the airborne path through a masonry cavity wall. The poor agreement with the results from the party walls tested in this chapter was due to flanking transmission.

Below critical frequency the "airtie" prediction for the structural and the airborne results from the party and external walls overestimated the strength of transmission. It is possible that the hydrodynamic short circuit that occurs on the surface of the walls in this frequency region was responsible for causing the apparent softness of the air in the cavity.

Except for the region below critical frequency the "airtie" concept is a convenient means of modelling the stiffness of the air in the cavity and when used with Price and Crocker's expressions for cavity coupling in an SEA model it allows the performance of a cavity wall to be correctly predicted.

Finally the results from this chapter show that variation of at least 5 dB in the structural performance and 3 dB in the airborne performance of similar party test walls can be expected. For modelling walls with very soft wall ties, where both airborne and structural transmission occurs, this may result in some uncertainty in the overall predicted performance.
Chapter 5
Effect of the number of ties on
double wall performance

5.1 Introduction

In this chapter, the performance of two double walls in which the number of wall ties
varies, is examined. In the first part of the chapter the theoretical effect is examined
by studying the behaviour of an SEA model of a cavity wall separating two rooms.
The results from two test walls are then described and compared with predicted data
obtained from an SEA model.

One of the test walls was similar to a party wall, having two identical leaves of dense
masonry. Theoretically this represents a specialised case, so the results from a second
wall with two different leaves are also presented. The construction of this wall was
similar to that used in an external cavity wall, consisting of a leaf of dense masonry
and a leaf of lightweight aerated concrete masonry.

5.2 The predicted effect of varying the number of wall ties

This section looks at the relationship between coupling and level difference for a
cavity wall with two identical leaves. The trends described for this wall are identical
to those that would occur in a wall where the properties of the leaves differed. The
results are not intended for comparison with the test walls described in this chapter,
instead they illustrate the kind of behaviour that they might be expected to exhibit.

The coupling loss factor between the two leaves of the cavity wall is given as,
\[
\eta_{23} = \frac{r Y_3}{\rho_{22} \omega \left[ (Y_2 + Y_3)^2 + \left( \frac{\omega}{k_f} \right)^2 \right]}
\]

(5.1)

where \( k_f \) is the tie stiffness, measured using the method described in chapter 3. The coupling is proportional to the number of ties in the wall and as the number of ties per square metre, \( r \), increases so too does the coupling.

In order to examine this relationship, predictions were made for a wall that separated two identical rooms that had volumes of 60 \( m^3 \) and a reverberation time of 0.5 seconds at all frequencies. The walls were assumed to be 4.0 \( \times \) 3.0 \( \times \) 0.1 m, made from concrete with a surface density of 200 Kg/m\(^2\) and a longitudinal wavespeed of 2200 m/s and separated by a 50 mm wide cavity. Predictions were made, initially, for the wall with no ties using the CLF for an "airtie" obtained from eqn(2.82). The effect of adding a single steel tie with a cross sectional area of 10 mm\(^2\) was then examined using eqn(2.60) (and a predicted stiffness) to obtain the structural coupling. The coupling across the air in the cavity was added to the structural coupling to give a single value for cavity coupling. Further predictions were then made to examine the effect of doubling the number of ties until thirty two were present in the wall.

Fig 5.1 shows the predicted CLFs for transmission across the cavity. As the number of ties per square metre of wall, \( r \), is doubled, so the CLF increases by approximately 3 dB at all frequencies. As the ties all have the same stiffness, the number present in the wall does not effect the transition point between the low frequency approximation to the high frequency approximation given by eqn(2.64). For the ties used, the structural coupling is much stronger than the coupling via the air in the cavity. Adding the first tie to the wall causes the CLF to rise by more than 3 dB because the "airtie" is less stiff than the steel ties. At high frequencies the air in the cavity displays an increased stiffness due to the start of cross cavity modal behaviour. At these frequencies the coupling via the air is the dominant transmission mechanism.
Fig. 5.1 The predicted effect of varying the number of ties, on the CLF of a cavity wall.
The predicted structural level difference is shown on Fig 5.2. At low frequencies the prediction made using the model is not strictly valid as the walls should be modeled as a single subsystem. However, due to the strong coupling, equipartition of energy occurs between the two leaves of the wall resulting (for the case where the two leaves of the wall are identical) in a 0 dB level difference, which is correct. At high frequencies the level difference rises at 6 dB per octave. At higher frequencies the coupling across the air in the cavity dominates and the level difference flattens off. When sufficient ties are present in the wall to render the airborne path insignificant, every doubling in the number of ties results in a drop of 3 dB in the level difference, corresponding to a doubling of the power flowing across the cavity. As ties are added the range of frequencies where the level difference is approximately zero increases.

Fig 5.3 shows how varying the number of ties affects the airborne level difference. At low frequencies the data all tends to the same value, the level difference that would be expected for a single wall with a surface density and bending stiffness equal to the sum of the single leaf values. At frequencies below the mass-spring-mass resonance (given by eqn(2.65)) the wall should not be modeled as two separate subsystems and as a result the level difference is 3 dB lower than would be predicted for a single subsystem model.

In the low frequency region where the ties offer little attenuation across the cavity, the level difference rises at 6 dB per octave. Above the critical frequency of the wall, the level difference rises at 18 dB per octave until reaching the region where the cross cavity resonances occur. These cause the level difference to rise less quickly. As with the structural data the effect of doubling the numbers of ties was to cause the level difference to drop by 3 dB.

5.3 The party test wall

In order to test the theory for tie coupling a test wall was constructed in a transmission suite as described in chapter 3. It consisted of two 100 mm thick leaves of concrete blockwork, which had a surface density of 201 Kg/m² and a longitudinal
Fig. 5.2 The predicted effect of varying the number of ties, on the structural level difference of a cavity wall.
Fig. 5.3  The predicted effect of varying the number of ties, on the airborne level difference of a cavity wall.
wavespeed of 2200 m/s, giving the critical frequency as 297 Hz.

Increasing the number of ties in the wall was made possible by the use of replacement wall ties. These are designed for remedial work in cavity walls where the existing ties have corroded or where insufficient ties were built into the wall during construction. A diagram of one of these ties installed in a brick wall is shown in Fig 5.4. It consists of a 7 mm diameter stainless steel rod with an M6 thread at both ends. The tie fixes itself to the inner and outer leaves of the wall using two expanding nuts which run on the threads.

The ties were inserted into the wall via a 10 mm diameter hole drilled the complete way through the free standing leaf of the wall and 65 mm into the built in leaf. The hole was cleared of debris, a tie was inserted into it and the expanding nuts were tightened until the correct torque was reached. The hole was then filled with mortar and finished flush with the wall surface.

Initially tests were carried out on the wall with no ties present and these results are described in chapter 4. Ties were then added so that their numbers doubled between each set of tests, the sequence being 0,1,2,4,8,16,32,64. The ties were distributed as evenly as possible over the area of the wall without making their positioning regular or grid-like. No ties were fixed within 200 mm of the wall perimeter to reduce the possibility of any damage occurring to the free standing leaf of the wall during the drilling of the holes.

Although small amounts of debris fall into the cavity during the hole drilling procedure, inspection of the cavity (made possible by the fact that the mastic seal in the gap between the two test chambers was omitted for this test wall), revealed that this was mainly fine dust and small granular particles which would not cause flanking transmission.
Fig. 5.4  A replacement wall tie built into a cavity wall.
Third octave band measured results

The predictions for comparison with the results from this test wall were made using the SEA model described in chapter 3. The structure of the test chambers was included in the model to account for transmission from the source room structure to the test wall and from the free standing leaf of the test wall to the receiving room. The structural CLF between the two walls was obtained from eqn(2.60), using the measured value of tie stiffness, \( k_i \), equal to \( 30 \times 10^6 \) N/m. To this was added the coupling via the air in the cavity obtained using eqn(2.82). For this wall, where the bulk modulus of the air in the cavity was assumed to be \( 1.4 \times 10^5 \) N/m\(^2\), the total stiffness of the air in the cavity was \( 17.7 \times 10^6 \) N/m, equivalent to 0.6 of a replacement tie.

For this wall with no ties present, the cavity can be modelled adequately using only the "airtie" as the resonant and non-resonant paths via the cavity are unimportant. It should be borne in mind, however, that the "airtie" overpredicts the strength of transmission below the critical frequency of the test wall. There will therefore be some uncertainty in this frequency region in the predictions made for the wall with few ties. For the wall tested with many ties, the effect of the air on overall wall performance becomes negligible.

Regardless of the number of ties present, the direct path for airborne transmission through the wall is only dominant above it's critical frequency. Below critical frequency paths via the receiving room floor dominate transmission. The strength of these paths is determined by the coupling between the two leaves of the cavity wall, which for a wall with identical leaves is predicted correctly by the SEA model.

Structural level difference
The structural level difference measurements between the two leaves of the test wall were made in both directions. The results for transmission in opposite directions were similar so only the data for transmission from the wall, which was coupled to the test chamber around four edges, to the wall that was built free standing are described.
Fig 5.5 shows the level difference for the wall with no ties compared with the data for the wall with one tie. It can be seen that there was a greater drop in the level difference at high and low frequencies (between 8 dB and 11 dB) and a lower drop in the middle frequency region (between 3 dB and 5 dB). In this region (around the critical frequency) radiation of sound into the cavity and the subsequent excitation of the second leaf may have caused the dip in the data for the wall with no ties. This effect can be seen in the predicted data for the wall with no ties given in Fig 4.3. The importance of this path would be more pronounced when there are no ties present. The large drop in level difference obtained by the addition of the first tie, in Fig 5.5, shows that the structural path is more important than the airborne path across the cavity, as was predicted. Omitting transmission via the resonant modes in the cavity from the SEA model of the wall with ties should not, therefore, result in any significant error in the predicted data.

Fig 5.6 shows the measured and predicted structural level difference data for the wall as the number of ties was increased. It can be seen that the curves are all parallel and drop by about 3 dB for each doubling of wall ties, as predicted. The exception to this was the data for the wall with two ties. The addition of the second tie caused the level difference to drop a little more than 3 dB at some frequencies and as a result the curves for this wall and the wall with four ties are less than 3 dB apart.

For large numbers of ties the measured curves displayed dips at low frequencies which were probably the mass-spring-mass (MSM) resonances. These dips are not well defined and occur at the frequencies given in the table below.
Fig. 5.5 The effect of adding a single replacement wall tie on the structural level difference of a cavity party wall.
Fig. 5.6  Measured and predicted structural level difference for a cavity party wall where the number of replacement ties is varied.
<table>
<thead>
<tr>
<th>Number of ties</th>
<th>Measured dip frequency Hz</th>
<th>Predicted MSM frequency Hz</th>
<th>Predicted dip frequency Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>80</td>
<td>102</td>
<td>72</td>
</tr>
<tr>
<td>32</td>
<td>100</td>
<td>143</td>
<td>101</td>
</tr>
<tr>
<td>64</td>
<td>160</td>
<td>202</td>
<td>143</td>
</tr>
</tbody>
</table>

Table 5.1 Measured and predicted frequencies for the mass-spring-mass dip in the structural level difference.

In each case the measured dip is lower than the predicted MSM resonance frequency. The explanation for this is that the dip in the curve is not caused by the MSM resonance but by an anti-resonance on the receiving wall which occurs at a frequency that is $\sqrt{2}$ below the resonance. The third column of data shows the frequency that this dip is predicted to occur at and it can be seen that these are close to the measured values. This mechanism is discussed further in chapter 10.

Below the MSM resonances, the measured curves converge on a value of level difference of approximately 0 dB as predicted. Above the MSM resonances, the measured curves increase with a slope of 6 dB per octave as predicted. When only a few ties are present in the test wall, the level difference curves exhibit many dips and peaks, due probably to fluctuations in coupling due to discrete modal effects as the tie may be on a node or an antinode. These fluctuations are less pronounced as the number of ties increases because the fluctuations will tend to cancel out.

The effect of the first cross cavity resonance in the predicted data is much more pronounced than in the measured data for the wall with few ties. The prediction shows a dip of about 10 dB in the level difference, however, the measured results show only a levelling off in the data. It was not possible to gather data at the higher frequencies because of the low response of the receiving subsystem.
The best agreement between the results is found when many ties are present in the wall. The model does not account for the effect of the MSM resonance, so the poor agreement which is obtained at low frequencies would be expected. At frequencies above the MSM resonance the agreement between the measured and predicted data is usually within 1 dB. Modelling the effect of the resonance is discussed in chapter 10.

Agreement between measured and predicted data is worst for walls with few ties at low frequencies. The worst case was for the wall with only one tie present, the difference being up to 5 dB. In chapter 9 it is shown that the power flow across the tie is correctly modelled. The error is either due to the measurement technique or to an underestimate of the predicted receiving wall TLF. The measured level difference is the difference between the spatial average of the modal responses of both leaves. The SEA prediction also uses a spatial average of wall response to obtain the level difference. For a wall with one tie however the power transmitted is not determined by the spatial average of the modal response. Modes on the source wall that do not exhibit a high response at the tie location will not transmit power efficiently. The measured level difference will therefore be higher than the true level difference at these frequencies.

**Airborne level difference**

The airborne level differences were only measured in the direction from the small test room to the reverberant room. The results for the wall with no ties and with one tie are shown in Fig 5.7. The results are shown as normalised level differences, normalised to $T_{60} = 0.5$ s. Although adding a tie to the wall did lead to a drop in the level difference, the effect was not as pronounced as with the structural level difference. The trend in Fig 5.7 is the same as that for the structural data on Fig 5.5, the drop in level difference at low and high frequencies being greater than that in the region around the critical frequency. The average change in level difference is, however, only about 3.5 dB as opposed to 8 dB for the structural measurements. The fact that a drop in level difference occurred, again supports the assumption that the path via the ties is quite strong, however, the changes in both the airborne and
The effect of adding a single replacement wall tie on the normalised airborne level difference of a cavity party wall.
structural level differences should have been the same. At these frequencies very high level differences were being measured and it is possible that there were other paths present which are not included in the model.

This lends weight to the suggestion made in chapter 4 that flanking transmission affected the results for this wall when it was tested with no ties. In chapter 4 it was concluded that the most likely flanking path was from the cavity, through the mastic joint around the perimeter of the free standing wall, into the receiving room.

Fig 5.8 shows how the measured and predicted airborne level difference (normalised to $T_{60} = 0.5$ s) between the two test rooms varied as the number of ties was increased. The measured curves all show the same general trend above the critical frequency. They are relatively straight rising at a rate of about 18 dB per octave. In this frequency region every doubling of the number of ties results in a drop of about 3 dB in the level difference. At high frequencies all the curves show some levelling off and those for the walls with only a few ties all tend to the same value. This occurs at 2 KHz, approximately the same frequency as first predicted cross cavity resonance. At this frequency the coupling between the two leaves of the test wall due to the air in the cavity is very strong. For low numbers of ties, at high frequencies, the structural path is relatively weak. The airborne path would therefore dominate the cavity coupling in this frequency region and as a result the level differences for the walls would all be very similar. As more ties are added the structural path becomes stronger and the airborne coupling ceases to be as dominant. However, there is little high frequency data over 2 KHz (due to low response of the receiving subsystem and background noise) and the levelling off could be due to air leakage.

The MSM resonances can be seen in the measured data in the low frequency region. For 64 ties it can be seen in the 200 Hz band, for 32 ties in the 125 band and for 16 ties, in the 80 Hz band. These occur a third octave higher than the dips measured in the structural data. For airborne transmission the increased response of the walls at resonance leads to stronger transmission at the resonance frequency and hence a dip in the level difference. This differs from the behaviour of the structural data and is discussed further in chapter 10.
Fig. 5.8  Measured and predicted normalised airborne level difference for a cavity party wall where the number of replacement ties is varied.
All the curves display a dip at 63 Hz and there are two possible explanations for this. It could be due to a wall resonance. If there is no slip plane between the leaves (as may be reasonable when there are many ties) then the first mode based on the total stiffness and total mass of the two leaves is 58 Hz. For a single leaf the predicted first resonance is 18 Hz. The alternative explanation is a room resonance. The second vertical axial mode in the receiving room occurs at 68.8 Hz. The wavelength of this mode is 5 m which means that an antinode occurs 1.25 m above the floor. Most of the microphone positions were at a height of between 1 m and 2 m above the floor, in the region of the antinode. The measured receiving room sound pressure would therefore have been higher than the true mean pressure causing the dip observed in the level difference.

The dip in the measured data at 63 Hz is particularly pronounced when there are 8 ties, due possibly to the MSM resonance occurring in the same band.

As with the structural data the agreement with the prediction is best for the walls where a large number of ties are present. For the walls with 16, 32 and 64 ties the agreement at frequencies above the critical frequency of the test wall was good, the measured and predicted data being within 1 or 2 dB of each other. The agreement for the wall with low numbers of ties is not as good. At high frequencies the slope of the measured data changes and it drops below the predicted curve. At these frequencies very high level differences were being measured and as the agreement in the structural data was good in this region, other flanking paths probably affected the results.

In the region around the critical frequency of the test wall, the agreement between the predicted and measured data is poor. For building structures the standard equation for the radiation efficiency at critical frequency, eqn(2.29), consistently overestimates the magnitude of the dip. For the wall with low numbers of wall ties there was also poor agreement at these frequencies in the structural data.

Below the critical frequency there is a wide spread in the measured curves which is not predicted. Again, uncertainties in the TLF of the test wall could be a source of
error. For the wall with many ties, the agreement with the predicted curves is better except at the MSM frequencies, a phenomenon not accounted for in the model. At the lowest frequency band all the measured data converges around the predicted curves. In the model, the floor slab of the receiving room is the dominant radiating surface. Transmission via paths through this subsystem is determined by the structural coupling between the two leaves of the cavity wall, which is predicted correctly for the case where both leaves are identical. The ties exhibit infinite stiffness behaviour in this frequency region and so paths via the floor will be unaffected by the number of ties present.

**Narrowband data**

In addition to the measured third octave data, narrow band measurements of the airborne and structural level difference were also made. These allow the behaviour of the wall to be observed in more detail.

**Measured data**

Figs 5.9, 5.10 and 5.11 show measured levels and level differences for the wall with 2, 8 and 32 ties. The upper part of the figures show structural vibration data, where the two upper curves are source and receiving wall acceleration levels and the third curve is the level difference. The lower part of the figures show the airborne data. The top curve is the sound pressure level difference and the lower two curves are the sound pressure levels measured in the source and receiving rooms. The measurements were performed at 20 positions and the 95% confidence interval is around ± 2 dB.

Also shown on the figures are the MSM frequencies predicted using eqn(2.65) and what may be the measured resonances. The predicted resonance is always a little higher than the measured frequency as with the third octave data.

Increasing the number of ties in the wall improves the spatial distribution and the effects of discrete modes become less apparent. This can be seen most clearly in the structural responses of the receiving walls. For the data with two ties the strong
Fig. 5.9 Narrowband airborne and structural data for a cavity party wall with two replacement wall ties.

Predicted resonance = 40.4 Hz.
Fig. 5.10 Narrowband airborne and structural data for a cavity party wall with eight replacement wall ties.
Predicted resonance = 143.3 Hz.

Possible measured resonance.

Fig. 5.11  Narrowband airborne and structural data for a cavity party wall with thirty-two replacement wall ties.
fluctuations in the response of the receiving leaf results in several dips and peaks in the level difference curve. The response of the receiving leaf becomes smoother as the number of ties was increased and the spatial distribution was improved, resulting in the level difference being smoother. This behaviour would be expected as adding more ties to the wall increases their spatial distribution, allowing more modes on the source leaf to transmit power to the receiving leaf.

The narrowband results also show some evidence of the different types of behaviour that is predicted to occur above and below the MSM resonance. Below the resonance it is assumed that the air in the cavity is very stiff and the two leaves of the wall behave as a single thick wall. Above this frequency, the two leaves become decoupled and the wall behaves as two thin walls. For the purposes of modelling this using SEA this means that as the frequency increases and approaches the MSM resonance the wall changes from behaving as a single subsystem below the resonance to behaving as two subsystems above it.

Modelling the wall as two subsystems is straightforward. Modelling the two leaves of the wall as a single subsystem, below the resonance, is a little more difficult. The mass of the single subsystem model of the wall will be equal to twice that of a single leaf of the cavity wall. Deciding on the stiffness is, however, more complicated. A choice has to be made as to whether a slip plane exists between the two leaves or not. If a slip plane does exist, the bending stiffness is equal to twice that of a single leaf. The impedance will therefore be twice that of a single leaf. The measured response of the test wall (assuming the source of excitation has a flat force spectrum) would, therefore, be 3 dB higher above the MSM resonance than below it. If no slip plane exists, then the bending stiffness would be about 23 times higher than a single leaf. The response of the wall in this case—would be 8.3 dB higher above the MSM resonance than below it.

A plastic-headed hammer was used as the source of excitation for the measurements made on the test walls. The force spectrum of the hammer is fairly flat over the frequency range of interest so it can be assumed that any change observed in the response of the test walls occurred as a result of a change in the wall impedance. The
predicted MSM resonance for the wall with 8 ties was 73.6 Hz and for the wall with 32 ties it was 143 Hz. From Fig 5.10 and 5.11 it can be seen that a change in response did occur, the measured levels being lower below the resonance than above it. For the wall with 8 ties, a change in response of about 7 dB occurred and for the wall with 32 ties the change was larger, around 10 dB. This suggests that there may have been a transition in the behaviour of the wall from having a slip plane when no ties were present to it's complete absence when there were many stiff ties.

This has implications for the way in which a cavity wall is modelled below the MSM resonance. The theory presented in chapter 2 is for a two subsystem model but contains a correction which is based on the assumption that a slip plane exists. For walls with few or soft ties this is probably a reasonable assumption. This correction, required to account for the single subsystem behaviour of the cavity wall below the MSM resonance, is simple in this case as both the one subsystem model and the two subsystem model share the same critical frequency.

If the slip plane is not present the wall becomes much stiffer and the critical frequency of the wall, when modelled as a single subsystem, occurs at a lower frequency. This makes it possible for the cavity wall to exhibit two critical frequencies. If the MSM resonance occurs at a high frequency, as it does for walls with many stiff ties, there could be a critical frequency dip below the resonance, where the wall behaves as a single stiff subsystem and a critical frequency dip above the resonance, where it behaves as two subsystems.

The fact that two critical frequencies could occur is interesting, what is more important, however, is the occurrence of increased radiation below the MSM resonance. This means that the airborne performance of the cavity wall will be far lower than the prediction obtained using the model that assumes the existence of a slip plane. For this test wall the predicted effect is to cause the airborne level difference of the direct path to drop by between 10 and 15 dB in this region.

The absence of a slip plane also has consequences for the structural coupling between the test wall and the floor slabs of the test suite that it is built off. The concrete floor
slabs are designed to be structurally isolated from each other, however, if the cavity wall exhibits the behaviour of a single stiff wall, a tee joint wall be formed between these three structures and the isolation between the two test rooms will be lost. Direct structural transmission can then occur from one chamber to the next, bypassing the test wall. The test wall will however be stiffer than the floor slabs and the transmission loss between the two floors will be high. This mechanism is not accounted for in the SEA model used in this thesis and there will, therefore, be some uncertainty in the predicted airborne level difference below the MSM resonance for test walls with stiff ties.

For walls with stiff ties there is no simple correction that can be made to the SEA model and the performance must be obtained using two predictions. One below the MSM resonance, where the wall is treated as a single stiff subsystem and one for frequencies above the MSM resonance, obtained from the conventional two subsystem model.

5.4 The external test wall

The effect of transmission across wall ties in an external wall was investigated using the same replacement wall ties that were used in the party wall. The wall is described in detail in chapter 4. It consisted of one leaf of dense concrete blocks and a leaf of lightweight aerated concrete blocks separated by an 80 mm wide cavity. It was built in a transmission suite to ensure that the two leaves were structurally isolated from each other and the results for these measurements are discussed in chapter 4. The ties were added after the tests on the wall with no ties were completed and measurements were performed with 1, 2 and 4 ties present.

Before performing the tests the stiffness of the tie was measured. This was done to determine whether the bond between the expansion bolt on the tie and the aerated blockwork affected the tie stiffness. The results are discussed in chapter 3. From the measured MSM resonance, the stiffness of the tie was found to be $20 \times 10^6$ N/m, slightly softer than the same tie used in the dense concrete blocks.
The SEA model for this wall was described in chapter 4. The additional CLF for the wall ties, obtained using eqn(2.60), was added to the model to provide the predicted data for this chapter.

**Measured results**

Fig 5.12 shows the measured and predicted structural level differences. The agreement between both sets of data is reasonable at all frequencies. The prediction appears to overestimate the effect of the first cross cavity resonance in the 2 KHz band. At low frequencies, below the MSM resonance, modelling the leaves of the wall as two separate subsystems is not strictly valid, the error being the ratio of the mobility of the two leaves. In this frequency region, the level difference should be 0 dB.

Measured and predicted airborne level differences are shown on Fig 5.13. Agreement at frequencies above the critical frequency of the two leaves is reasonable. As with the data for the wall with no ties, the agreement in the region of critical frequency is poor, this is however, due to the use of eqn(2.29), which overestimates the radiation efficiency in this region. Below critical frequency the predicted level difference is lower than the measured data; this is the same result that was obtained for the party wall in this frequency region. Dips occur in the measured level difference in the 50 and 63 Hz bands. The predicted MSM resonances are 40, 48 and 62 Hz for the wall with 1, 2 and 4 ties respectively. These are not accounted for in the model and the agreement between measured and predicted data is poor in this region.

**5.5 Conclusions**

This chapter examined the effect that varying the number of wall ties had on the performance of a cavity party wall and an external cavity wall.

Overall the agreement between the measured results and the predicted data, obtained
Fig. 5.12  Measured and predicted structural level difference for an external cavity wall where the number of replacement ties is varied.

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Fig. 5.13 Measured and predicted normalised airborne level difference for an external cavity wall where the number of replacement ties is varied.
from an SEA model was good. This suggests that the theory for tie coupling works for walls that have two identical leaves and for walls where the leaves have different properties.

There were, however, a few areas where agreement was not good.

When few ties were present in the wall, the prediction overestimated the strength of transmission below critical frequency. This is due to the affect of the "airtie" which was used to model the coupling due to the stiffness of the air in the cavity. In chapter 4 this was found to overpredict the transmission below critical frequency.

At critical frequency the large dips in the airborne predicted level difference were not observed in the measured results. These occurred because eqn(2.29) was used to predict the radiation efficiency, despite its known limitations in this frequency region.

The final region where poor agreement occurred was around the frequency of the MSM resonance. This mechanism was not accounted for in the SEA model.

The effects of the MSM mechanism and radiation efficiency at critical frequency are examined in detail in chapter 10. The theories presented there were deliberately omitted from the predictions in this chapter so that any uncertainty associated with modelling them did not confuse the predicted results obtained for varying the number of ties. As the effects of these mechanisms are limited to discrete frequency bands their omission had only a minor affect on the overall prediction.

There was some evidence of the MSM resonance in the measured data. Dips were observed in the region where the resonances were predicted. The dips in the structural data, however, appeared at lower frequencies than those in the airborne data. This provides some justification for the approach adopted in chapter 10, where the resonance was accounted for by modelling the wall as a mass-spring-mass system.

The theory for cavity walls shows that the wall behaves as a single thick wall below
the MSM resonance and as two single walls above it. Evidence of this change in behaviour was observed in the change in the response of the test wall when it was excited by a plastic-headed hammer.

By comparing the change in response below and above the resonance it was possible to gauge the change in impedance and hence the change in stiffness of the wall. For a wall with no ties a slip plane will exist between the two leaves. The measurements showed that as replacement ties were added to the wall it's stiffness increased until the slip plane was totally absent.

This existence, or otherwise, of a slip plane only affects the coupling between the test wall and the rooms it faces into. The structural behaviour is unaffected as a level difference of 0 dB occurs below the MSM resonance irrespective of whether or not the slip plane is present. The expression for the direct airborne path through a cavity wall with ties, discussed in chapter 2, assumes the existence of a slip plane. For walls with few or soft ties the slip plane will probably be present and the theory will be correct.

For walls with many stiff ties two models must be used to predict the airborne performance. One below the MSM resonance, which models the wall as a single stiff subsystem to account for the lower critical frequency caused by the increase in stiffness. Above the resonance frequency the prediction from the normal two subsystem model can be used as the two leaves become decoupled and the coupling with the rooms is the same as that for a single thin wall.
Chapter 6
The performance of a double wall with different types of tie

6.1 Introduction

In this chapter, the way in which the stiffness of wall ties affects the transmission loss of a cavity wall is examined. The first part of the chapter looks at the theoretical effect that the stiffness of the ties has by studying the performance of an SEA model of two rooms separated by a cavity wall. The second part of the chapter presents measured data from tests carried out on walls that were nominally identical except for the ties. The five types of ties that were examined are shown in Fig 3.14. These were the butterfly tie, the hook tie, the double triangle tie, the bar tie and the replacement tie.

6.2 Predicted effect of tie stiffness on coupling

The equation for the coupling across a cavity due to wall ties is given in chapter 2 as,

\[ \eta_{23} = \frac{r Y_3}{\omega \rho (Y_2^2 + Y_3^2 + \left( \frac{\omega l}{Es} \right)^2)} \]

(6.1)

The term in this equation which is affected by the tie stiffness is,
This can be varied from zero to infinity by varying the length, cross sectional area, or the material from which the ties were made.

When measured values of stiffness are used this term becomes,

\[
\left( \frac{\omega l}{E_s} \right)^2
\]

(6.2)

To see how varying the tie stiffness affected the performance, a prediction was made using an SEA model in which the stiffness of 25 ties was varied. This was done by doubling the cross sectional area (from an initial area of 1 mm\(^2\)) every time a new prediction was made. Included in the prediction was the coupling between the two leaves of the wall due to the air in the cavity, obtained using eqn(2.82). The cavity was assumed to have a width of 50 mm and surfaces with an absorption coefficient equal to 0.4. The two CLFs were summed to give a single CLF for transmission across the cavity. The results are not intended for comparison with the measured data from the test wall. Instead they illustrate the effects that should be observed when walls with ties of different stiffnesses are tested.

Fig 6.1 shows the predicted CLFs for coupling between the two leaves of the wall for the different tie stiffnesses. The CLF displays two types of behaviour. In the low frequency region it behaves like an infinitely stiff tie and in the high frequency region it behaves like a resilient tie. The stiffness of the ties was varied between zero, where the stiffness of the air in the cavity represents the only coupling and infinity, where the ties display no resilient behaviour. As the number of ties was fixed, the low frequency region of the CLF does not change. This is unlike the behaviour described
Fig. 6.1 The predicted effect of varying the stiffness of ties, on the CLF of a cavity wall.
in chapter 5 for changing the number of ties in a wall. Changing the number of ties causes the whole CLF curve to shift up or down with no change to its shape. At very low frequencies, where both the air and the metal ties are effectively infinitely stiff, the contribution of the air is much less than the ties because the air is modelled as one tie whereas the structural coupling is modelled as 25 metal ties. This gives the air contribution as $10 \log \frac{1}{25}$ or -14 dB relative to the metal ties in this region.

As the stiffness of the ties is increased, the infinite stiffness behaviour is exhibited over a wider range of frequencies and the resilient behaviour does not start until a higher frequency is reached. The transition frequency is given by eqn(2.64).

Once the ties are of a sufficiently high stiffness and the contribution from the air becomes negligible it can be seen that the coupling increases by 6 dB for every doubling of the tie stiffness. This is because the CLF is proportional to the square of the tie stiffness in eqn(6.1).

At high frequencies the CLF for transmission across the air in the cavity is increased by cross cavity modal behaviour and this causes the levelling off of the CLF in this region. As a result, the potential isolation offered by the resilient behaviour of the ties is lost, the dominant transmission path changing from the ties to the air in the cavity.

The envelope drawn by the curve for the coupling via the air in the cavity and the curve for the infinitely stiff ties, represents the entire range of CLFs that exist for this wall with twenty five ties.

The structural level differences for the two leaves of the wall, obtained from the use of these CLFs in the SEA model, are shown on Fig 6.2. At low frequencies, where the structural CLF is approximately equal to the TLF, the level difference is near zero. At high frequencies the TLF is greater than the CLF and the level difference curve is higher.

As with the CLF data, the level difference of the soft ties is very close to the level difference for the wall with no ties. As a result, it is not until the ties are much stiffer
Fig. 6.2 The predicted effect of varying the stiffness of ties, on the structural level difference of a cavity wall.
than the air that the 6 dB drop with every doubling of the tie stiffness becomes apparent. At high frequencies, the cross cavity modal behaviour dominates the level difference, limiting the highest level difference that can be attained. Again, the curves for the level difference for the wall with only coupling via the air and the curve for infinitely stiff ties, represent an envelope for which all the measured structural level differences for the wall tested should lie.

Fig 6.3 shows the predicted airborne level difference data. Again, the curve for the infinitely stiff ties and the curve for the wall with no ties, represent the envelope inside which all the level difference curves for the wall should lie. The infinite stiffness curve is very close to the result that would be expected from a single wall with a bending stiffness and surface density equal to the sum of the values for the two leaves of the double wall. At low frequencies all the walls display infinite stiffness behaviour and the curves are very close to each other, rising at 6 dB per octave. As the frequency increases, the ties begin to behave resiliently and the 6 dB drop in level difference for every doubling in tie stiffness becomes apparent. Above the critical frequency of the wall in the model, the slope of the level difference curve changes to 18 dB per octave and this is reduced to approximately 12 dB per octave once the cross cavity modes start to appear.

6.3 Construction of the test wall

The basic test wall that was used to measure the performance of the ties was described in detail in chapter 3. It consisted of two leaves of masonry with a surface density of 201 Kg/m² and longitudinal wavespeed of 2200 m/s, separated by an 85 mm wide cavity. The critical frequency for the leaves of the wall was 297 Hz. The stiffness of the ties used in this chapter were measured in chapter 3 and are given in the table below.
The effect of varying the stiffness of wall ties, on the airborne level difference of a cavity wall.

Fig. 6.3
### Table 6.1 Measured wall tie stiffnesses.

<table>
<thead>
<tr>
<th>Tie type</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butterfly tie</td>
<td>$1.1 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Hook tie</td>
<td>$2.1 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Double triangle tie</td>
<td>$4.3 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Replacement tie</td>
<td>$30 \times 10^6$ N/m</td>
</tr>
<tr>
<td>Bar tie</td>
<td>$60 \times 10^6$ N/m</td>
</tr>
</tbody>
</table>

A new wall had to be built each time a different type of tie was tested. To enable the results for different types of tie to be compared, the basic wall was kept the same.

The performance of two of these walls, where the only transmission across the cavity was via the air, was studied in chapter 4 and the results showed that there was some variation between them. To examine whether there was any significant variation in the performance of these walls when a structural path across the cavity was present, a single replacement tie was added to each and the structural and airborne level differences were measured. The results are shown in Fig 6.4 and 6.5. With the structural path present, it can be seen that the performance of the two walls is very similar. This means that the variation is in the airborne path across the "airtie". Therefore, when the ties are sufficiently stiff for structural transmission to dominate, it is reasonable to compare results from different test walls.

### 6.4 Hook ties

The hook ties could be removed from the test wall, so it was possible to obtain data for this wall with and without structural coupling across the cavity. The ties, which are shown in Fig 3.14, are of 2.5 mm diameter stainless steel wire and have a measured stiffness of $2.1 \times 10^6$ N/m. The test wall had twenty-five of these,
Fig. 6.4 The structural level difference of two similar walls with one wall tie.
The normalised airborne level difference of two similar walls with one wall tie.

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Fig. 6.5

The normalised airborne level difference of two similar walls with one wall tie.
positioned every second course vertically, with a horizontal separation of 900 mm.

**Structural level difference**

The measured and predicted structural level differences are shown in Fig 6.6. It can be seen that the addition of the ties resulted in a measured drop of around 5 dB in the level difference at frequencies above 80 Hz. There is a dip in the curve for the wall with ties at 31.5 Hz which is probably the mass-spring-mass (MSM) resonance. If the stiffness of the air is included, the predicted resonance frequency is 38 Hz, a third octave band higher than the observed dip.

Three predicted curves are shown on the figure. The prediction that includes both the metal tie and the "airtie" coupling is around 3 dB lower than the measured data. However, from the measured data for this wall with no metal ties, it is known that the "airtie" overestimates the coupling, particularly at the low frequencies. Neglecting the air coupling and using only the metal tie coupling, gives a predicted curve that displays much better agreement with the measured data, though there is then no predicted cross cavity dip at high frequencies. The final curve is a prediction made using the measured air coupling obtained from the measured structural difference for the wall when it had no ties. This was added to the coupling for the metal ties to give the total coupling across the cavity. This removes any uncertainty associated with the air coupling and allows the effect of the hook ties to be seen more clearly. The ties had only a very small effect on the overall transmission causing the performance to drop by between 1 and 2 dB.

**Airborne level difference**

The airborne level differences (normalised to $T_{60} = 0.5$ s) for the wall, with and without, ties are shown on Fig 6.7. From 80 to 500 Hz the addition of the ties resulted in a drop of up to 10 dB in the level difference. At the lowest frequencies the two measured curves converge. This is the frequency region where the two leaves act as a single wall. At high frequencies the two measured sets of data converge as it is the "airtie" that dominates transmission, the metal ties having little effect.
Fig. 6.6  Measured and predicted structural level difference for a cavity wall with 25 hook ties.
Results for the wall with no wall ties
Results for the wall with 25 ties.
Prediction with "airtie" and metal tie coupling.
Prediction made with measured "airtie" coupling and metal tie coupling.
Prediction with just metal tie coupling.

Fig. 6.7 Measured and predicted normalised airborne level difference for a cavity wall with 25 hook ties.
As with the structural results three predictions were made, one with and one without an "airtie" and one with the measured "airtie". At frequencies below 500 Hz, the measured data shows good agreement with the prediction made without the "airtie". This is consistent with the structural data. As with the high frequency data for this wall with no ties, discussed in chapter 4, the poor agreement that was obtained between the measured data and the prediction made using the measured "airtie", suggested that airborne flanking affected the performance of this wall.

Repeat test for air leak

This wall was tested twice, once very soon after construction had been completed and a second time a month later. This was done to determine whether the change in mass of the wall (brought about by the evaporation of the water used during construction) and the increase in strength of the mortar joints affected the wall's performance. The airborne data for the wall tested at one week and at one month is shown in Fig 6.8. This shows that there was a negligible change in the performance of the wall below 630 Hz but that above 630 Hz the performance of the wall changed significantly. The data gathered a month after the completion of the wall, showed a drop in level difference that increased with increasing frequency, to reach a maximum drop of about 10 dB. Close inspection of the wall revealed that drying shrinkage had caused gaps to open up around its perimeter. The wall that was built in around all four sides had a narrow gap along its top edge and drying shrinkage caused a long tear to appear in the mastic joint along one edge of the free standing leaf. These were only noticeable on close inspection. The gaps resulted in air leakage paths and were responsible for the deterioration in the walls performance. The gaps were repaired and the walls were retested. This data is also shown on Fig 6.8. It can be seen that the repairs resulted in almost the complete restoration of the wall's performance.

The structural level differences obtained for the test on the wall at one week and one month are plotted on Fig 6.9. For these tests a loudspeaker was used as a power input into the source room rather than exciting the structure with a hammer. It can be seen that there is very little difference between the two sets of data, especially at high frequencies. The affects of the drying shrinkage are therefore confined to the airborne
The effect of a damaged perimeter seal on the normalised airborne level difference of a cavity wall with 25 hook ties.
Wall tested after one week.

Wall tested after one month with damaged seal.

Fig. 6.9 The effect of a damaged perimeter seal on the structural level difference of a cavity wall with 25 hook ties.
performance of the wall, only.

Discussion
The tests performed on this wall, after the ties had been removed, showed that the theory for transmission across the cavity via the "airtie" overestimated the coupling due to the air. As the hook ties were relatively soft, the overestimate in the "airtie" coupling caused the predicted airborne and structural level differences to be too low. By omitting the "airtie" from the SEA model and including only the transmission across the metal ties, the quality of the prediction was improved.

Tests made on this wall after the ties were removed allowed the air coupling to be measured in the absence of the ties. This enabled a prediction to be made using the measured air coupling and the predicted tie coupling. The agreement between this prediction and the measured structural data was very good. The agreement between the airborne data was however poor, suggesting that flanking transmission had affected the results above 500 Hz. This was probably present on all the party walls but became less important as the ties became stiffer.

6.5 Butterfly ties

The butterfly ties tested in this wall are shown in Fig 3.14. They were made from 3 mm diameter galvanised mild steel wire. There were twenty five ties in the wall, spaced at 900 mm centres horizontally and every second course of blockwork vertically. The free length of the wall ties was 85 mm for which the measured stiffness was $1.1 \times 10^6$ N/m. These were the softest ties measured and so should give results between those for the hook ties and no ties.

Structural level difference
The measured and predicted structural level difference for the test wall is shown in Fig 6.10. It was not possible to test this wall without ties so the data for the two walls
Nominally identical cavity walls with no ties.

Cavity wall with 25 butterfly ties.

Predicted structural level difference.

Fig. 6.10 Measured and predicted structural level difference for a cavity wall with 25 butterfly ties.
that were tested without ties is plotted on the figure for comparative purposes. It is assumed that the two results for the walls are typical. It can be seen that the addition of the butterfly ties resulted in a drop of about 5 dB in the level difference at low frequencies. At the higher frequencies the level difference is almost the same as the lowest level difference that was measured on the walls without structural coupling.

There is reasonable agreement between the measured and predicted data, with the prediction being slightly lower than the measured results. The measured curve shows some levelling off at frequencies above 630 Hz. This occurs two third octave bands before the predicted curve starts to show any evidence of the first cross cavity resonance. This was possibly caused by the porosity of the concrete blocks which would make the effective cavity width greater than the measured width. Using a wider cavity in the prediction would result in lower cross cavity resonances.

At low frequencies the agreement is good. For the hook ties, which have a similar stiffness, the inclusion of the "airtie" overestimated the coupling. This makes it difficult to generalise on whether the theory for air coupling is accurate.

**Airborne level difference**

The airborne level difference (normalised to $T_{60} = 0.5$ s) is shown in Fig 6.11, together with the data for the two walls without ties. The results for the wall with ties is only about 2 dB lower than the lower limit of the data from the walls without ties.

Also shown on the figure is a predicted level difference for the wall with "airtie" and metal tie coupling. The measured results are very close to the no-ties case. This would be expected as the ties are very soft and have little effect on transmission. The theory predicts a lower level difference than was measured and this is consistent with the results from the wall with hook ties and the walls with no ties.

At high frequencies the measured data levels off, starting at 500 Hz. It is thought that this is due to the creation of gaps caused by wall shrinkage, similar to that observed in the hook tie wall. This feature of the curve was not identified until after the wall
Fig. 6.11 Measured and predicted normalised airborne level difference for a cavity wall with 25 butterfly ties.
was demolished. Fig 6.12 shows the airborne level difference for the wall with butterfly ties plotted with two sets of level difference data for the test wall with hook ties, one curve for the damaged wall and one for the repaired wall. At frequencies above 500 Hz the data for the damaged wall with hook ties and the wall with butterfly ties are very similar, both curves being lower than the curve for the undamaged wall. This suggests that the problems that occurred on the wall with hook ties also occurred on the wall with butterfly ties. This damage would not be expected to affect the structural results.

6.6 Double triangle ties

The double triangle ties tested in this thesis can be seen in Fig 3.14. The ties were of galvanised mild steel wire with a diameter of 4 mm and had a measured stiffness of $4.3 \times 10^6$ N/m for a free length of 85 mm. The wall contained twenty-five ties, positioned every second course vertically and at 900 mm centres horizontally.

Structural level difference

The structural level difference is shown in Fig 6.13, together with the data obtained for the two walls without ties. It can be seen that adding the ties resulted in a drop of about 5 dB in the level difference at frequencies above 200 Hz. At low frequencies, the effect of the MSM resonance, which is predicted to occur at 52 Hz, is responsible for the measured level difference being negative.

The predicted results for the structural data are also plotted on the figure. These show reasonable agreement with the measured data, particularly between 100 Hz and 1 KHz. As would be expected, in the region of the MSM resonance the agreement is poor because the model does not include this mechanism. At frequencies above 1 KHz, the dip in the measured data is two third octaves higher than the dip predicted from the first cross cavity mode.
Fig. 6.12 Comparison of the normalised airborne level difference for a damaged wall with hook ties and the data for the wall with butterfly ties.
Fig. 6.13 Measured and predicted structural level difference for a cavity wall with 25 double triangle ties.
Airborne level difference

Fig 6.14 shows the airborne level difference data for the test wall plotted with the results for the two walls without ties. At low frequencies cavity walls behave as single stiff walls so the addition of the ties makes little difference in performance. In the mid frequencies, the change in performance is about 10 dB and at high frequencies, where the "airtie" becomes important, the metal ties have little affect.

It can be seen that there is good agreement between the predicted and the measured airborne data. Above the critical frequency of the test wall the two curves are almost identical, although there is insufficient data to examine the first cross cavity resonance in detail. Below critical frequency, there is reasonable agreement between the two sets of data. As with the structural data, the dip at the MSM resonance is not accounted for by the model and the agreement at the bands around the 50 Hz third octave is poor.

6.7 Replacement wall ties

Although no tests were performed on the wall with replacement wall ties when 25 ties were present, tests were performed with 32 ties present. The predicted results for the wall with 32 ties are only 1 dB lower than the prediction for 25 ties. This difference was so small that the results for the wall with 32 replacement ties were included in this chapter for comparative purposes. The ties had a measured stiffness of $30 \times 10^6$ N/m.

Structural level difference

The replacement ties were added to the wall after it was built and this made it possible to measure the level difference before the ties were added. This allows a comparison to be made between the data for the wall with and without ties. Fig 6.15 shows the structural level difference for the wall before any ties were added and for the wall after 32 ties were added. It can be seen that the addition of the ties resulted in a drop in level difference of about 20 dB over most of the frequency range. In the
Nominally identical cavity walls with no ties.

Cavity wall with 25 double triangle ties.

Predicted airborne level difference.

Fig. 6.14  Measured and predicted normalised airborne level difference for a cavity wall with 25 double triangle ties.
Nominally identical cavity walls with no ties.

Cavity wall with 32 replacement ties.

Predicted structural level difference.

Fig. 6.15 Measured and predicted structural level difference for a cavity wall with 32 replacement ties.
low frequency region, around the predicted frequency of the MSM resonance (142 Hz), the level difference for the wall with replacement ties is less than 0 dB. Above 1.6 KHz the data levels off, due possibly to the effect of the cross cavity resonance at 2 KHz.

The predicted data is also shown on the figure. The agreement between the two sets of data is good between 250 Hz and 1.6 KHz. The predicted curve shows only a slight dip at 2 KHz as air coupling is not important for a wall of this type with many stiff ties. At low frequencies the agreement is not as good because of the effect of the MSM resonance.

**Airborne level difference**

Fig 6.16 shows the airborne data for the test wall, again plotted with the data for the wall before the tie was added. As with the structural data, the addition of the ties resulted in the level difference dropping by about 20 dB in the mid frequency region but this diminished with increasing frequency to about 12 dB at 1 KHz.

The agreement between measured and predicted data is generally good. The dip in the region of the first cross cavity mode, in the measured data, is a little deeper than in the predicted results and may be a result of other flanking paths. In the region of critical frequency, the drop in level difference shown in the predicted data is not evident in the measured results. At frequencies below the critical frequency there is reasonable agreement between the measured and predicted results, the measured data being distributed evenly on either side of the predicted curve. The MSM resonance for this wall was predicted to occur at 143 Hz. Below this frequency, single wall behaviour occurs and as the ties are stiff there will not be a slip plane between the two leaves. In this frequency region, the SEA model used to make the prediction treated the wall as two subsystems, one for each leaf; this is clearly inappropriate. A tee joint between the test wall and the chamber floor slabs would have been required to model the coupling correctly. This was not done, and there is therefore some uncertainty in the predicted airborne results in this frequency region.
Fig. 6.16 Measured and predicted normalised airborne level difference for a cavity wall with 32 replacement ties.
6.8 Bar ties

The bar ties, shown in Fig 3.14, were much more substantial than the other ties examined and had a measured stiffness of 60 x 10^6 N/m per tie. They consisted of galvanised mild steel bars with a cross section of 20 mm x 3 mm. There is a twist at the centre of the tie to form the drip and the ends of the ties are cut and bent into a fish tail shape to give a mechanical key in the mortar bed. The wall contained twenty-five ties, built into every second course vertically and at 900 mm centres horizontally.

**Structural level difference**

Fig 6.17 shows the structural level difference data for this wall, plotted with the data obtained from the two walls without ties. It can be seen that the addition of the bar ties resulted in a drop in level difference of about 20 dB. The MSM resonance frequency for the wall (predicted at 178 Hz), results in a shallow dip in the data between 63 Hz and 250 Hz. The dip at 4 KHz is caused by the second cross cavity resonance and there is a drop in the measured data in this region.

Except at the frequencies where the MSM resonance dip occurred in the measured data, the agreement between the measured and predicted curves was quite good, the difference between the two sets of data being about 1 dB.

**Airborne level difference**

The airborne data for the wall with and without ties is shown on Fig 6.18. As with the structural data it can be seen that the addition of the ties resulted in a large drop in level difference. Over most of the frequency range the data dropped by around 20 dB but at the lower frequencies, where both the walls with and without ties begin to exhibit single wall-like behaviour, the effect of the ties was less. There is a dip in the data at 160 Hz and 200 Hz which could be caused by the MSM resonance.

Overall the agreement between the measured and predicted curves is good. At low frequencies the agreement is better than was obtained for the walls with soft ties. This
Fig. 6.17 Measured and predicted structural level difference for a cavity wall with 25 bar ties.
Nominally identical cavity walls with no ties.

Cavity wall with 25 bar ties.

Predicted airborne level difference.

Fig. 6.18 Measured and predicted normalised airborne level difference for a cavity wall with 25 bar ties.
is probably as a result of the high stiffness of the bar ties which extended the single wall like behaviour up to much higher frequencies. However, as with the prediction for the replacement ties, the wall was not modelled correctly in this region. It was modelled as two thin walls rather than a single very stiff wall. This would have formed a tee joint with the two chamber floor slabs and there is therefore some uncertainty in the airborne prediction at these frequencies.

In the frequency region above 178 Hz (the predicted MSM frequency), the agreement between the two curves is also good. The slopes of the two curves are the same and the measured data is about 2 dB higher than the prediction. The exception is at 315 Hz, where the dip at critical frequency is not apparent on the measured data. This is a consequence of using eqn(2.29), which overestimates the radiation efficiency in this region.

6.9 Discussion

In the first part of this chapter it was shown that all the results for a given wall, with a given number of ties, would lie inside an envelope drawn by the curve for the wall with only air coupling and the curve for the wall with infinitely stiff ties. The structural envelope and the data obtained from the tests in this chapter are shown in Fig 6.19. The measured and predicted results were plotted separately for clarity. The measured data, on the whole, lies within the two curves. The curves for the soft ties lie on the edge or just outside the upper limit of the envelope due to the uncertainty about the air coupling. The first cross cavity resonance is another region of uncertainty. Most of the measured data shows a dip in this region but not all at the same frequency. The penetration of the air in the cavity into the pore structure of the blockwork is a possible explanation for the variation. At low frequencies some of the data lies below the curve for the infinitely stiff ties. This is as a result of the MSM resonance, which is not included in the theoretical model. A method of modelling the resonance is presented in chapter 10. It was omitted from the model used in this chapter to avoid any uncertainties associated with it, from confusing the predicted behaviour of varying the tie stiffness. As the resonance is restricted to a narrow range
Fig. 6.19 Measured and predicted structural level differences for walls with 25 ties.
of frequencies, it's omission does not seriously affect the overall accuracy of the prediction.

The airborne data is shown on Fig 6.20. It shows that apart from dips in the data caused by MSM resonances, almost all the measured data lies within the lower limit of the envelope. The measured curves all converge at low frequencies where single wall behaviour occurs and at high frequencies they display shallow dips around the frequency of the first cross cavity resonance. The worst agreement is for the butterfly ties in the frequency region below critical frequency, where the measured level difference was higher than the upper limit of the envelope. These ties were the softest tested and were susceptible to any errors caused by the use of the "airtie", which at these frequencies overestimated the strength of the coupling.

6.10 Conclusions

Measurements were made on a series of walls that were identical in design except for the ties that were built into them. A variety of ties were tested with stiffnesses ranging from the very soft (similar to the stiffness of the air in the cavity), to very stiff.

The measured results for the walls in which the stiff ties were tested showed good agreement with predicted data. This was because transmission across the ties dominated the performance of the wall and this is predicted accurately using the theory presented in chapter 2.

Chapter 4 showed that there was some uncertainty associated with using an "airtie" to model the air in the cavity. The stiffness of the soft ties was similar to the stiffness of the air in the cavity and the transmission across each was therefore similar. Errors associated with modelling the air, therefore, had a large affect on the overall prediction. When the measured air coupling was used in a prediction for a wall with soft ties, the results showed good agreement with the measured structural data. The airborne results did not agree well indicating that airborne flanking had occurred
Fig. 6.20  Measured and predicted normalised airborne level differences for walls with 25 ties.
above 500 Hz. This would only affect the airborne results from the walls tested with soft ties. The structural path across the cavity of walls with stiff ties dominated transmission. The effects of flanking on overall airborne performance would be negligible for these walls.

The theoretical effect of varying the stiffness of a fixed number of ties on the performance of a cavity wall was examined. It was found that above the mass-spring-mass resonance, the airborne and structural performance of a cavity wall changes by 6 dB for every doubling of the tie stiffness. This is because the coupling is related to the square of the tie stiffness. Below the mass-spring-mass resonance ties are infinitely stiff and the behaviour of a given wall is independent of the type tie.

The theory also showed that a region exists where all the predictions for a wall with a fixed number of ties with any stiffness will lie. This region is bound by the curve for the wall with no ties and the curve for the wall with a fixed number of infinitely stiff ties. Except where the theory was uncertain, all the measured data fell in this region.

Finally it was found that drying shrinkage can seriously affect the performance of a test wall. The severity of the effect will depend on the material from which the wall is built and the quantity of water absorbed during construction. For some of the walls tested in this chapter, the shrinkage was sufficient for gaps to open up in the mortar joint between the top of the test wall and the aperture in the test chamber. These only appeared some weeks after the wall had been completed and the measurements made shortly after construction were not affected. For tests performed over an extended period of time, shrinkage could pose a problem. If identified, however, filling the cracks was found to restore the performance of the wall.
Chapter 7
Transmission between parallel plates
coupled along a line

7.1 Introduction

Chapters 5 and 6 concentrated on the transmission of sound across wall ties. This chapter examines the transmission that occurs in another important group of joints which are commonly encountered in double walls. These are joints where the two leaves of a double wall are coupled along a line. In buildings, there are several joint types that consist of parallel plates connected along lines, either at their edges or along their centres. Some examples are shown in Fig 7.1.

The first group are joints commonly found in cavity walls and arise out of the practice of closing the cavity to prevent the ingress of moisture and vermin. At window and door openings this is done by returning one of the leaves to meet the other, as shown in part a of the figure. The top of an external cavity wall is usually closed by laying a course of bricks that couple the internal and external leaves along their top edges as shown in Fig 7.1b. On party walls, where the cavity construction is carried up into the loft space to meet the underside of the roof, the cavity is occasionally closed with a course of slates bedded in mortar, in the manner shown in part c of the figure. This is done to prevent water vapour in the cavity from attacking the underside of the roof timbers. Where the cavity construction is not continued into the loft space, a form of construction that is occasionally used is shown in Fig 7.1d. A course of masonry is laid across the top of the party wall to close the cavity and the construction is continued in the loft space with a single skin of masonry. Fig 7.1e shows a detail that is occasionally used where the solid construction of the substructure gives way to cavity construction above ground level.
Common examples of joints consisting of parallel plates coupled along lines.
Fig 7.1f shows another important group of joints. These occur on dry lined walls where thin sheets of plasterboard are fixed on strips of timber to a thicker, stiffer wall. Coupling can occur at the perimeter of door and window openings forming a joint consisting of two plates coupled along an edge. The battens that are used to fix plasterboard at intervals along a wall, result in joints which can best be modelled as two plates coupled at a line along their centres.

The coupling for this joint type is strong and the joints tend to be long. It would therefore be useful to predict the transmission that occurs. This chapter reviews the existing theories for modelling this type of joint. A new theory for modelling the joint is then presented and compared with measured results from a test wall.

6.2 Review of existing theory

Several authors have examined the problem of plates coupled along lines.

Sharp [3] produced an expression, based on impedances, that accounts for the transmission through rigid line connections between the leaves of a double wall. When this is used, together with an approximate expression for the transmission through a structurally isolated double wall, it is possible to predict the wall’s airborne performance. Gu and Wang [36] modified Sharp’s expressions to account for resilient line connections. Both theories provide a convenient means of predicting how line coupling affects the performance of a double wall. These are, however, impedance models and so are limited to the transmission of bending waves on the wall, which are normally incident on the joint. In addition, they are not in a form which SEA techniques can be easily applied to.

Zaborov [37] examined the problem of two parallel plates coupled along two opposite edges with beams. He produced solutions, based on a wave model, for the transmission of bending waves from one plate to the other. Two cases were examined. The first was where the stiffness of the plates was greater than that of the beams, where he found that the transmission of bending waves was dominant. The
second case was where the beams were stiffer than the plates and here it was necessary to consider the generation of other wave types to account for transmission.

Lin and Garrelick [38] used a wave model and Fourier techniques to study the problem. Their model consisted of two infinite parallel plates, coupled by spatially periodic line connections, onto which a sound wave was incident at an arbitrary angle. They showed that for low order modes, the performance of the wall was equivalent to that of a single wall with similar mass. When the structural wavelength of the bending waves on the plates was a multiple of the bridge spacing, the structural path across the cavity dominated. At other frequencies the transmission was dominated by the airborne path between the two plates.

Bhattacharya, Mulholland and Crocker [9] examined transmission through a tie plate that connected two parallel plates along their centres. Their model assumed that the tie was capable of supporting wave motion. Solutions were produced for a bending wave on the top parallel plate, normally incident on the junction, for the case where the tie plate was flexurally much softer than the two parallel plates. They showed that the incident bending wave generated both a bending and a longitudinal wave on the tie plate. Of these two waves, the longitudinal wave dominated the generation of bending waves on the second parallel plate. The bending wave on the tie plate lost some of its energy in the generation of a small amplitude longitudinal wave on the second plate. The dominant effect, however, was a reflection at the boundaries resulting in a standing wave. This lost its energy as sound radiation into the airspace between the two plates.

An approximate expression was presented to account for the transmission of bending waves from the upper parallel plate to the tie plate. The same expression was also used to determine the transmission of bending waves from the tie plate to the second parallel plate. No expression was given for the transmission of bending waves on the top plate to longitudinal waves on the tie plate, or for the transmission of longitudinal waves on the tie plate to bending waves on the lower plate. This was despite the authors having identified this as being the dominant mechanism of transmission.
For joints where the tie plate has a flexural stiffness comparable to that of the parallel plates, an interaction occurs between the bending wave and the longitudinal wave on the tie plate. In this case, each becomes responsible for the transmission of bending and longitudinal waves on the second parallel plate. The modal interaction on the tie plate was cited as a reason for the inappropriateness of models that predict transmission based on two junctions, e.g., a tee joint between the top plate and the tie and a second tee joint between the tie and the lower plate.

The parallel plates examined in this chapter are all connected by tie plates that are very short. Over the frequency range of interest they will support neither bending nor longitudinal waves and it is not helpful to consider them as plates. The tie is better thought of as a stiffness element that couples the plates. While this theory provides some insight into the behaviour of this joint at high frequencies, it is too complicated for predicting the performance at typical building acoustics frequencies.

Using impedances, Crocker [25] produced an expression for non-resonant transmission across a sound bridge between two parallel plates. It was, however, assumed that the power flow was due to bending moments on the source plate, causing flexure of the bridge which in turn generated a moment on the receiving plate. Normally the flexural stiffness of a structural bridge is less than the axial stiffness and according to Cremer et al. [14], it is the transmission of forces rather than bending moments that is the dominant transmission mechanism for normal point acting sound bridges.

Craik [17] used an impedance model to derive eqn(2.71), which can predict the non-resonant transmission of forces across the tie between two parallel plates. The theory can be easily incorporated into an SEA model but it is limited to bending waves that are incident normally on the joint.

7.3 Theory for parallel plates connected along a line

This section describes a wave model for two parallel plates coupled along a line.
Transmission coefficients can be determined for randomly incident bending waves and these are convenient for use in an SEA model. The most general method for considering the coupling between plates connected at a line was given by Cremer et al. [14]. Although joints with three and four plates were not specifically considered, the equation presented for a two plate joint can be rewritten for these forms of construction. This procedure is commonly used for other joint types and was adopted for modelling the four plate joint discussed here.

Figure 7.2 shows four semi infinite plates connected along a common edge, at $x=0$, by an infinitely stiff and thin, inertia-less connector. A plane bending wave on the source plate (plate 1), with unit velocity $\hat{v}$, is incident on the junction at an angle $\theta_i$ with a velocity given by [14],

$$v_1 = \Phi_1 e^{-ik_x \cos \theta_i x + ik_z \sin \theta_i z + io t}$$

(7.1)

The spatial dependence in the $z$ direction and dependence on time is common to this wave and all secondary waves generated and will be omitted for clarity.

The incident wave is reflected at the junction producing a travelling wave on plate 1 [14],

$$\Phi_1 e^{ik_x \cos \theta_i x}$$

(7.2)

and a nearfield wave [14],

$$\Phi_1 e^{k \sqrt{1 + \sin^2 \theta_i} x}$$

(7.3)
Fig. 7.2  A sketch of four parallel plates coupled along an edge.
where $r$ is the reflection ratio for the travelling wave and $r_1$ is the reflection ratio for the nearfield wave. The total velocity on plate 1 at $x=0$ is the sum of these three velocities,

$$v_1(x) = \hat{v}_1 \left( e^{-ik_1 \cos \theta_1 x} + r e^{ik_1 \cos \theta_1 x} + r_1 e^{k_1 \sqrt{1 + \sin^2 \theta_1} x} \right)$$

(7.4)

In addition to the reflected wave, the incident wave also generates three pairs of transmitted travelling and nearfield waves on the remaining three plates. On plate 2 these are transmitted at an angle $\theta_2$ to the normal and have velocity [14],

$$v_2 = \hat{v}_1 \left( t_2 e^{-ik_2 \cos \theta_2 x} + t_{12} e^{-k_1 \sqrt{1 + \sin^2 \theta_2} x} \right)$$

(7.5)

where $t_2$ is the transmission ratio for the travelling wave and $t_{12}$ is the transmission ratio for the nearfield wave. On the third plate the waves are transmitted at an angle $\theta_3$ to the normal and have velocity [14],

$$v_3 = \hat{v}_1 \left( t_3 e^{ik_3 \cos \theta_3 x} + t_{13} e^{k_1 \sqrt{1 + \sin^2 \theta_3} x} \right)$$

(7.6)

On the fourth plate the waves are transmitted at an angle $\theta_4$ to the normal and have velocity [14],

$$v_4 = \hat{v}_1 \left( t_4 e^{-ik_4 \cos \theta_4 x} + t_{14} e^{-k_1 \sqrt{1 + \sin^2 \theta_4} x} \right)$$

(7.7)

At the junction, at $x = 0$, the velocity of all four plates must be the same and the following relationships can be obtained,
\[ v_1 - v_2 = 0 \]  
\[ v_1 - v_3 = 0 \]  
\[ v_1 - v_4 = 0 \]

(7.8) 
(7.9) 
(7.10)

Substituting for \( v \) from eqn(7.4) to eqn(7.7), allows the above equations to be rewritten as,

\[ r + r_1 - t_2 - t_{12} = -1 \]  
\[ r + r_4 - t_3 - t_{43} = -1 \]  
\[ r + r_1 - t_4 - t_{14} = -1 \]

(7.11) 
(7.12) 
(7.13)

In addition to the velocities at the junction being equal, the angular velocities, \( \Omega \), on the four plates must also be equal.
Using the relationship between the velocity and angular velocity on a plate \[14\],

\[
\Omega_x = \frac{\delta v_x}{\delta x}
\]

(7.17)

and the expressions for the plate velocities, the boundary conditions for angular velocity can be rewritten as,

\[
\begin{align*}
&ik_1 \cos \theta_1 r + k_1 \sqrt{1 + \sin^2 \theta_1} r_i + ik_2 \cos \theta_2 t_2 + k_2 \sqrt{1 + \sin^2 \theta_2} t_{i2} - ik_1 \cos \theta_1, \\
&ik_1 \cos \theta_1 r + k_1 \sqrt{1 + \sin^2 \theta_1} r_i - ik_2 \cos \theta_2 t_2 - k_2 \sqrt{1 + \sin^2 \theta_2} t_{i2} - ik_1 \cos \theta_1, \\
&ik_1 \cos \theta_1 r + k_1 \sqrt{1 + \sin^2 \theta_1} r_i + ik_4 \cos \theta_4 t_4 + k_4 \sqrt{1 + \sin^2 \theta_4} t_{i4} - ik_1 \cos \theta_1
\end{align*}
\]

(7.18)

(7.19)

(7.20)
At the junction the sum of the moments, \( M \), must equal zero,

\[
M_1 + M_2 + M_3 + M_4 = 0
\]  
(7.21)

The relationship between bending moment per unit width and the plate velocity is given by [14],

\[
M = \frac{B}{i\omega} \left[ \frac{\delta^2 v}{\delta x^2} - \mu (k_1 \sin\theta_1)^2 \right] v
\]  
(7.22)

where \( B \) is the bending stiffness per unit width for the plate and \( \mu \) is Poisson’s ratio. Applying this to the plate velocities allows eqn(7.21) to be rewritten as,

\[
-B_1 k_1^2 r (\cos^2 \theta_1 + \mu \sin^2 \theta_1) + B_2 t_2 k_2^2 (\cos^2 \theta_2 + \mu \sin^2 \theta_2) - B_3 t_3 k_3^2 (\cos^2 \theta_3 - \mu \sin^2 \theta_3) + B_4 t_4 k_4^2 (\cos^2 \theta_4 + \mu \sin^2 \theta_4) + B_1 r_1 (k_1^2 - \mu k_1^2 \sin^2 \theta_1) - B_2 t_1 r_2 (k_2^2 - \mu k_2^2 \sin^2 \theta_2) + B_3 t_2 r_3 (k_3^2 - \mu k_3^2 \sin^2 \theta_3) - B_4 t_3 r_4 (k_4^2 - \mu k_4^2 \sin^2 \theta_4) - B_1 k_1^2 (\cos^2 \theta_1 + \mu \sin^2 \theta_1)
\]  
(7.23)

where,

\[
k_n^2 = k^2 (1 + \sin^2 \theta)
\]  
(7.24)

is the nearfield wavenumber.

Finally, at the junction the sum of the forces, \( F \), must equal zero,
For a plate the relationship between the velocity and the force per unit width at the boundary is given by [14].

\[
F = \frac{B}{i\omega} \left[ \frac{\delta^3 V}{\delta x^3} - (2 - \mu) (k_1 \sin \theta_1)^2 \frac{\delta V}{\delta x} \right]
\]

(7.26)

This allows eqn(7.25) to be rewritten as,

\[
-i B_1 k_1^3 \left( \cos^3 \theta_1 + 2 \sin^2 \theta_1 \cos \theta_1 - \mu \sin^2 \theta_1 \cos \theta_1 \right) - \\
i B_2 k_2^3 \left( \cos^3 \theta_2 + 2 \sin^2 \theta_2 \cos \theta_2 - \mu \sin^2 \theta_2 \cos \theta_2 \right) - \\
i B_3 k_3^3 \left( \cos^3 \theta_3 + 2 \sin^2 \theta_3 \cos \theta_3 - \mu \sin^2 \theta_3 \cos \theta_3 \right) - \\
i B_4 k_4^3 \left( \cos^3 \theta_4 + 2 \sin^2 \theta_4 \cos \theta_4 - \mu \sin^2 \theta_4 \cos \theta_4 \right) + \\
B_1 t_1 (k_{n1}^3 - 2 k_{n1} k_1^2 \sin^2 \theta_1 + \mu k_{n1} k_1^2 \sin^2 \theta_1) + \\
B_2 t_2 (k_{n2}^3 - 2 k_{n2} k_2^2 \sin^2 \theta_2 + \mu k_{n2} k_2^2 \sin^2 \theta_2) + \\
B_3 t_3 (k_{n3}^3 - 2 k_{n3} k_3^2 \sin^2 \theta_3 + \mu k_{n3} k_3^2 \sin^2 \theta_3) + \\
B_4 t_4 (k_{n4}^3 - 2 k_{n4} k_4^2 \sin^2 \theta_4 + \mu k_{n4} k_4^2 \sin^2 \theta_4) - \\
-i B_1 k_1^3 \left( \cos^3 \theta_1 + 2 \sin^2 \theta_1 \cos \theta_1 - \mu \sin^2 \theta_1 \cos \theta_1 \right)
\]

(7.27)

Equations (7.11) to (7.13), eqn(7.18) to (7.20) and eqn(7.23) and (7.27) are a set of eight simultaneous equations that can be solved for the reflection and transmission ratios. These allow the distribution of the incident power amongst the four plates to be determined. The transmission coefficient \( \tau \) is related to the transmission ratio \( r \) through [14],

\[
\tau_{12} = \frac{\rho_{s2} c_{B2}}{\rho_{s1} c_{B1}} \left| t_2 \right|^2
\]

(7.28)
Solving these equations by hand would be tedious and result in solutions that are unwieldy. It is, however, possible to solve the equations for specific angles of incidence using numerical methods and then determine average transmission coefficients, $\tau_{av}$, for randomly incident waves using,

$$\tau_{av} = \int_{0}^{1} \tau_{\theta} \, d(\sin\theta)$$

(7.29)

where $\tau_{\theta}$ is the transmission coefficient for a wave incident on the joint at an angle $\theta$. If this is done for the joint type shown in Fig 7.2, a transmission coefficient that is independent of frequency is obtained. This is convenient as it means that it is only necessary to compute the transmission coefficients at one frequency. Two transmission coefficient curves, plotted as a function of angle of incidence, for a joint of this type are shown on Fig 7.3. The angular average value for the transmission coefficient is found by integrating these curves in the manner shown in eqn(7.29).

The curves are for transmission between a concrete wall (with $C_i = 2200 \, \text{m/s}$, $\rho = 2010 \, \text{Kg/m}^3$, $h = 0.1 \, \text{m}$), and a sheet of plasterboard ($C_i = 2400 \, \text{m/s}$, $\rho = 1200 \, \text{Kg/m}^3$, $h = 0.0125 \, \text{m}$), coupled along a line at their centres. The top graph is for transmission from the concrete to the plasterboard and the bottom graph is for transmission in the opposite direction. The curve for transmission from the block wall to the plasterboard varies slowly with increasing angle of incidence and only displays a peak at oblique angles of incidence.

For transmission in the opposite direction it can be seen from the lower graph that the transmission coefficient peaks at a smaller angle of incidence and then drops to zero. This corresponds to a total internal reflection of part of the incident wave resulting in no power being transmitted to the concrete wall. This occurs at an angle given by Cremer et al [14] as,
Fig. 7.3 Typical transmission coefficients for four parallel plates coupled along an edge.
\[ \sin \theta_1 - \chi \] (7.30)

where \( \chi \) is given by eqn(7.31).

In order to make the theory more useful, the equations were solved many times for four plate joints where the properties of the plates were varied. To do this it was necessary to make a simplification to the model. It was assumed that plates 1 and 2 had the same physical and material properties and that plates 3 and 4 had the same material and physical properties, ie

\[ B_1 = B_2, \quad B_3 = B_4. \]

\[ \rho_{s1} = \rho_{s2}, \quad \rho_{s3} = \rho_{s4}. \]

and,

\[ h_1 = h_2, \quad h_3 = h_4. \]

In buildings, it is this configuration of plates that is most commonly encountered in joints of this type. Solutions were obtained for values of \( \psi \) and \( \chi \) ranging between 0.01 and 100, where,

\[ \chi = \sqrt[4]{\frac{B_1 \rho_{s2}}{B_3 \rho_{s1}}} \] (7.31)

and,
\[ \psi = \frac{B_3 m_3}{B_1 m_1} \]

(7.32)

This is the same notation that is used by Cremer et al [14]. Figures 7.4 and 7.5 show the transmission loss between plate 1 and plates 2 and 4. The transmission losses between plate 1 and plates 3 and 4 are almost identical, therefore only the curves for transmission to plate 4 are given.

It can be seen that the smallest attenuation is 6 dB, obtained when the four plates all have identical physical and material properties. This corresponds to each plate receiving a quarter of the incident power. For transmission across the connection to plates 3 and 4, minima occur in the curves when \( \chi > 1 \) and \( \psi = \chi \). For cases where \( \chi < 1 \), the transmission loss increases rapidly with decreasing values of \( \chi \). This is caused by total internal reflection of components of the incident wave, resulting in less power being transmitted to plates 3 and 4. It occurs when the flexural stiffness of the lower plates is greater than that of the source plate ie \( \chi < 1 \).

### 7.4 Normal incidence solution for four plates

It is possible to obtain simple expressions for the transmission coefficient if the upper plates in Fig 7.2 have the same properties, the lower plates have the same properties and the incident wave is assumed to be normally incident on the joint. This is done by setting,

\[ k_1 = k_2 \]

\[ k_3 = k_4 \]

and,
Fig. 7.4  Random incidence transmission loss for a joint between four parallel plates, for transmission from plate 1 to plate 2.
Fig. 7.5 Random incidence transmission loss for a joint between four parallel plates, for transmission from plate 1 to plate 3 or 4.
\[ \theta_1 = \theta_2 = \theta_3 = \theta_4 = 0 \]

in the random incidence equations. Solving the resulting equations gives the transmission coefficients, defined by eqn(7.28), as,

\[ \tau_{12} = \frac{\psi^2 + 2\chi\psi + 2\chi^2 + 2\chi^3\psi + \chi^4\psi^2}{4[(\chi + \psi)(1 + \chi\psi)]^2} \]

(7.33)

and,

\[ \tau_{13} - \tau_{14} = \frac{\chi\psi(1 + \chi^2 + \psi^2 + \chi^2\psi^2 + 4\chi\psi)}{4[(\chi + \psi)(1 + \chi\psi)]^2} \]

(7.34)

In chapter 2, an impedance model was presented for predicting the performance of joints of this type. This only considered the transmission of forces and so will not give identical results to the wave model examined here. If the inter-layer coupling the two plates in the impedance model is assumed to be infinitely stiff, the agreement between the transmission losses from the two predictions was within about 1.5 dB for all the walls tested in this thesis. It would be expected, however, that the results from the normal incidence wave model would give the most accurate prediction.

It is possible to evaluate eqn(7.34) in the same manner as the random incidence equations to obtain curves for plates where the material and physical properties were varied. The results are plotted on Fig 7.6 and 7.7. Of greatest interest is Fig 7.7, which shows the transmission loss between plate 1 and plates 3 and 4. For normal incidence, the transmission loss to both plates is identical so only one graph has been given. When \( \chi > 1 \), the normal incidence solution and the random incidence solution (on Fig 7.5) are almost identical. When \( \chi < 1 \) the agreement between the two solutions is very poor, the transmission loss for normal incidence being much lower than the random incidence transmission loss.
Fig. 7.6 Normal incidence transmission loss for a joint between four parallel plates, for transmission from plate 1 to plate 2.
Fig. 7.7 Normal incidence transmission loss for a joint between four parallel plates, for transmission from plate 1 to plates 3 or plate 4.
The region of similarity between the random and normal incidence curves can be explained by considering the transmission coefficient shown on the top part of Fig 7.3. Here, $\chi > 1$ and the transmission coefficient is a slowly changing function of the angle of incidence. As a result the angular average for this curve will be close to the value at normal incidence.

Transmission in the opposite direction is represented by the region where $\chi < 1$. Here there will be a significant difference between the angular average of the curve in the lower part of Fig 7.3 and the value at normal incidence because of the total internal reflection that occurs on the source wall. As the difference in the material properties becomes more marked, $\chi$ becomes smaller and the angle where internal reflection occurs gets smaller. This results in the difference between the normal and random incidence solutions becoming more marked.

It is possible to correct the normal incidence solution to account for this phenomenon. If the normal incidence transmission coefficient, $\tau_n$, is substituted for $\tau_s$ in eqn(7.29) and the region of integration after internal reflection is subtracted, it is possible to obtain a corrected transmission coefficient, $\tau_c$, for cases where $\chi < 1$, given by,

$$
\tau_c = \int_0^1 \tau_n \, d(\sin\theta) - \int_{\chi}^1 \tau_n \, d(\sin\theta)
$$

(7.35)

This becomes,

$$
\tau_c = \chi \tau_n
$$

(7.36)

This is just a manifestation of the result that Kihlman [15] obtained using reciprocity to determine transmission coefficients for structural joints. For two coupled plates, plate 1 and plate 2, the transmission coefficients are related through,
\[ k_1 \tau_{12} - k_2 \tau_{21} \]  

(7.37)

from which,

\[ \tau_{12} - \lambda \tau_{21} \]  

(7.38)

Figure 7.8 shows the corrected normal incidence transmission loss between the source plate and either plates 3 or 4, obtained using eqn(7.36). The difference between this and the exact solution, obtained using the random incidence equations, is shown at the foot of the figure. The largest difference is around 1.7 dB.

The corrected normal incidence equations provide an accurate and convenient means of predicting the random incidence transmission loss for joints like the one shown in Fig 7.2, where plates 1 and 2 are identical and where plates 3 and 4 are identical.

7.5 Normal incidence solution for three and two plate joints

For joints that consist of three parallel plates connected along a line (ie joints where any one of plates 2, 3 or 4 is omitted from Fig 7.2), it is highly likely that the properties of the plates will all be different. If this is the case, it is not feasible to solve the random incidence equations and produce graphs showing how the transmission loss varies with varying plate properties. Solving the normal incidence equations for an arbitrary combination of 3 plates results in solutions that are too clumsy to be of much use. As this is the case, it is necessary to solve the random incidence equations for any specific joints that may be encountered.
Fig. 7.8 Corrected normal incidence transmission loss for a joint between four parallel plates, for transmission from plate 1 to plate 3 or plate 4. (Difference between the corrected and the exact solutions shown at the foot of the figure.)
Two plate joints where plates 2 and 4 are omitted are commonly found in buildings, eg at the edges of doors and at window openings in cavity walls. The normal incidence transmission coefficient for this joint is a simple expression,

\[ \tau_{13} = \left[ \frac{2\sqrt{\chi \psi (1 - \chi)(1 - \psi)}}{\chi(1 - \psi)(\psi - 1) - 2\psi(1 + \chi^2)} \right]^2 \]  

(7.39)

Provided \( \chi \) and \( \psi \) do not have values between 0.1 and 10, this equation is accurate to within 1 dB. To model walls where the plates have similar properties, the random incidence equations must be used, with the properties of plates 2 and 4 in Fig 7.2 set to zero.

7.6 Measured results

Joints consisting of parallel plates connected along a line are commonly found in the external envelope of buildings where the cavity is closed around openings in the wall, or at wall heads. In order to verify the theory for parallel plates, a test wall with a form of construction typical of an external cavity wall was built and tested in a transmission suite.

The wall consisted of a dense concrete blockwork leaf and a lightweight aerated concrete blockwork leaf with an 80 mm cavity between them. The dense blockwork had a surface density of 201 Kg/m\(^3\) and a longitudinal wavespeed of 2200 m/s, giving it a critical frequency of 297 Hz. The surface density of the aerated blockwork was 76.5 Kg/m\(^3\) and it had a longitudinal wavespeed of 1700 m/s, the resulting critical frequency being 384 Hz. Both leaves were 4.0 x 3.0 m and 0.1 m thick.

Structural isolation between the two leaves was provided by building one on each side of the gap at the common opening between the two test chambers. To reduce flanking transmission, the lightweight leaf was only coupled to the test chamber along it's
base. A gap was left between the test wall and the chamber around the three remaining sides. This was packed with a closed cell foam and sealed with a silicone mastic joint.

This is the same wall that is described in chapter 4. The results from the initial tests, performed on the wall with no structural connections between the two leaves, are given in that chapter. After the completion of these tests, a rigid line connection was introduced, coupling the two leaves structurally. A block was carefully removed from the centre of each course on the lightweight leaf. This was done by drilling out the mortar from the beds and perpends around the blocks. The bridge was formed by building small lengths of the lightweight block into the hole with a strong cement mortar. These were butt jointed to the dense concrete leaf and bonded into the lightweight leaf in the manner shown in Fig 7.9. The line connection ran the full height of the wall and was isolated from the structure of the test chamber, at it’s top and bottom, with layers of closed cell foam. This change in construction divided each leaf of the test wall into two subsystems, the numbering for which is also shown on the figure.

**Four plates coupled along a line**

The results for the test wall with no structural coupling are discussed in chapter 4. The SEA model used to provide predicted data for comparison with the measured results from this wall worked reasonably well, the agreement between the two sets of data shown on Fig 4.10, being good.

The wall with the line connection was tested for airborne sound insulation and also for structural transmission. The predicted data was obtained from the same SEA model that was used to provide data for the wall with no structural connections in chapter 4. The additional CLFs for transmission across the line connection were obtained from the solution of the random incidence equations and added to the model. Each leaf was effectively divided in two by the joint to give two walls 3.0 x 2.0 m. The coupling between the test wall and the two rooms was recomputed to account for the reduced size.
Receiving Room.

Line connection made from aerated concrete bonded into walls 3 and 4 and butt jointed onto walls 1 and 2.

Wall 3. Aerated concrete 3 x 2 m.
Wall 4. Aerated concrete 3 x 2 m.
Wall 1. Dense concrete 3 x 2 m.
Wall 2. Dense concrete 3 x 2 m.

Source room.

Fig. 7.9 Horizontal section through the test wall used to study transmission between parallel plates coupled along a line.
Fig 7.10 shows the measured and predicted airborne data (normalised to $T_{60} = 0.5$ s) for the wall before and after the line connection was introduced. The addition of the line connection resulted in a drop in sound insulation at all frequencies. In the low frequency region this was only of the order of a few dB but in the higher frequency regions drops of up to 30 dB were obtained. The prediction for the wall with the line connection overestimates the transmission at high frequencies by a fairly constant 3 dB. In the region of critical frequency this difference is much greater. This is probably due to the use of eqn(2.29), which is not very accurate at predicting the radiation efficiency for masonry walls in this frequency region. Paths via the cavity were omitted from the model as the results for the wall tested without structural coupling showed that these were unimportant. Their inclusion in the model with line coupling would have no effect on the predictions.

Fig 7.11 shows the measured and predicted structural level differences. The wall is symmetrical about the joint so measurements were only performed with two of the leaves as source subsystems, one dense and one lightweight. Measurements made in the opposite direction would have given very similar results. The agreement between the measured and predicted results is reasonable, the slopes are similar and they are within 3 dB of each other at most frequencies. Fluctuations in the measured data at low frequencies are probably due to discrete modal effects, caused by the reduced size of the walls forming the joint. These effects are predictable eg [39], but this was not done for this test wall.

**Three plates coupled along a line**

To obtain data for a joint that consists of only three plates, one of the walls forming the four plate joint was demolished. The wall removed was the lightweight wall, wall 4 in Fig 7.9. This had to be done very carefully to prevent damage to the joint between the remaining three plates. The mortar joint between wall 4 and the remainder of the structure was cut and then the wall was knocked down.

Airborne and structural measurements were performed on the wall. The SEA model was adjusted to account for the loss of wall 4 by recomputing the CLFs for the joint.
Fig. 7.10 A comparison between the measured and predicted normalised airborne level difference of an external cavity wall, before and after the introduction of a line connection.
Fig. 7.11 Measured and predicted structural level differences for a joint between four parallel plates.
using the random incidence equations. In addition to changes in the structural coupling, the removal of wall 4 resulted in the creation of a non-resonant path between the two rooms via wall 2.

The measured and predicted airborne level differences (normalised to $T_{60} = 0.5$ s) are shown on Fig 7.12. Removing wall 4 had only a small affect on the measured results, the most noticeable being in the region of critical frequency. For this wall, the coupling of wall 2 to both rooms resulted in a slight lowering of the predicted level difference. As with the data for the wall with a four-plate joint, the prediction is around 3 dB lower than the measured results at high frequencies. Agreement in the region of critical frequency is poor because of the choice of equation for calculating radiation efficiency. At low frequencies the agreement is slightly worse than at high frequencies, the difference being around 5 dB.

Figures 7.13 to 7.15 show the structural data for the wall. Again discrete modal effects caused by the small size of the test walls are probably responsible for the fluctuations in the measured data at low frequencies. Despite this, the agreement between the measured and predicted data is reasonable at all frequencies, the largest discrepancies being around 3 dB. Transmission from wall 2 to wall 3 is the only exception to this, the agreement between the measured and predicted results being poor.

Two plates coupled along a line
The final set of measurements performed on this wall were made to study the behaviour of two parallel plates coupled along one edge. To do this, one of the dense concrete leaves, wall 2, was demolished in the same manner as wall 4. This left walls 1 and 3 forming the two-plate joint.

As there was no wall separating the two test rooms after the demolition of wall 2, only structural level difference measurements were performed. The CLFs for the structural joint were calculated from the solution of the random incidence equations and these were used in the full SEA model of the test chambers to provide predicted
Fig. 7.12  Measured and predicted normalised airborne level difference of a wall with a three parallel plate joint.
Fig. 7.13  Measured and predicted structural level difference of a joint between three parallel plates, for transmission from plate 1 to plates 2 and 3.
Fig. 7.14 Measured and predicted structural level difference of a joint between three parallel plates, for transmission from plate 2 to plates 1 and 3.
Fig. 7.15  Measured and predicted structural level difference of a joint between three parallel plates, for transmission from plate 3 to plates 1 and 2.
data for comparison with the measured results.

Fig 7.16 shows a comparison between the measured and predicted structural level differences for the joint. The agreement for transmission from the aerated to the dense concrete leaf is reasonable, up to 1.6 KHz. Above this frequency the measured level difference rose slightly, unfortunately there is no data at higher frequencies to determine whether the trend continued. For transmission in the opposite direction, the difference between measured and predicted curves is less than 3 dB up to 1 KHz. Above this frequency the measured level difference drops to around 5 dB below the predicted curve.

7.7 Discussion

The physical and material properties of the walls in the joint studied here, were not significantly different. The theoretical model predicts the coupling will be strong in this case and this was confirmed by the measurements. Strong coupling can lead to a violation in the assumptions made in SEA. For the particular wall studied, although coupling was strong, the measured level differences were significantly higher than the equipartition levels (-5 dB for transmission from the dense to the lightweight leaf and 5 dB for transmission in the opposite direction). The assumption that the walls forming the joint could be modelled as individual subsystems was therefore valid and the results from the SEA model are reliable.

The good agreement between the measured and predicted data indicates that where joints of this type are encountered in buildings, it should be possible to predict the transmission that will occur. One form of construction where problems may be encountered is with walls that have window or door openings. Although the coupling at the joint should be correctly modelled, if the opening forms a large proportion of the total wall area then it is unlikely that the modal density of the wall will be given by eqn(2.14). Reducing the area of the wall in the equation to account for the opening would help to improve the prediction of modal density but for walls where openings represent a large proportion of the total area, uncertainties in the modal density may
Fig. 7.16  Measured and predicted structural level difference for a joint between two parallel plates.
limit the use of the theory.

In addition to this problem, designs intended to improve the thermal insulation of dwellings have made it common practice to close the cavity around openings in a different manner. Instead of returning the outer leaf of a cavity wall to butt rigidly against the inner leaf, foamed plastic board is commonly used to close the cavity and also to prevent "cold bridges". This would decouple the two walls and the effect of a resilient connection would have to be introduced into the above theory to account for this. Whilst it is not possible to predict the performance using the theory presented in this chapter, the impedance model in chapter 2 can be used to predict the transmission of forces for cases where the inter-layer coupling the two plates is resilient. This is only accurate for normal incidence but the results show that the effect of a resilient layer is to reduce the coupling across the cavity and this is of benefit in sound transmission problems.

The form of construction used for the test wall would not be used in real buildings. To prevent moisture from bridging the cavity it is necessary to incorporate a damp proof course into the junction between the two leaves and it is this detail that has been omitted from the test wall. This is typically a layer of bitumen-impregnated felt or polyethylene. As these are very thin, they are likely to be very stiff and should not greatly affect the behaviour of the joint if there is good contact between the leaves.

7.8 Conclusions

A theory for predicting the transmission across line connections between the leaves of a cavity wall was presented. The agreement between this and the results from a masonry test wall was good. The coupling for this type of joint is very strong if the leaves of the wall have similar properties. This is usually the case for cavity walls and transmission via this path could lead to a major reduction in the performance of the wall.
Chapter 8
Effect of a dry lining on wall performance

8.1 Introduction

Chapters 4 to 7 examined the behaviour of double walls where the two leaves had similar properties, high surface densities and bending stiffnesses. The transmission paths across the cavity were examined. Of these, the airborne path due to stiffness of the air in the cavity, and the structural paths due to wall ties and line connections were found to be important. Paths that involved resonant behaviour in the cavity were found to be unimportant. This meant that it was not necessary to model the cavity as a subsystem when predicting the wall performance. This chapter studies the behaviour of a different type of wall for which transmission via the cavity is very important.

The masonry cavity walls studied in previous chapters are a very common form of double wall construction. Another common form of double wall and the one considered in this chapter, consists of a heavy core wall with a light secondary leaf. The light leaf is typically plasterboard on a frame. It is this form of construction that is examined in this chapter. One leaf was built from 100 mm dense concrete blockwork and the second leaf was built from 6 mm thick plywood. Tests were made on the wall with no structural sound bridges between the two walls, with point connections and with line connections. Tests were also performed with and without added cavity absorption.

It was found that the performance of this test wall could not be predicted using the simple four subsystem model described in chapter 2. The plywood wall has a strong non-resonant path from the cavity to the room it faces into. It is therefore necessary to introduce the cavity into the model as a subsystem.
The first part of this chapter describes the test wall. The performance of the two leaves of the wall when tested individually is then discussed and compared with predicted results. The performance of the double wall with and without ties and battens is then described and compared with predicted data.

8.2 Construction of the test wall

A section through the wall is given in Fig 8.1. It consisted of a dense masonry leaf and a lightweight plywood leaf. It was built in a transmission suite, with one leaf built on either side of the gap separating the two test rooms to ensure that they were structurally isolated from each other. The masonry wall was built in the smaller source room and was butt jointed to the aperture between the two rooms around four sides. It had a surface density of 201 Kg/m², a thickness of 0.1 m and a longitudinal wavespeed of 2200 m/s giving it a critical frequency of 297 Hz. The surface of the wall facing into the source room was sealed with two coats of cement paint. The surface facing into the cavity was left untreated. The plywood wall was built on the reverberation chamber side. It was fabricated from 3 mm thick plywood sheets. These were glued together to form a single 6 mm thick sheet of plywood with a surface density of 4 Kg/m². This provided a single homogeneous sheet of plywood measuring 2.94 x 3.94 m without the need for a studwork frame to fix it to. The measured longitudinal wavespeed for the plywood was 3100 m/s and the resulting critical frequency for a 0.006 m thick sheet is 3507 Hz. The plywood sheet was fixed at its perimeter into a wooden frame with screws and then sealed with a silicone mastic. The frame was screwed into the aperture and the gap between it and the structure of the test room was also sealed with mastic. The nature of the construction of the test chambers and the fact that it was necessary to fix the plywood wall into a frame meant that the narrowest cavity that could be obtained was 100 mm wide.

8.3 Single wall performance

The performance of the leaves of a dry lined wall when tested individually provide
Subsystems 1, 4, 5, 6, 7, 8, 9

Source room.
Subsystem 1

Subsystems 2, 3

Receiving room.
Subsystem 4

Concrete wall 100 mm thick, built in around four sides.
(Subsystem 2)

Ply wall 6 mm thick, in a wooden frame.
(Subsystem 3)

Cavity 100 mm wide

Side walls (subsystems 7 and 8)

Fig. 8.1 Section through the dry lined test wall.
data which is useful in describing the performance of the double wall. After the tests had been completed on the double wall, each of the two leaves was tested individually. The airborne level difference and damping measurements were made on each leaf separately. The prediction for the concrete wall was made using the SEA model shown in Fig 8.2. The ceiling the floor and the side walls of the source room were coupled to the test wall, the ceiling and floor as corner joints and the side walls as inline joints. There was no structural coupling to the receiving room. All the TLFs were obtained using eqn(2.91). The exception was the test wall which had a TLF equal to the sum of the CLFs plus a value of 0.008 for internal losses. The TLF of the receiving room was obtained from measured data. The extra subsystems were necessary to account for the flanking transmission paths that were present.

Fig 8.3 shows the measured and predicted airborne level difference for the concrete wall. The agreement between the measured and predicted curves is reasonable. At low frequencies the agreement is good however the predicted critical frequency dip in the 315 Hz band did not occur in the measured data, there being a difference of about 10 dB at this frequency. At higher frequencies the agreement improves except for the data above 1.6 KHz where there is a difference of about 5 dB. This may have been caused by transmission through the pore structure of the blocks. The concrete they were made from was open textured and it is possible that the cement paint which was used to seal the wall ceased to be effective at high frequencies.

The SEA model for the plywood wall is shown on Fig 8.4. This is a much simpler model than was used for the concrete wall because the large difference between the physical properties of the test wall and the test chambers mean that the coupling between the two can be neglected. Fig 8.5 shows the measured TLF of the plywood test wall measured when the concrete wall was not present. It can be seen that it is a level curve at about 105 dB. The fact that it varied only slightly with frequency suggests that the TLF is dominated by the ILF for the material giving a damping due to internal losses of 0.03.

The measured and predicted airborne level difference for the plywood wall is shown in Fig 8.6. Agreement between the measured and predicted curves is reasonable
Subsystems 5 and 8 are coupled
Subsystems 6 and 7 are coupled

Fig. 8.2 The SEA model for a single concrete block wall and test chambers.
Fig. 8.3 Measured and predicted airborne level difference for a single leaf concrete block wall.
Fig. 8.4 The SEA model for a single leaf plywood wall and test chambers.
Fig. 8.5 Measured damping of a single leaf plywood wall.
Fig. 8.6 Measured and predicted airborne level difference for a single leaf plywood wall.
between 63 Hz and 1 KHz. At the critical frequency there is a very large predicted dip which does not appear in the measured data.

The agreement between the measured and predicted data for the single walls is generally quite good, verifying that the theory for excitation and radiation from walls works. The exception to this, however, occurs in the region around the critical frequencies of both walls, where the predicted transmission is far stronger than the measured results. This is due to the use of eqn(2.29) which overestimates the value of radiation efficiency at critical frequency. Chapter 10 examines radiation efficiency in more detail and presents an improved prediction at critical frequency. As the effects of the overestimate are limited to a narrow range of frequencies eqn(2.29) has been used in this chapter. This avoids any confusion that might arise out of any uncertainties that may be associated with the theory in chapter 10.

8.4 Double walls with no structural sound bridges

The double wall described in this section was tested when the only coupling between the two leaves was via the air in the cavity. Initially there was no absorption added to the cavity.

A 35 mm thick glass fibre quilt was then fixed into the cavity. The plywood leaf of the wall was removed and the quilt was tacked loosely to the face of the concrete wall so that it protruded into the cavity but did not touch the plywood wall when it was replaced. As the plywood has a low surface density, contact with the quilt could have affected it’s response and damping. The concrete wall was so heavy that the small additional mass added by the quilt would have a negligible effect on it’s response. After screwing the plywood wall back into it’s frame the perimeter was sealed with mastic and the measurements of airborne and structural level difference were repeated.

Measured results

The airborne level difference for the double wall with and without added cavity
absorption is shown in Fig 8.7. Also shown for comparison is the level difference for the single leaf concrete wall. It can be seen that the addition of the plywood wall resulted in a considerable improvement in the level difference; an improvement which increased with increasing frequency. Below 125 Hz, when there is no quilt, there was a slight deterioration of about 3 dB compared with the performance of the single concrete wall. The addition of the ply leaf results in the wall exhibiting a mass-spring-mass (MSM) resonance. If the air in the cavity is assumed to have a bulk modulus of $1.4 \times 10^5$ N/m$^2$, then for a cavity width of 0.1 m the predicted frequency for the resonance from eqn(2.65) is 93 Hz. This was probably responsible for the deterioration in the walls performance at low frequencies.

Adding the quilt resulted in a significant increase in the level difference. Below 125 Hz the data increased by about 4 dB and for frequencies above this the increase was about 10 dB.

Fig 8.8 shows the structural level difference for transmission in each direction between the two leaves of the wall before the cavity absorption was added. Both curves have similar shapes with slopes increasing at about 3 dB per octave at low frequencies and then showing a sharp increase at frequencies above 500 Hz where they start to rise at 18 dB per octave. The different masses of the two leaves result in the performance being different for transmission in opposite directions. Comparing the structural data with the airborne data in Fig 8.7, it can be seen that the change in the structural level difference at 500 Hz also occurs in the airborne level difference. The negative structural level differences that were measured for this wall occur because of the massive difference between the mass of the two leaves. The velocity of the plywood is higher than that of the core wall in these regions, however, it's lower mass means that the energy level difference is positive, the energy flowing from the core wall to the dry lining.

The airborne and structural measurements were repeated after extra absorption had been added to the cavity. This caused the level difference above 80 Hz to rise in both sets of data. The increase was modest up to 160 Hz but it increased by a fairly constant 10 dB in the airborne results and increases of up to 10 dB were obtained in
Measured data for a single concrete wall.

- Measured data for a double wall with cavity quilt.

- Measured data for a double wall with no cavity quilt.

Fig. 8.7 Measured airborne level differences for a single leaf concrete block wall and a dry lined double wall, with and without, acoustic quilt in the cavity.
Transmission from the ply to concrete wall with no quilt in the cavity.

Transmission from the concrete to the ply wall with no quilt in the cavity.

Transmission from the concrete to the ply wall with quilt in the cavity.

Fig. 8.8 Measured structural level difference between the leaves of a dry lined wall.
the structural data.

It is clear that changing the absorption in the cavity changed the performance of both the airborne and structure-borne results. This indicates that the cavity has to be modelled as a subsystem in any SEA model of the wall.

Predicted results

Three different methods were used to obtain predicted data for the dry lined wall. The theory presented by Cremer et al [14] and the expressions given by Sharp [3] are used to provide the first two predictions. The third prediction was produced using an SEA model, which allowed the behaviour of the wall to be studied in more detail than the classical techniques, enabling the important transmission paths to be identified.

Cremer's model

The behaviour of the structural data at high frequencies is similar to the behaviour that would be expected from Cremer's model for parallel plates [14]. The initial assumptions made in Cremer's parallel plate theory are that the cavity is filled with a fibre mat which has a flow resistance high enough to prevent lateral motion of the air. Cremer's model predicts that the addition of a light-weight plate to a heavy wall or floor results in an increase in attenuation above the MSM resonance for the system which rises at 12 dB per octave. This is similar to the results obtained for the test wall at high frequencies.

The measured improvement in the airborne level difference for the single concrete wall brought about by the addition of the ply wall is shown on Fig 8.9. This was obtained by subtracting the level difference for the single concrete wall from the data for the double wall. For both walls the level difference rises at about 12 dB per octave in the mid and high frequency region before levelling off at frequencies above 1 KHz. The first cross cavity resonance occurs in the 1.6 KHz band and this causes an increase in the coupling which results in the attenuation being reduced. This is the limit of validity for Cremer's model.
Fig. 8.9 Measured and predicted change in the airborne level difference of a single leaf concrete wall due to the addition of a dry lining.
Also shown on the figure is the predicted improvement that would be expected from Cremer's model for the addition of the plywood to the single concrete wall. This was obtained using eqn(2.73). The predicted curve has the same slope as the measured data but it is about 5 dB higher than the data for the wall with the added cavity absorption. The theory assumes that cavity absorption with a sufficiently high flow resistance is present to prevent the air from undergoing lateral motion and setting up standing waves. The cavity on the test wall was not filled with quilt. There was still a large amount of space unoccupied and it is possible that the addition of more quilt would have resulted in further improvements by further reducing standing waves.

Another possible explanation for the disagreement between the measured and predicted curves stems from one of the assumptions made in the model. The prediction assumes that the plates are infinite so that a reverberant field does not occur on the structures. The finite size of the plywood wall however, would result in a reverberant field. It is not known then whether the 5 dB shortfall was due to this limitation of the model or whether it could be attained by the addition of more absorption to the cavity.

By adding the predicted improvement (due to the addition of the plywood wall) to the predicted curve for the airborne level difference of the single concrete wall it is possible to obtain a predicted level difference for the double wall. This is shown in Fig 8.10. Since cross cavity resonances are not accounted for, the agreement at high frequencies is poor. However, at low frequencies where no resonances occur, the agreement is reasonable. In the mid frequencies a fortunate combination of the predicted level difference for the single wall being underestimated in the region of the critical frequency was combined with the 5 dB overestimate in the predicted improvement due to adding the plywood wall to produce a region where the agreement with the measured data appears to be good. Had the prediction for the single wall not underestimated the walls performance at critical frequency, the agreement between the data on Fig 8.10 would not have been as good. Part of the reason for the poor agreement is that this model does not include any non-resonant paths, from the rooms to the cavity and it requires that the cavity possesses high damping. Whilst this model is fairly successful at predicting the change in performance that can be expected from the addition of a dry lining to a wall for a
Fig. 8.10  Predicted airborne level difference of a dry lined wall from Cremer's [14] parallel plate theory.
structural excitation source, it does not work well for airborne sources. This is because non-resonant transmission to and from the cavity is not accounted for.

**Sharp's model**

A simplified theory has been suggested by Sharp [3] which predicts the behaviour of a double wall from a knowledge of the performance of its individual leaves. If it is assumed that the cavity is heavily damped, the behaviour of the wall can be divided into three frequency regions. The first region is below the MSM resonance frequency where the wall is assumed to behave as a single wall with a mass and bending stiffness equal to the sum of the individual wall values. Between the MSM resonance and the first cross cavity resonance the transmission loss, $D$, is given by,

$$D = TL_1 + TL_2 + 20 \log(f) - 29$$

(8.1)

where $TL_1$ and $TL_2$ are the transmission losses of the individual leaves and $l$ is the cavity width. The final region is above the frequency of the first cross cavity resonance where the transmission loss is given by,

$$D = TL_1 + TL_2 + 6$$

(8.2)

Fig 8.11 shows a comparison between the measured data and a curve obtained using the predicted level differences for the single walls in the above equations. The agreement is reasonable, with the predicted curve lying between the two measured curves over most of the frequency range. The overestimate of the dip at critical frequency in the predicted curve for the single wall is responsible for most of the poor agreement. If the measured values for the level difference are used in place of the predicted values in the above equations, the agreement with the data for the double wall with added cavity absorption is much better. This is shown on Fig 8.12. The agreement is good over most of the frequency range except above 1 KHz where
Predicted level difference.

Measured level difference with quilt in the cavity.

Measured level difference without quilt in the cavity.

Fig. 8.11 Measured and predicted airborne level difference for a dry lined wall using Sharp's [3] equations and predicted single wall results.
Fig. 8.12 Measured and predicted airborne level difference for a dry lined wall using Sharp's [3] equations and measured single wall results.
the predicted curve overestimates the measured data by about 4 dB.

This theory is capable of providing predicted data that shows good agreement with measured results, provided the cavity is sufficiently absorbent. However, it does not predict how the performance of the wall changes as the amount of absorption in the cavity is reduced from a high level to a low level.

**SEA model**

One of the greatest disadvantages with the above expressions is that they are unable to predict the change in performance due to absorption. In addition, however, they do not provide any information about the behaviour of the structural level difference, they are not written in a form that can be used in a general SEA model and they cannot be expanded to include other forms of coupling.

A prediction was made using the five subsystem SEA model of the double wall shown in Fig 8.13. In addition to the subsystems that formed the direct path between the source and receiving room, the walls ceiling and floor slab that were coupled to the core wall were also included. These subsystems are shown in bold in Fig 8.2.

For this model there are four important transmission paths. The first is the non-resonant path from the source room to the receiving room via the cavity, path 1-[2]-5-[3]-4. The form of notation used in chapter 1 is used here where [] denotes that the transmission is non-resonant, passing through the structure that the subsystem represents but not via the resonant modes. The second is the resonant path which involves radiation from the core wall into the cavity which then excites the ply wall, path 1-2-5-3-4. The third path, 1-2-[5]-3-4, is via the "airtie" (described in chapter 2) which directly couples the two leaves of the wall.

It should be noted that the choice as to which is the source and which is the receiving subsystem in a path is to a certain extent arbitrary and does not affect the path's performance ie the transmission loss for path 1-2-3-4 will equal the transmission loss of path 4-3-2-1.
Fig. 8.13  SEA model for a dry lined wall with no structural sound bridges.
Modelling the behaviour of the cavity is difficult because of its small width compared with its length and height. At high frequencies, where cross cavity modes occur, it is possible to model it as a normal room using the expressions for wall/room coupling given in chapter 2. For most cavities, however, the room-like behaviour only occurs at high frequencies, so for much of the frequency range of interest only axial and tangential modes are present. Under these circumstances modelling the cavity as a room is inappropriate. Price and Crocker [20] produced expressions for resonant and non-resonant transmission, to and from the cavity, at frequencies below the first cross cavity resonance. These are given in chapter 2.

The coupling between the leaves of the test wall due to the stiffness of the air in the cavity was initially modelled as an "airtie" using eqn(2.76). The air was modelled as a single tie with a stiffness obtained using eqn(2.74) multiplied by the area of the test wall. The bulk modulus of the air was assumed to be $1.4 \times 10^5$ N/m$^2$, the cavity width was 0.1 m and the surface area of the wall was 12 m$^2$. In addition to using the predicted "airtie", the measured CLF for transmission from the core wall to the dry lining was used to give two results for a measured "airtie"; one with and one without quilt present in the cavity. This was done to examine the airborne performance of the wall with the correct structural coupling.

The TLF for the structure of the test chamber was assumed to be given by eqn(2.91). The sum of the CLFs plus an ILF of 0.008 was used for the TLF of the core wall. The ply leaf was assumed to have a TLF equal to the sum of the CLFs and an ILF of 0.03.

The cavity damping could not be predicted accurately. Price and Crocker tested double walls which had absorbent material distributed around the cavity perimeter and in their theory they assumed that only absorption distributed in this location contributed to the cavity damping. Their expressions for calculating the damping are, therefore, based on the value of absorption coefficient for the damping material placed there. For the test wall the absorption was distributed differently, the bulk of it being due to the concrete blocks of the core wall or the quilt that was fixed over it's surface.
Measured values of absorption for the concrete blockwork and for the glass fibre quilt were used in eqn(2.90) to determine the TLF below the first cross resonance. Above this frequency, eqn(2.88) was used. For the wall without the quilt, the absorption of the blockwork was assumed to be effective only around the cavity reveal which had an area of 1.4 m$^2$. For the wall with the quilt present, the whole area of the quilt, 12 m$^2$, was assumed to be effective in providing damping because it protruded into the cavity.

Attempts were made to measure the reverberation time in the cavity but the decay curves were unreliable. As a result there is no data for comparison with the predicted results. Measured data is only available for the double masonry wall. The measurement technique was subsequently refined and measured data was obtained for the masonry cavity walls described in chapters 4, 5 and 6.

The measured value of the reverberation time was used to obtain the TLF for the receiving room.

**SEA results**

Fig 8.14 shows the measured and predicted structural level difference curves for transmission via the predicted "airtie" from the core to the plywood leaf of the wall, path 2-[5]-3. The predicted curve is up to 13 dB higher than the measured data at low frequencies. The agreement in the high frequency region is also poor. The resulting airborne level difference for this path, 1-2-[5]-3-4 is shown in Fig 8.15. It is, at it's best, 10 dB higher than the measured data for the wall with absorption in the cavity.

Instead of using predicted values for the "airtie", the energy level difference between the core wall and lining, measured using a plastic-headed hammer as a power input, was used to work backwards to determine what the actual value of "airtie" coupling must have been, in order to give the correct structural results.

The predicted airborne data for path 1-2-[5]-3-4 obtained using the measured "airtie" is also shown in Fig 8.15. The predicted curves are around 20 dB higher than the measured data. However, they do share some of the characteristics of the measured
Fig. 8.14  Predicted structural level difference using an "airtie".
Fig. 8.15  Predicted airborne level difference using a predicted and a measured "airtie".
results. They show a rise in level difference with the addition of the quilt to the cavity but the increase is less than for the measured data. They also show the same convergence at low frequencies that was obtained for the measured data. The predictions for transmission via the "airtie" path show that even if the structural level difference is predicted correctly, there are other paths which are more important in determining the airborne transmission.

Fig 8.16 shows the predicted structural level differences for the resonant path across the cavity in which the core wall radiates into the cavity, excites the modes in the cavity which in turn excite the plywood. At low frequencies the predicted level difference results are much higher than the measured data and at high frequencies they are lower than the measured data. The improvement in wall performance brought about by the increased cavity absorption is also over-predicted. This suggests, at least for the high frequency data, that the predicted coupling between the leaves of the wall and the cavity is not correct, Price and Crocker’s expression overestimating it’s strength.

The predicted airborne level differences of three transmission paths through the wall are shown in Fig 8.17. One is the resonant path, 1-2-5-3-4, from the source room through the core wall to the cavity and then through the ply wall to the receiving room. The second is the non-resonant path into and out of the cavity, path 1-[2]-5-[3]-4. The final path, 1-2-5-[3]-4, is for resonant transmission through the core wall into the cavity and then non-resonant transmission through the lining into the receiving room. Also shown is the sum of all the paths. It can be seen that the resonant path is unimportant except at the critical frequency of the dry lining where it forms the dominant path, although a dip as deep as this would probably not be measured for a real wall. It occurs because eqn(2.29) overestimates the radiation efficiency at critical frequency. This problem is examined further in chapter 10. It can also be seen that the non-resonant path, 1-[2]-5-[3]-4, from the source room to the receiving room via the cavity, is unimportant. The final path in Fig 8.17, 1-2-5-[3]-4, which involves resonant transmission from the core wall into the cavity and then non-resonant transmission from the cavity to the receiving room, is the path that is largely responsible for the predicted transmission of sound through this wall.
Fig. 8.16 Predicted structural level difference for the resonant path across the cavity of a dry lined wall.
Fig. 8.17 The airborne level difference of the important paths across a dry lined wall with no quilt in the cavity.
The predicted airborne performance of the wall with all the transmission paths included is shown again on Fig 8.18 along with the measured results. The measured "airtie" CLFs were used in the prediction because of the poor agreement that was obtained when the predicted "airtie" was used. This is not, however, an important transmission path for airborne sound and has no significant effect on the prediction. Above the critical frequency of the core wall the agreement between the measured and predicted curves is good. Below the critical frequency of the core wall the agreement is not as good, the predictions being between 10 and 15 dB higher than the measured level differences. Part of the discrepancy at low frequencies can be accounted for by the incorrect modelling of the wall below the MSM frequency (93 Hz). Below this frequency it is incorrect to model it as two separate subsystems and a single subsystem representation would be more correct. For the dry lined wall tested, the core wall was much stiffer and heavier than the dry lining, and the overall behaviour of the wall would be almost identical to that of the core wall. The low frequency part of the predicted level difference for the core wall is also plotted in Fig 8.18 and shows reasonable agreement with the measured data in this region.

Discussion

The performance of this test wall is significantly different from that of the walls tested in chapter 4, where both leaves were of concrete. The behaviour of the cavity was found to be important in determining the overall behaviour of the wall and increasing the absorption and hence the damping of this part of the construction resulted in significant changes in the performance of the wall.

The measured and predicted structural data for this wall showed poor agreement. Two paths exist, one involving resonant transmission into the cavity, path 2-5-3, modelled using Price and Crocker's [20] expressions and one due to the stiffness of the air, path 2-[5]-3, modelled using an "airtie". The poor agreement that was obtained at low frequencies was probably caused by the MSM resonance. This is predicted at 93 Hz and it is likely that in this frequency region, the level difference would exhibit a dip, in the same manner as the results for the masonry walls in chapters 5 and 6. As this mechanism is not included in the model, the predictions in this frequency region would be expected to be higher than the measured results. At high frequencies the
Predicted level difference for the wall with quilt in the cavity.
Predicted level difference for the wall without quilt in the cavity.
Measured level difference for the wall with quilt in the cavity.
Measured level difference for the wall without quilt in the cavity.
Predicted level difference for the core wall.

Fig. 8.18 Measured and predicted airborne level difference of a dry lined wall with no ties or battens.
predicted structural level difference obtained using the predicted "airtie", overestimated the strength of transmission. Behaviour of this nature was observed in the results for masonry cavity walls in chapter 4, at frequencies below the critical frequency of the test wall. It was suggested that the hydrodynamic short circuit that occurs on the surface of the wall might have reduced the stiffness of the air in the cavity, leading to lower transmission. For the dry lined wall the critical frequency of the plywood leaf was 3507 Hz. This means that the entire range of frequencies where data was gathered lay below the critical frequency. It is probable therefore that the actual stiffness of the air was lower than predicted, hence the overestimate of the transmission made by the "airtie" prediction.

In order to model the coupling between the two leaves of the wall correctly it proved necessary to use a measured value of cavity coupling. This path, however, was found to be unimportant in determining the airborne performance of the wall. This is because of the high critical frequency of the dry lining which means that it is a poor radiator of sound over a wide range of frequencies.

At low frequencies, the two leaves of the wall act as one and the airborne transmission is determined by the performance of the core wall. At high frequencies, the dominant path, path 1-2-5-[3]-4, involves resonant transmission from the core wall into the cavity followed by non-resonant transmission through lining (for transmission in the direction that the tests were made). This is similar to Sharp's results where the same paths dominate transmission through the core wall and lining when they are tested separately. Sharp then added the values for TL to give the total performance of these walls when they were tested together as a double wall. Had Sharp modelled the cavity in his theory and used level differences rather than the transmission losses of the two leaves of the wall, predicting the change in the wall's behaviour with changing cavity absorption would have been possible.

8.5 Dry lined wall with point connections

This section describes tests carried out on a dry lined wall with wall ties connecting
the core wall to the dry lining.

**Test wall**

To examine the effect of point connections on the performance of the test wall, ties were inserted into the dry lined wall described at the beginning of this chapter. Fig 8.19 shows how the ties were fixed into the wall. The ties were similar to the remedial wall ties used in the wall described in chapter 5. The expanding bolt mechanism from a remedial tie was fixed to the end of a length of M6 threaded rod. A 10 mm diameter hole was drilled through the plywood panel and through this a 10 mm diameter hole was drilled into the concrete wall. The tie was inserted through the plywood into the block wall and secured with the expanding bolt. This left the end of the rod protruding through the plywood panel. An aluminum plate was screwed onto the rod until it just came into contact with the face of the plywood leaf. It was secured between two nuts and four small wood screws were used to fix it to the plywood. Mastic was gunned around the edge of the plate to seal any possible gaps.

**SEA model**

The predictions for this wall were made using the five subsystem model shown in Fig 8.20. This model is identical to the one used to make the predictions for the dry lined wall with no sound bridges except for the addition of two extra paths to account for the presence of the wall ties. The first extra path results from the direct coupling that takes place between the core wall and the dry lining via the tie, path 2-[tie]-3. The CLF for this path was obtained using eqn(2.60) where the ties were assumed to have a stiffness of $30 \times 10^6$ N/m. In addition the core wall was assumed to be coupled to the receiving room as a result of nearfield radiation that occurs from the dry lining in the vicinity of the tie, giving rise to path 2-[3]-4. Eqn(2.85) was used to determine the CLF for this path.

**Results**

Structural and airborne level differences were measured first with no added absorption present in the cavity. Initial tests were performed with one tie, the number of ties was then doubled until eight ties were present giving results for 1, 2, 4, and 8 ties. Absorption was then added to the cavity and the measurement procedure was...
Fig. 8.19 The method for fixing wall ties to the dry lined wall.
Non-resonant path from source room to receiving room

Non-resonant path from source room to cavity
Non-resonant path from cavity to receiving room

Source Room. Subsystem 1.
Core Wall. Subsystem 2.
Cavity. Subsystem 5.
Dry lining. Subsystem 3.
Receiving Room. Subsystem 4.

"Airtie" and tie/batten coupling.

Nearfield radiation.

Fig. 8.20  The SEA model for a dry lined wall with ties or battens.
Fig 8.21 shows the measured structural level difference for transmission from the core wall to the dry lining. Also plotted, for comparative purposes, are the curves for the wall with no ties measured with and without added cavity absorption. At low frequencies the ties had little effect on the level difference and the added absorption made little difference to the results. At high frequencies the addition of the ties reduces the level difference. The effect was largest for the addition of the first tie and the addition of subsequent ties resulted in a 3 dB drop in level difference each time their number was doubled.

Adding quilt to the cavity made little difference to the results at low frequencies and resulted in a small increase in the level difference between 250 and 500 Hz. The predicted critical frequency of the core wall (297 Hz) occurs in this region and at these frequencies the wall radiates more sound into the cavity which in turn excites the lining. This path for transmission between the two leaves, path 2-5-3, is affected by the damping in the cavity and may account for the observed results in this region.

The measured and predicted structural level difference data is shown in Fig 8.22. The measured data is for the wall with added cavity absorption except for the curve for the wall with eight ties. This wall was not tested with extra absorption, however, as the damping had little effect on the measured data at high and low frequencies, any error associated with assuming that the cavity was damped should be small and limited to the region around the critical frequency of the core wall. The good agreement between the measured and predicted data at low frequencies resulted from the use of the measured "airtie". At the higher frequencies the path via the steel ties becomes more important and the level difference predicted using the CLF, given by eqn(2.60), shows reasonable agreement with the measured data. The poor agreement between the measured and predicted curves for the wall with eight ties between 160 Hz and 400 Hz is probably caused by the low damping of the cavity in the test wall.

The measured airborne level difference data is shown on Fig 8.23. For the wall with no quilt in the cavity, the results for 0, 1, 2, 4, and 8 ties are all identical. Therefore
Fig. 8.21  The effect of adding wall ties on measured structural level difference for transmission from the core wall to the dry lining of a dry lined wall.
Fig. 8.22 Measured and predicted structural level difference for transmission from the core wall to the dry lining of a dry lined wall with wall ties and quilt in the cavity.
Fig. 8.23 The effect of adding wall ties on the measured airborne level difference of a dry lined wall.
only one curve (the results for the wall with no ties) has been used to represent this data on the figure. Adding absorption to the cavity reduces the strength of the transmission paths via the air in the cavity. Despite this, however, the air is still the dominant transmission mechanism, the metal ties only starting to affect the wall’s performance at high frequencies.

Fig 8.24 shows the measured and predicted airborne level difference data for the wall with added cavity absorption. Above the critical frequency of the core wall (297 Hz) the agreement between the measured and predicted data is good. Non-resonant transmission from the cavity dominates transmission, the nearfield radiation from the dry lined wall at the tie locations becoming important only for higher numbers of ties at higher frequencies. Below the critical frequency of the core wall agreement is poor, however, as with the prediction for this wall with no ties part of this stems from modelling the wall incorrectly below MSM frequency. The predicted level difference for the core wall gives a good estimate of the double wall performance at these frequencies. This curve is shown at low frequencies and gives reasonable agreement with the measured data. There is however a small frequency region, between 100 Hz and 250 Hz (above the MSM resonance and below the critical frequency), where agreement remains poor.

**Discussion**

Significant drops in structural level difference between these two leaves of the wall were obtained upon adding the ties. However, these were not reflected in the airborne level difference results. It was only when the damping of the cavity was increased significantly, by the addition of the quilt, that the small effects of the ties became apparent in the airborne data. These effects were minor and were only observed at high frequencies when the ties were present in sufficient numbers. The dominant path for airborne transmission through this wall was the same as the one for the wall with no ties, path 1-2-5-[3]-4; resonant transmission into the cavity from the core wall and then non-resonant transmission from the cavity to the receiving room. The airborne results are not affected by the transmission path between the two leaves of the double wall, either through the air or through the metal ties. The slight drop in the airborne level difference arising from the addition of the ties was caused by nearfield radiation
Sound pressure level difference (dB).

Frequency (Hz).

- × - Measured data for one tie.
- • - Measured data for two ties.
- + - Measured data for four ties.
- ⬤ - Measured data for core wall.
- × - Predicted data for one tie.
- ⬤ - Predicted data for two ties.
- + - Predicted data for four ties.
- ⬤ - Predicted data for core wall.

Fig. 8.24 Measured and predicted airborne level difference for a dry lined wall, with wall ties and quilt in the cavity.
from the area around the ties on the dry lining.

8.6 Dry lined wall with line connections

Line connections between the leaves of a double wall result in a large departure from the behaviour of an equivalent wall without connections. For dry lined walls it is common to fix the lining to the structural wall using battens. The typical sheet size of the material used in dry lining is approximately 2.4 x 1.2 m. This is fixed around its perimeter and usually along its centre to the battens. The resulting length of the line connection per sheet of dry lining is therefore 12 m and it is apparent that this would have a detrimental affect on the sound insulation of such a double wall.

Test wall
To examine the effect of line connections on the dry lined test wall the ties were removed and the holes, made in the plywood wall during the insertion of the ties, were patched. The plywood wall was then removed from its frame and a timber batten was fixed to the concrete wall. As a result of the width of the cavity, the batten had to be quite substantial, it had a cross section of 0.1 x 0.05 m and was 2.0 m long. It was fixed to the core wall using four large bolts and the gap between the batten and the wall, which arose out of the slight irregularities in the blockwork, was pointed with grout. The plywood wall was then replaced in its frame and fixed and sealed around its perimeter. Small screws at 30 mm centres were used to fix through the plywood into the batten. After the measurements had been performed, the plywood was removed and extra battens were added so that measurements were performed on the wall with one batten, two battens and with four battens. All the battens were 2 m long.

SEA model
Predictions were made using an SEA model identical to the one shown in Fig 8.20. The resonant and non-resonant paths to and from the cavity were identical to those in the model for this wall with no structural sound bridges. The measured "airtie" for the wall with no added cavity absorption was used to account for the coupling
between the two leaves of the test wall due the stiffness of the air in the cavity. The CLF for transmission across the battens was calculated using eqn(2.71) where the measured cross section and length of the battens were used along with the measured Young's modulus (equal to $10^{10}$ N/m²) to calculate the stiffness of the batten. The error in using this simple expression rather than the exact theory presented in chapter 7 is very small, the exact solution predicting coupling that is 1 dB stronger than the impedance model. Eqn(2.87) was used to calculate the CLF for nearfield radiation from the dry lining around the vicinity of the battens. The CLF for resonant transmission from the dry lining to the receiving room was adjusted to account for the increased boundary length caused by the addition of the battens. Every time a batten was added, the boundary length was increased by 4 m. The value for the cavity TLF was based on the area and absorption of the cavity reveal.

Results

Structural and airborne level difference measurements were performed on the wall with no absorption present in the cavity. The measurements on the wall with four battens were repeated with extra cavity absorption.

Fig 8.25 shows the measured structural level difference obtained for the wall with 0, 1, 2 and 4 battens, for transmission from the core wall to the dry lining. The addition of the battens resulted in drops in level difference of up to 40 dB in the frequency range above 315 Hz. Below 400 Hz the addition of one batten resulted in a drop of about 3 dB and subsequent additions caused further slight drops. This differs from the results that were obtained for the wall with ties, where no significant change in level difference occurred in the low frequency region until the ties were present in large numbers. This is because the coupling through the battens is stronger than that through the ties. Doubling the number of battens changes the level difference by about 3 dB at the mid and high frequencies.

The effect of adding absorption to the cavity on the data for the wall with four battens is shown on Fig 8.26. As expected from the SEA model, increasing the damping of the cavity has little effect on the structural level difference. The structural path across the cavity dominates transmission and this is unaffected by the cavity damping.
Fig. 8.25  Structural level difference for transmission from the core wall to the dry lining of a dry lined wall with battens and no quilt in the cavity.
Fig. 8.26 The effect of cavity damping on the structural level difference of a dry lined wall for transmission from the core wall to the dry lining.
Fig 8.27 shows the predicted and measured structural data for the wall. The use of the measured "airtie" ensured that the agreement below 315 Hz was reasonable. Above this frequency, where the battens form the dominant transmission path, the predicted results are about 3 dB higher than the measured data. Using the more accurate model in chapter 7 would have resulted in slightly improved agreement, the difference between this and the measured data, however, would still have been a constant 2 dB.

The airborne level differences are shown on Fig 8.28 for the wall with 0, 1, 2 and 4 battens. At frequencies above 400 Hz, the addition of the battens results in a drop in the level difference which increases as the number of battens increases. Below 400 Hz where the structural data shows that the battens caused a drop in the level difference, the airborne data shows little change. Adding the battens appears to have caused small improvements at some frequencies.

Fig 8.29 shows the airborne data for the wall with four battens with and without added cavity absorption. Increasing the damping of the cavity resulted in little change to the data immediately above 400 Hz, as for this wall the dominant mechanism is due to the battens. Above 1 KHz the absorption produces an increase of about 3 dB. Below 400 Hz adding the quilt produced a rise in level difference and the results are almost identical to those for the wall with quilt and no battens. At these frequencies the dominant path is the non-resonant path from the cavity which is affected by the damping but not the number of battens.

The measured and predicted airborne level differences are shown in Fig 8.30. Above the critical frequency of the core wall the agreement between the measured and predicted curves is reasonable. Below the MSM resonance it is more correct to model the wall as a single subsystem and for this model the performance would be similar to that of the core wall. The prediction for the core wall is shown at low frequencies and gives reasonable agreement with the measured data.

Discussion
The battens provided a transmission path across the cavity which was much stronger
Fig. 8.27  Measured and predicted structural level difference for transmission from the core wall to the dry lining of a dry lined wall with battens.
Fig. 8.28 Airborne level difference for a dry lined wall with battens and no quilt in the cavity.
Wall with no battens and quilt.
Wall with no battens and no quilt.
Wall with four battens and no quilt.
Wall with four battens and quilt.

Fig. 8.29 The effect of cavity damping on the airborne level difference of a dry lined wall with battens.
Fig. 8.30  Measured and predicted airborne level difference for a dry lined wall with battens and no quilt in the cavity.
than the path across the ties which was examined in the previous section. This resulted in much larger drops in the structural level difference than were observed in the data for the ties and it also produced effects which were observed in the airborne data. The predicted results for structural transmission were about 3 dB higher than the measured data, however, the prediction was based on an impedance model which was used to determine the coupling across the batten. Unlike the point connection where this type of approach is suitable for waves incident on the junction at any angle of incidence in the case of a line connection the solution is only correct for normally incident waves. The error was not large, however, the coupling from the exact model being 1 dB stronger.

The line connection also resulted in a greater nearfield contribution from the region of the batten on the plywood wall. At high frequencies this was a stronger path than the radiation of sound from the resonant modes of plywood wall and non-resonant transmission from the cavity.

8.7 Discussion

In buildings there are several forms of construction that will exhibit the same type of behaviour as the wall examined in this chapter. The most common are masonry walls finished with plasterboard fixed on plaster dabs, masonry walls finished with plasterboard fixed onto timber battens, independent plasterboard partitions and concrete floors that have a timber or chipboard walking surface. They are characterised by the large difference between the properties of the two leaves and they have a cavity between them. The discussion of the performance here is limited to direct transmission, the effects of flanking are mentioned at the end.

Plasterboard on dabs
A common method of finishing walls is to fix sheets of plasterboard onto the surface of the wall using dabs or ribbons of adhesive plaster. These fix the sheets along lines or at discrete points leaving a cavity behind. For this type of construction the cavity is very narrow, in the order millimetres. The stiffness of the air it contains will
therefore be very high resulting in a high MSM resonance frequency which will fall within the building acoustics range of frequencies and could cause annoyance. Below the resonance, the behaviour is the same as a single wall so, for a large range of frequencies, the wall behaves as if it was hard plastered. In addition to it’s effect on the MSM resonance, the narrow width of the cavity also means that it is doubtful whether a reverberant sound field could be set up in it. This would have the effect of reducing the strength of path 1-2-5-[3]-4 or precluding it altogether.

The stiffness of the cavity means that the "airtie" coupling would be expected to be strong, however, for airborne transmission, the results from the test wall showed that this mechanism was unimportant. In addition, the possible reduction of the cavity stiffness by the hydrodynamic short circuit which occurs over most of the frequencies of interest would further serve to lessen it’s importance. At frequencies above the MSM resonance, the dominant transmission mechanism is likely to be nearfield radiation from the plasterboard in the vicinity of the plaster dabs. As there are many of these, transmission would be strong.

**Plasterboard on battens**

This is an alternative technique for fixing plasterboard to walls. Strips of timber are nailed onto the masonry wall and sheets of plasterboard are then fixed to these. This again results in a cavity being formed behind the plasterboard but it is a little wider than the cavity behind plasterboard on dabs. The typical cavity width will be about 1.5 cm. For this form of construction the air in the cavity will still be quite stiff and the MSM frequency could still cause strong transmission within the building acoustics frequency range. There will therefore be a region where the wall behaves as if it were hard plasterboard. As with the plasterboard on dabs the "airtie" path is unlikely to be important. As the cavity is wider in this form of construction, it is possible that some resonant behaviour may occur in the cavity and transmission will occur via path 4-[3]-5-2-1. However, as with the wall with plasterboard on dabs, the dominant transmission path will be due to nearfield radiation from the plasterboard in the vicinity of the battens. These are very stiff and each sheet of plasterboard is normally fixed to about 12 m of battens.
Independent partitions

Independent partitions are similar to a wall with plasterboard on battens except that the plasterboard lining is fixed to a frame that is built independently of the masonry wall. This results in a wide cavity being formed but without any structural connections between the two leaves. The stiffness of the air in the cavity will be relatively low due to the increased cavity width. The MSM resonance will therefore occur at a low frequency, limiting single wall behaviour to a small range of frequencies. The low stiffness of the cavity also means that the "airtie" path will not be important.

Fixing the plasterboard to an independent framework means that there is no structural transmission between the leaves of the wall and hence no nearfield transmission via the dry lining. From all the potentially important paths identified in this chapter, only path 1-2-5-[3]-4 exists for this form of construction. It is common to place absorbent quilt in the cavity of this type of wall and provided sufficient is present, this path, though dominant, will be minimised.

Concrete Floors

Concrete floors often have a timber walking surface made from planking or more commonly from sheets of chipboard. These are normally laid on battens so that they can be nailed in place. To improve the performance of the floor if it separates two dwellings, it is usual to place resilient material between the underside of the batten and the concrete floor. Analysing the behaviour of floors is a little more complicated than for walls. Not only do airborne transmission paths have to be considered but the effect of people walking on the floor also gives rise to structural transmission.

The width of the cavity in a floor is greater than for plasterboard walls. The stiffness of the air in the cavity be lower and the MSM resonance frequency tends to occur at the lower end of the building acoustics frequency range. There is therefore only a small region where the floor behaves as a single subsystem. What can affect this, however, is the material used to provide the resilient support under the battens. This will be thinner than the cavity and as a result could have a high stiffness. This adds to the overall stiffness of the cavity and causes the frequency of the MSM resonance
to increase extending the single subsystem behaviour over a wider range of frequencies.

The primary role of the resilient layer is to reduce the strength of the structural path across the cavity to prevent annoyance to the occupants in the room below. The results from the test wall showed that for stiff line coupling across the cavity, the structural transmission was very strong. The inclusion of the resilient layer reduces the strength of this coupling and hence reduces the transmission.

In addition to improving the structural performance, the resilient layer might be expected to improve the airborne performance too. The results from the test wall showed that with battens present, transmission via the nearfield on the dry lining in the vicinity of the batten, path 1-2-[batten]-[3]-4, was found to dominate performance. The equation used to predict the performance of this mechanism assumes that the bridge is rigid. Cremer et al [14] gives the expression necessary to model a resilient bridge and this predicts that the transmission is reduced. Transmission via path 1-2-[batten]-[3]-4 would therefore be reduced.

Exactly how beneficial the resilient layer is depends upon the strength of the nearfield path (1-2-[batten]-[3]-4) relative to the path via the air in the cavity, path 1-2-5-[3]-4. The increased width of the cavity in this form of construction makes it more likely that a reverberant sound field will be set up and the potential for path 1-2-5-[3]-4 to be important is therefore greater for this form of construction than for a wall with plasterboard on battens or dabs. In addition, if the resilient layer reduces the strength of the structural path and the nearfield path by a large enough amount, the path through the cavity, path 1-2-5-[3]-4 will dominate the overall floor performance. However, provided the cavity contains sufficient absorption, transmission via this path can be minimised. The traditional technique for providing the resilient layer beneath the batten was to lay a glass fibre quilt over the top of the concrete floor before laying the battens and flooring. Not only did this provide the resilient layer, it also provided ample absorption in the cavity, tackling both the structural path and the airborne paths together. The disadvantage with this material is that it is friable and usually disintegrates in the region beneath the battens with the loss of it's isolating
A problem of this nature would be apparent from a comparison of the airborne and structural results for the wall made before and after the resilient material was introduced. The structural performance of path 2-[batten]-3, would show a marked improvement upon the addition of a suitable inter-layer. The airborne performance, whilst showing some improvement due to the weakening of the nearfield path through the batten, would be expected to show a smaller improvement than the structural paths. This is because the dominant path would change from the nearfield path 1-2-[batten]-[3]-4, to the non-resonant path through the cavity, path 1-2-5-[3]-4. The addition of extra absorption would then be required to reduce transmission via this path.

The effect of cavity absorption
Two distinct types of construction have been discussed in this section. These can be best characterised by the difference between their dominant transmission paths.

For plasterboard on dabs and on battens, the dominant transmission path involves structural transmission across the cavity. To increase the absorption in the cavity to reduce transmission via the path 1-2-5-[3]-4 would probably have a negligible effect on the overall performance.

For independent plasterboard partitions and concrete floors with a floating timber walking surface, the structural path is weak or non existent. For these forms of construction the cavity is wide enough to support a resonant sound field and the path 1-2-5-[3]-4 will be important. Increasing the absorption in the cavity is a convenient means of reducing transmission via this path. The results from the test wall showed that improvements of around 10 dB in the airborne performance could be obtained from the addition of absorption to a cavity that originally had very little. This agrees with the findings of Utley, Cummings and Parbrook [40] and Lee [24]. The affect of the location of the absorption within the cavity was not investigated however, this is an area where there is very little consensus in the literature.
Flanking transmission

At the beginning of this section it was stated that only direct transmission would be examined as to discuss the effects of flanking paths requires a knowledge of the form that the rest of the building takes. In general, however, for walls finished with plasterboard on dabs or on battens, it is likely that the direct path through the wall would be more important relative to the flanking paths than for floating floor or independent partitions.

8.8 Conclusions

The two leaves of the dry lined wall studied in this chapter had different physical properties. This resulted in the dominant mechanism of transmission through each leaf, when tested individually, being different at the frequencies of interest. For the core wall, which had a relatively low critical frequency, resonant transmission dominated and for the dry lining, which had a higher critical frequency, non-resonant transmission dominated. When tested together as a double wall this behaviour determined the dominant transmission path through the wall. This consisted of resonant transmission from the core wall to the cavity and then non-resonant transmission from the cavity to the receiving room, passing the dry lining.

The strong non-resonant transmission from the cavity to the receiving room means that changes in the construction, eg the addition of wall ties, which can have a significant effect on structural transmission between the leaves of the wall may not have a noticeable affect on the airborne level difference. This also means that transmission via the "airtie" is not important for this wall.

Modelling the dry lined wall is therefore different from modelling a masonry cavity wall. The walls tested in earlier chapters consisted of two leaves of dense masonry. For these walls, paths via the cavity are unimportant and it is not necessary to model the cavity when predicting their performance. For the dry lined wall it is necessary to include the cavity in the SEA model. One of the ways in which transmission can be reduced is to increase the damping of the subsystems that form the important
transmission paths. For a cavity the addition of an acoustic quilt is a convenient way to increase the damping and this was found to be an effective means of reducing transmission.

For the walls with ties and battens a new path is created, caused by nearfield radiation from the dry lining in the vicinity of the sound bridges. This path is independent of the cavity and affects airborne transmission. For the wall with ties this path was only important when the cavity damping was high but for the wall with battens the path is stronger and it is not necessary to increase the cavity damping to observe its effects.
Chapter 9
Direct power flow techniques

9.1 Introduction

The direct measurement of power flow provides a useful alternative to the method used in previous chapters, for studying the behaviour of structural joints. In these measurements the power flow was determined indirectly from the distribution of energy amongst the subsystems that form a structural joint. To do this it is necessary to know the structural damping of the subsystems and it is here that problems can be encountered. The most common method for determining the structural damping is to measure the decay of power in a subsystem after it has been excited. There are, however, occasions where it is not possible to measure the damping using this method and this leads to uncertainty in the measured power distribution amongst the subsystems in the joint. The direct measurement of power flow does not require any knowledge of structural damping and can prove useful in cases where there is uncertainty in the results obtained using the energy method.

Another area where power flow methods are useful is in distinguishing between the contributions from different transmission paths. The indirect method can only measure the sum of power flow from all paths. Although experiments can be designed so that the strength of the path under examination is dominant, this is not always convenient and in the case of real structures, it is not possible. Direct power flow methods allow the relative contribution of a single transmission path to be measured in the presence of power flow from other paths.

Two power flow techniques are investigated in this chapter. The first technique measures the power flow across wall ties using a method similar to that used in an
impedance head. The second technique is a two accelerometer method for measuring structural intensity. A brief description of the theory behind the techniques is given and the results from measurements performed on a model designed to verify that they worked, are presented. The results from measurements performed on the test walls using the power flow techniques are then described. The measurements made using the instrumented tie are described first. The results from the measurements made using intensity techniques are described at the end of the section.

9.2 Theory for measuring power flow across wall ties

If a point force excites a structure and the force, \( F \), and the velocity, \( v \), are known it is possible to measure the power flow, \( W \). It is given by the real part of the product of the force and the complex conjugate of the velocity [14],

\[
W = \text{Re}(Fv^*)
\]

(9.1)

where the \( * \) represents the complex conjugate.

If a force transducer and an accelerometer are used to measure the force and the acceleration, their time varying outputs, \( F(t) \) and \( a(t) \), can be used to obtain the power spectrum using a dual channel FFT analyser. The signal processing for the measurement is given by Verheij [41] as,

\[
\langle W \rangle_{\tau} = \frac{\text{Im} \ G(F, a)}{\omega}
\]

(9.2)

where \( \langle \rangle_{\tau} \) represents the time average of the power and \( \text{Im} \) represents the imaginary part of the complex quantity \( G \), the cross spectrum function between the force and the acceleration.
This technique for measuring power flow across ties is similar to the one used by Fahy and Pierri [42], who used an impedance head to measure the power flow across steel studs that coupled parallel steel plates. Initially they attempted to measure the power using a combination of a force transducer mounted on one of the ties and an accelerometer on one of the plates close to the tie. They encountered problems, however, and found that the results were sensitive to the tightness of the tie. Their solution was to modify one of the ties to accept an impedance head which they used successfully to measure the power flowing across the tie. The disadvantage with this method is that the tie has to be shortened to accept the impedance head and as a result it’s stiffness may change.

To measure the power flow across a cavity wall, a special tie was built which was instrumented with a force transducer and an accelerometer mounted very close to each other. Using a force transducer removes the necessity to reduce the length of the tie and by mounting the accelerometer directly onto the tie it was hoped that the problems encountered by Fahy and Pierri would not be repeated. The tie is shown on Fig 9.1. It consists of a length of M6 threaded rod onto which the expansion bolts from a remedial wall tie were fixed. This part formed the basic tie, across which the power flowed. The transducers were mounted between the two expanding bolt mechanisms. The force transducer was pre-loaded by tightening it between two nuts. A large brass disc with a threaded hole at it’s centre was used as a back nut and a thick brass washer and an M6 nut were used to pre-load the transducer. A small accelerometer was stud-mounted to the back nut as close to the centre of the tie as was possible.

Before assembling the tie, the accelerometer and the force transducer were calibrated using the procedures described earlier in chapter 3.

9.3 Theory for structural intensity

Structural intensity was measured using the technique proposed by Rasmussen and Rasmussen [43]. This combines the theory given by Noiseux [44] with a finite
Fig. 9.1  The instrumented wall tie.
difference method of measurement proposed by Pavic [45]. The technique, shown in Fig 9.2, uses two accelerometers mounted side by side on the test object, separated by a small distance, $\Delta$. The output from the accelerometers, $a_1$ and $a_2$ are fed via charge amplifiers into a dual channel FFT analyser. Using the expression given by Rasmussen and Rasmussen, the intensity, $I$, is given by Verheij [41] as,

$$\langle I \rangle_c = 2 \frac{\sqrt{Bp_s}}{\Delta} \frac{\text{Im} \ G(a_2, a_1)}{\omega^2}$$

where $B$ is the bending stiffness per unit width for the plate and $\rho_s$ is the mass per unit area.

There are several sources of error associated with this measurement technique. These fall into two main groups, limitations in the theory and errors associated with the finite difference method.

Thin plate bending wave theory was used to arrive at the expression for the intensity and this is only accurate to within 10% at frequencies below the frequency where the bending wavelength equals six times the plate thickness [14]. At this frequency the difference between the power flow predicted by the thin plate theory and the more accurate thick plate theory is around 1 dB [17]. The theory also requires that the wavenumber for bending waves is known. These can be obtained indirectly through measurements of longitudinal wavespeed and density and the errors associated with this are described in chapter 3.

The second group of errors occur as a result of using the finite difference technique with the output from the two accelerometers. The signal processing given by eqn(9.3) is identical to that used to measure airborne intensity. This means the equations, given by Elliot [46], used to predict the measurement error in acoustic intensity, are applicable to structural intensity measured using the two accelerometer technique. Of these, the finite difference error and the phase matching errors were found to be the
Fig. 9.2 The two accelerometer technique for measuring structural intensity.
most important. The phase mismatch that exists between the two accelerometers gives rise to an error in the measured intensity that affects the low frequency results. This was investigated and for the accelerometers used to measure intensity on the test walls this error was found to be negligible above 315 Hz. Below this frequency the phase mismatch resulted in a maximum error of about 2 dB. Finite difference errors become important at high frequencies when the bending wavelength begins to approach the same value as the accelerometer spacing $\Delta$. The spacing used on the test walls was 0.12 m and the largest finite difference error for the frequency range of interest was less than -1 dB.

The final limitation of this technique is similar to the limitation imposed by background noise on conventional measurements of sound pressure or surface acceleration. If, on a plate, a measuring surface is drawn around a region where there are no structural connections, the power entering the enclosed area should equal the power that leaves (assuming that the plate has a low internal loss factor). It follows that the average measured intensity for readings taken around the perimeter should also be zero. Measurements of this nature have been performed and values of intensity considerably greater than zero were obtained [47].

This is probably caused by all the errors described above combining to form a residual intensity. Measurements [47] suggest that the level of the residual intensity is related to the level of the reactive power in a structure. Adopting the notation used in acoustic intensity, the reactive power is contained in the reverberant field on a structure. In this field, on average, the power flowing in all directions is equal and the resulting nett power flow is zero. The residual intensity lies below the level of the reactive power by an amount that appears to depend upon the material properties of the test object [47].

Active power is the power that flows to coupled structures and it is this that the intensity technique attempts to measure. In general, this will be lower than the reactive power but provided it is higher than the residual intensity, it will be measurable. The residual intensity, however, sets a floor, below which it is not possible to perform any meaningful measurements of the active power flow.
Despite all these limitations the technique has been used by several other authors to study power flow across structural joints. Mayesenholder and Schneider [48] performed measurements to locate sound bridges introduced into a cavity wall built in a laboratory and Sorainen and Rytkonen [49] used the technique in a real building to locate a sound bridge on a floating floor. It has also been used to examine power flow through plates coupled along their edges. Kruppa [50] performed measurements on a tee joint between three walls built in a laboratory. All three groups of authors were able to map the direction of the power flow successfully but only Kruppa measured the magnitude of the power flow. Kruppa’s measurements were however qualitative and no predicted data was provided to compare with the measured results.

No work on determining the direction of the intensity vector is presented in this chapter. The technique was used instead to examine the magnitude of the power flow across wall ties in a cavity party wall and on an external cavity wall. Measurements were also made in an external wall where the two leaves were coupled along one edge. Predicted data is provided for comparison with the intensity data in order to assess the accuracy of the measured results.

9.4 Verification of power flow measurement techniques

In order to verify that the measurement techniques worked, measurements were performed on a steel model shown in Fig 9.3. It consisted of a 3.0 m long steel beam (cross section 65 mm x 6 mm) which was coupled to a 6 mm thick steel plate (which had dimensions of 3.0 m x 1.5 m) via the instrumented wall tie. The beam was supported near it’s centre by a thin steel wire and was supported by the tie at one end. The other end was supported by an electrodynamic shaker, coupled to the beam via a flexible plastic rod and an impedance head. The plate was supported on a sheet of foamed plastic to increase it’s damping and remove power from the system. This helped to reduce the feedback of power into the beam. The subsystem numbering was chosen to agree with the convention used for the cavity wall measurements. Narrowband measurements were performed using a dual channel FFT analyser. The data was then converted into third octaves by summing between the upper and lower
The test rig for verifying power flow measurement techniques.

Power input.

SEA model of the test rig.

Fig. 9.3 The steel model used to verify the measurement technique for the instrumented tie and structural intensity.
cut off frequencies of the standard third octave filters.

**Tie measurements**

The first measurement that was performed to verify that the tie worked, compared the power entering the beam with the power leaving it. The power entering the beam was obtained from the impedance head using the signal processing given in eqn(9.2). This equals the power leaving the beam. It was assumed that losses from the beam due to the radiation of sound were negligible and that the dominant loss would be due to the structural coupling with the plate. The power flow via this path was measured using the instrumented tie. To this were added the losses due to internal damping of the beam. Reverberation time measurements on the beam indicated that the internal loss factor was around 0.0012. This value was used with the measured energy level on the beam to obtain the power loss due to internal damping.

Fig 9.4 shows the power input, measured with the impedance head, compared with the dissipated power and the power flow, measured using the tie. Transmission via the tie is the dominant path, this being about 1 dB below the input power. The dissipated power is around 6 dB lower than the power flow measured using the tie. At high frequencies the coupling between the beam and the plate is very weak and internal losses begin to dominate. Fig 9.5 shows the sum of the dissipated power and the tie power compared with the input power. The agreement between the two curves is good and suggests that the tie is capable of providing a reliable measurement of the power flow over the range of frequencies examined.

The second measurement that was performed compared the power input to the plate, measured using the tie, with the power dissipated in the plate. The dissipated power was obtained from the measured energy level on the plate and the measured TLF for the plate. This is shown on Fig 9.6. The agreement is not quite as good as for the data on the beam, however, the uncertainties in determining the power loss on the plate are greater than those for the measurements on the beam. The 95% confidence interval for the measured energy level was around 2 dB and that for the damping was about 1 dB. Taking this into account the agreement between both sets of data is reasonable.
Fig. 9.4 The measured input power and output powers for the beam on the steel model.
Fig. 9.5  A comparison between the measured input power and the sum of the output powers for the beam on the steel model.
Fig. 9.6 A comparison between the input power measured using the instrumented wall tie and the dissipated power for the plate in the steel model.
The measurements show that the tie was able to measure power flow with as much accuracy as a propriatry transducer and provided data which agreed well with measurements made using the more traditional indirect methods.

**Intensity measurements**

The steel model was also used to verify the intensity technique. Two small accelerometers (B&K Type 4374) were used to reduce the effects of mass loading. The intensity was measured on the beam and around a 0.4 m diameter circle on the plate, centred on the tie. As with the measurements made using the tie, the intensity was measured using a narrowband analyser and the results were converted into third octaves by summing the data between the upper and lower cut off frequencies for the bands.

Fig 9.7 shows the intensity measured on the beam and the plate plotted with the power flow measured using the instrumented tie. The intensity measurement made on the beam shows good agreement with the power measured using the tie at all frequencies. The agreement between the tie measurement and the intensity measured on the plate is good at frequencies above 500 Hz. Below this frequency the agreement is poor, the intensity being around 5 dB lower than the power measured using the tie. The intensity measurement on the plate was made at a distance of 0.2 m from the tie. It is possible that the proximity of the intensity probe to the tie meant that the nearfield affected the results. The wavelength of bending waves on the plate is 0.4 m at 350 Hz. Below this frequency the measurement was performed at a distance of less than a half wavelength from the tie, in the a region where it would have been affected by the nearfield. At 500 Hz the probe is three quarters of a wavelength from the tie and the effects of the nearfield will be significantly reduced.

The results obtained using the intensity technique were satisfactory. The results from the plate at high frequencies and the intensity measured on the beam were encouraging, the agreement with the data obtained using the tie being good. The poor performance of this technique on the plate at low frequencies is probably due to locating the probe too close to the source of excitation.
Fig. 9.7 A comparison between the power flow measured using the instrumented wall tie and measured on the beam and the plate of the steel model, using structural intensity.
The influence of residual intensity

One of the limitations associated with the measurement of power flow using the two accelerometer technique is the effect of residual intensity. Fig 9.8 illustrates how this can affect an intensity measurement. It shows three independent measurements of the power flow across a wall tie in a party cavity wall. The instrumented tie was used to provide the first set of data and the intensity measured on the source and receiving walls provided the other two.

The measurement performed on the receiving wall shows good agreement with the power measured using the tie and is within about 2 dB at all frequencies. The agreement between the power flow measured using the tie and the intensity measured on the source wall is not as good. At high frequencies tie coupling is weak and the strength of the active power flow across the tie is small relative to the reactive power. The true intensity is therefore low and all that was measured was the residual intensity. For the measurement made on the receiving wall, the tie is the dominant power input. The active and the reactive power on this wall will therefore be similar and the residual intensity will not affect the data.

The consequences of this are that for structural joints where the coupling is relatively weak it is necessary to measure the intensity on the receiving subsystem, where the reactive power and hence the residual intensity is low relative to the active power.

Residual intensity is being investigated by Craik and Ming [47], who have suggested that it is related to the reactive power in a structure. Measured data shows that the residual intensity lies some way below the power contained in the reactive sound field. As the reactive power is increased, however, the residual intensity rises by a similar amount. There exists, therefore, a margin between the reactive power and the residual intensity where it is possible to measure active power flow using the two accelerometer technique.
Fig. 9.8 A comparison between the power flow measured across the instrumented wall tie and measured using structural intensity on the source and receiving leaves of a cavity party wall.
The power flow measurements were all made on cavity walls built in a transmission suite as shown in Fig 9.9. One leaf of the wall was built in each room so that the only structural transmission path was via the tie. A loudspeaker was used as a power source and was placed in the smaller of the two rooms. The surface acceleration level was measured at twenty positions on both of the walls. The measurement was performed using narrow band analysis so the data could be compared with the results from the tie. This gave an acceleration level that had a 95% confidence interval of around 3 dB. The acceleration levels were converted into velocities to enable the energy on the two subsystems to be determined using eqn(2.11). In addition to these measurements, the reverberation time of the receiving wall was measured to provide damping data using eqn(2.88).

Two indirect measurements of power flow were made to compare with the data obtained using the direct power flow methods. The first was a predicted measure based on the energy level in the source wall and the second was obtained from the power dissipated in the receiving wall.

The predicted measure of the power flow was obtained using the measured acceleration data from subsystem 2. In SEA the power transmitted from subsystem \( i \) to subsystem \( j \) is given by, \( E_i \omega \eta_{ij} \). The power flow from subsystem 2 to 3 across the tie was obtained using,

\[
W_{23} = E_2 \omega \eta_{23}
\]

(9.4)

where \( E_2 \) was measured and \( \eta_{ij} \) was predicted. The coupling loss factor was obtained from eqn(2.60) where the measured tie stiffness obtained in chapter 3 was used.

The second indirect measure of power flow was obtained from the measured acceleration data obtained from subsystem 3. For the receiving wall, the input power
Experimental set up for measuring power flow across wall ties.

SEA model of the system.

Fig. 9.9 The subsystem numbering for the direct power flow measurements made in a transmission suite.
equals the power output. The power dissipated is,

\[ w_{23} = E_3 \omega \eta_3 \]  

(9.5)

where \( \eta_3 \) is the total loss factor of the wall.

Intensity measurements of the power flow across ties were made around the perimeter of a 0.5 m diameter circle, centred on the tie under examination. The intensity was measured using a probe which consisted of two accelerometers positioned side by side and fixed with a thin layer of beeswax. The accelerometers had a separation, \( \Delta \), of 0.12 m. The probe was moved around the perimeter of the circle and the intensity was measured at 24 positions. From these, the average intensity was determined and by multiplying this by the length of the perimeter of the circle the power flow through the measurement surface and hence the power flow across the tie was found.

To measure the power flow across the line joint between the two leaves of the external wall, a different measurement technique was adopted. A plastic-headed hammer was used to excite the source subsystem and an accelerometer mounted to this subsystem was used to measure the source energy. The intensity was measured simultaneously, the probe being fixed to the receiving wall, 0.5 m from the joint. The probe was moved along the length of the joint, the intensity being measured at 12 positions. At each position the source wall was excited for 16 seconds using the hammer and the surface acceleration of the source wall and the intensity on the receiving wall were measured. The probe and the accelerometer were then moved and the measurement was repeated. The surface acceleration was used to determine the energy on the source wall and this was used with the power flow, measured using the intensity probe, to obtain the CLF for the joint using eqn(9.4). This was determined for each measurement position and the CLFs were then combined to give an average CLF for the joint.
9.6 Results for the instrumented tie

The instrumented tie was used to study the power flow in three different types of cavity wall. The source leaf of each wall was made from dense masonry blocks. The receiving leaf on each wall was different. One wall had the second leaf made from dense concrete blocks, one had aerated concrete blocks and one had a lightweight plywood leaf. For each wall the tie formed the only structural connection between the two leaves.

Results for a dry lined wall

A full description of the dry lined wall and the data obtained using conventional measurement methods are given in chapter 7. It consisted of a leaf of dense concrete blocks separated from a much lighter plywood leaf by a 100 mm wide cavity. Using the notation shown in Fig 9.9, the concrete leaf which was in the source room is subsystem 2 and the ply leaf which is in the receiving room is subsystem 3.

The power flow measured using the tie and the results from the two indirect techniques are plotted on Fig 9.10. At frequencies below 630 Hz the power dissipated in the plywood wall was much higher than the input power measured using the tie. In this same frequency region, however, the agreement between the power measured using the tie and the predicted power flow is quite good. Above 630 Hz the agreement between all the curves is good implying that at high frequencies the path via the tie is dominant. At low frequencies the difference between the direct measure of power flow and the indirect power measured on the receiving leaf can be explained if the transmission across the air was much greater than across the tie. The data from the instrumented tie shows that the eLF for the tie not only predicts the power flow for the structural path across the cavity correctly at high frequencies but it also predicts the correct power flow in the low frequency region.

Results for an external wall

The external wall consisted of a leaf of dense concrete blockwork and a leaf of aerated concrete blockwork, separated by an 85 mm wide cavity. This form of construction is similar to that used in the external envelope of domestic buildings. The
Fig. 9.10 A comparison between the power flow measured using the instrumented wall tie and two indirect measures of power flow for a dry lined wall with one tie.
results from the indirect measurements performed on this wall are described in chapters 4 and 5.

A comparison between the power measured directly using the tie and the two indirect measures of the power is given in Fig 9.11. The agreement between the predicted power flow based on the energy on the source wall and the power measured using the tie is reasonable and within the margin that would be expected from the 95% confidence interval for the measured surface acceleration levels. The dissipated power from the receiving wall shows reasonable agreement with the direct power flow at high frequencies, however, at low frequencies it is around 5 dB lower than the measured data obtained from the tie. In chapter 3 the difficulties encountered in the measurement of the TLF of the free standing leaf of the test wall were discussed and for this wall it was necessary to use a predicted TLF in eqn(9.5). The discrepancy between the dissipated power and the direct power at low frequencies suggests that the predicted damping is too low in this region.

Results for a party wall
The test wall consisted of two identical leaves of dense masonry separated by an 85 mm wide cavity. This is a form of construction typical of a domestic party wall and the results from the conventional measurements performed on the wall are described in chapters 4 and 5.

A comparison between the power measured directly and the two indirect measures is shown on Fig 9.12. The direct measurement of power flow and the dissipated power measurement show good agreement over most of the frequency range. The power flow predicted from the source wall energy level is however slightly higher than the direct measurement. As the frequency increases, the agreement between the predicted power flow from the source wall and the power measured using the tie improves.

A possible explanation for the difference between the predicted power flow from the source wall and the power measured using the tie can be found in the narrowband data in Fig 9.13. This gives the power flow measured using the three methods but the results have been given over a narrower range of frequencies for clarity. It shows that
Fig. 9.11 A comparison between the power flow measured using the instrumented wall tie and two indirect measures of power flow for an external cavity wall with one tie.
Fig. 9.12 A comparison between the power flow measured using the instrumented wall tie and two indirect measures of power flow for a cavity party wall with one tie.
Fig. 9.13 A comparison between the narrowband power flow measured using the instrumented wall tie and two indirect measures of power flow for a cavity party wall with one tie.
the agreement between the power flow measured using the tie and the dissipated power is quite good, the shapes of the curves being similar. The predicted power flow based on the source wall energy is, however, generally higher and smoother than the direct measurement, which shows very large fluctuations. Although the same peaks appear in the predicted power, because it is based on the spatial average energy level on the source wall the relative importance of each mode is dependent on it's relative importance within the spatial average. The power that an individual mode is able to transmit across the tie, however, only depends upon the strength of it's response at the tie location. As an extreme example of this, a mode that exhibits an antinode at the tie location would transmit a great deal of power to the receiving wall and a mode which exhibited a node at the tie location would transmit little. As the frequency increases and the measurement bandwidth becomes wider, the number of modes that are effective at transmitting power across the tie will rise and the third octave curves for the direct power and predicted power flow would be expected to converge.

Measurement of tie coupling loss factor

Equation(2.4) can be rearranged to give the CLF in terms of the energy level difference between the two leaves of the wall and the TLF of the receiving leaf. This is an indirect measure of coupling and it relies on the accurate measurement of the TLF. For the masonry walls examined a predicted TLF was used and this results in some uncertainty in the measured CLF.

An alternative technique is to use the power flow measured with the tie to obtain the CLF. This does not require that the damping of the receiving subsystem is known. The power balance equation for the cavity wall is given by eqn(9.4). If the power flowing across the tie and the energy in the source subsystem are known, the CLF for the tie can be determined. Figure 9.14 shows the predicted CLF for the tie in the external wall obtained by using the measured value of tie stiffness, 20 x 10^4 N/m in eqn(2.60). Shown also are the measured CLF obtained using the energy difference method and using the instrumented wall tie. The agreement between both measured curves and the predicted curve is good at high frequencies. At low frequencies the CLF measured using the wall tie shows a spread around the predicted curve and at very low frequencies the measured data is around 4 dB below the predicted curve.
Fig. 9.14 Comparison between the measured and predicted coupling loss factor for a wall tie. Measurements made using the instrumented tie and an indirect method.
The CLF measured using the energy method is up to 10 dB lower than the predicted curve at low frequencies, this is probably due to an under estimate of the receiving wall damping in this region.

The predicted CLF assumes that the energy in the source wall is distributed equally amongst the modes and as a result the predicted curve is smooth. In the discussion above, it was suggested that as a result of the discrete location of the tie, some modes would be more successful than others at transmitting power. Fluctuations would therefore be expected in both of the measured CLFs if they are based on the power flow across just one tie.

**The affect on power flow across a single tie, of increasing the number of ties**

One of the assumptions made in deriving the equation for tie coupling, eqn(2.60), was that the power flow across each wall tie was uncorrelated with the power flow across any other. If this is the case, the addition of ties to a wall should leave the power flow across any existing ties unaffected. Measurements of the power flowing across the instrumented wall tie were made each time the number of ties present in the external type was increased. This allowed any variation in the power flow, as the number of ties was increased, to be seen. The results for the wall with 1, 2 and 4 ties are shown in Fig 9.15. The measured power flows for the wall with 1 and 2 ties are almost identical except at low frequencies where the power flow appeared to drop upon the addition of the second tie. The mass-spring-mass resonance occurs in this frequency region and may be responsible for the drop in power flow. As the number of ties is increased, the resonance frequency rises. For 1 tie it is predicted at 38.8 Hz, for 2 ties at 47.7 Hz and for four ties at 61.6 Hz. In the region of the resonance the wall behaves as a single subsystem and the power flowing across the tie should be the same in both directions resulting in no net power flow. When four ties were present on the wall, slight changes occurred in the measured power at high frequencies. It may therefore be concluded, at least for the wall with few ties, that the addition of extra ties does not affect the power flow across the existing ties.

**Measurement of tie stiffness in-situ**

In addition to using the tie to measure power flow, it can also be used to measure
Fig. 9.15 Variation in the power flow across the instrumented tie caused by the addition of ties to the wall.
impedance, \( Z \), the ratio of the force, \( F \), applied to a body and the resulting velocity, \( v \) [14],

\[
Z = \frac{F}{v} = \frac{i\omega F}{a}
\]

(9.6)

This can be obtained using the frequency response function between the force and acceleration signals from the instrumented tie, using a FFT analyser. For a tie excited along its longitudinal axis, at frequencies well below its first longitudinal resonance, its impedance, \( Z_t \), is related to its stiffness, \( k_t \), by [17],

\[
Z_t = \frac{k_t}{i\omega}
\]

(9.7)

The impedance measured in this way is the sum of the tie impedance and the wall impedance. The tie, however, has an imaginary impedance and it may be assumed that at high frequencies where the wall is multi-modal, that the wall has a real impedance. The tie impedance was taken to be the imaginary part of the frequency response function, from which the stiffness of the tie was found using eqn(9.7). For the tie used in this measurement, the measured tie stiffness was found in chapter 3 to be \( 20 \times 10^6 \) N/m. This was converted into decibels by taking \( 20 \log Z \) and is plotted against the stiffness measured using the instrumented tie in Fig 9.16. The narrowband stiffness is slightly higher than the value obtained from the resonance measurements, however, this is probably due to the fact that the accelerometer is not positioned at the end of the tie. It was located between the face of the source wall and the centre of the tie and as a result it will measure a higher value of stiffness. The actual value of the measured stiffness would be expected to lie somewhere between the value for a full length tie and a tie of half this length. The third curve on the figure is the stiffness that a tie of half the length would be expected to exhibit, based on the stiffness measured using the resonance method. Most of the narrow band data
Fig. 9.16 Tie stiffness measured using the instrumented wall tie.
lies between the two stiffness curves obtained from the resonance measurement.

The measurements made using the tie suggest that both the stiffness measured using the concrete block method and hence the tie CLF obtained using eqn(2.60) are correct.

9.7 Measurement of power flow across ties using intensity

The instrumented tie proved to be a convenient and accurate method of measuring the power flow across a wall tie. It would not be practical, however, to continue adding instrumented ties to examine the power flow across walls with more than one tie. The intensity technique is a convenient solution to this problem. It allows the power flow across a tie to be measured despite the presence of the power flow from other ties. Before proceeding to do this, however, it is necessary to investigate the influence that residual intensity has on the measurement.

Intensity measurements were made on the external cavity wall described in chapter 4. This was tested with 1, 2, and 4 replacement ties and the power flow across each of the ties was examined by measuring the intensity around circular measuring surfaces drawn on the receiving wall around each tie.

The addition of each new tie increases the strength of the reactive power in the receiving wall. The strength of the active power flowing across any individual tie will, however, remain fairly constant. Measurements were therefore made to assess whether the increasing strength of the residual intensity, resulting from the addition of more ties, affected the measurement of the intensity around the instrumented tie.

The results from these measurements are shown in Fig 9.17. The instrumented tie is not affected by residual intensity so it was used to provide an accurate measure of the power flow across the wall tie. The residual intensity was obtained from a narrowband measurement made around a circular measuring surface enclosing an area with no structural coupling. It was found to fluctuate in an arbitrary manner between positive and negative values. The narrowband results were converted into third octave
Fig. 9.17 Change in the residual intensity (for the two accelerometer structural intensity technique), on the receiving leaf of an external cavity wall, caused by the addition of wall ties.
data by summing between the upper and lower cut off frequencies for the standard measurement bands. Depending upon the sum within the measurement band, the results were positive or negative. The negative values are indicated on the figure as solid squares. It was not possible to measure the reactive power on the receiving wall, however, the total power (the sum of the reactive and active powers) can be obtained using the measured energy on the receiving wall, $E$, in [14],

$$W = 2c_p k^2 Bv^2 = 2c_p E$$

(9.8)

From the figure it can be seen that, as ties are added to the wall, the level of the active power across the instrumented tie remains relatively constant whilst the reactive power and the residual intensity rise. From the measurements made, the residual intensity would not be expected to affect the results from the wall with 1 and 2 ties, however, when 4 ties are present in the wall there are some frequencies where the effects of residual intensity might influence the data. Intensity measurements for any further doubling of the tie numbers would probably not be possible.

In order to determine whether the residual intensity affected the intensity measurements, the power flow across the instrumented tie measured using intensity was compared with the power flow measured using the tie. These should be the same and any deviations will probably be caused by the residual intensity. Fig 9.18 shows the power flow across the instrumented tie measured using the two methods. In general the agreement between the two measurement techniques is satisfactory, however, when four ties are present in the wall, the intensity underestimates the power flow at frequencies where the power measured using the tie is low. Despite this, the agreement between the two measurements is still reasonable and the residual intensity does not appear to have had a significant affect.

**Variation of power flow across different ties**

An explanation for the behaviour of the narrow band power flow data obtained for the instrumented tie, in Fig 9.13, was that the contribution that any single mode on
Fig. 9.18 Comparison between the power flow measured using the instrumented tie and the power flow measured using the structural intensity technique.
the source wall could make to the total power flow across the tie was dependent on it's response at the tie location, ie modes which exhibited an antinode at the tie location would transmit a significant amount of power whereas modes exhibiting nodal behaviour would not. If this is indeed the case, it would be expected that the power flow across additional ties inserted into the wall would be different as their position relative to the mode pattern on the source wall would differ. Fig 9.19 shows the power flow measured using intensity on the wall with two ties present. The intensity was measured around each of the ties in turn and the third curve is the sum of the two. The two power flow spectra for the individual ties are different. The original tie dominates the power flow around the 160 Hz band and the second tie around the 250 Hz band. At high frequencies the power flow across both ties is similar.

The power flow from each tie on the wall, with four ties present, is shown on Fig 9.20. As the number of ties is increased, the importance of any individual tie diminishes and the ability of any single tie to dominate the total power flow is reduced. What in effect is happening is that more of the modes on the source wall are able to contribute to the power flow to the receiving wall and the effect of discrete modes or groups of modes is reduced.

The CLF for the tie measured using intensity helps to illustrate this. In the prediction for the CLF it is assumed in SEA that the energy in a wall is distributed equally amongst it's modes. This being the case the predicted CLF for this type of structural joint is a smooth curve. As shown in Fig 9.21 the CLF for a single tie, whilst showing reasonable agreement with the predicted curve, did fluctuate about it. The figure shows how the CLF measured using the intensity technique changed as the number of ties was increased. Apart from the 3 dB increase in the CLF due to each doubling of the number of ties, it can be seen that as the number of ties increased the measured CLF curve became smoother and fluctuated less around the predicted curve. This suggests that as the spatial distribution of the ties improves so the discrete effect of modes on the source wall diminishes.
Fig. 9.19  Power flow across the ties in an external cavity wall with two ties, measured using structural intensity.
Fig. 9.20 Power flow across the ties in an external cavity wall with four ties, measured using structural intensity.
Fig. 9.21 Comparison between the measured and predicted tie coupling loss factor, (measured using intensity).
9.8 The use of intensity techniques for measuring power flow across plates coupled along lines

In addition to measuring power flow between plates coupled at discrete points, an attempt was also made to measure the power flow between two parallel plates that were coupled along one edge.

The measurement was performed on the wall described in chapter 7, after the demolition of leaves 2 and 4 in Fig 7.9. The results from the conventional measurements performed on this wall are discussed in chapter 7.

In addition to these measurements, the CLF for transmission from the aerated leaf to the dense leaf was measured using the intensity technique in the manner described above. The results from the measurement are shown in Fig 9.22. The predicted curve was obtained by solving the random incidence equations for the joint, given in chapter 7. Plotted with this is the CLF measured using the energy difference method and the CLF measured using the intensity technique. Both the measured curves show reasonable agreement with the predicted data, however, the CLF obtained using the intensity technique gives better agreement at low frequencies, being within about 2 dB of the prediction. As with the data for the tie CLF, the measurement made using intensity does not require that the damping of the receiving subsystem is known and it is possible that this is the reason for the improved agreement.

9.9 Conclusions

This chapter examined two methods for the direct measurement of power flow.

The first method was to use a force transducer and an accelerometer fixed to a wall tie to measure the power flowing across it when built into a cavity wall. It was found that the tie was able to measure power flow with as much accuracy as the more traditional indirect measurement methods and had the advantage that it was not necessary to know the structural damping of the test object.
Fig. 9.22 Comparison between the measured and predicted coupling loss factor for two parallel walls coupled along one edge. Measurements made using structural intensity and an indirect method.
In addition it was possible to use the instrumented tie to measure tie stiffness \textit{in-situ}. The results showed reasonable agreement with the stiffness measured using the resonance technique, described in chapter 3. The power flow results showed that when this measured stiffness is used in eqn(2.60), the predicted power flow agrees with the directly measured power.

The second power flow technique that was investigated was structural intensity. A method that uses two accelerometers mounted side by side separated by a small distance, was used. The power flow measured using this method worked well on building materials, the results showing good agreement with the power flow measured using the instrumented tie.

There is, however, a limitation to this measurement method. It is not possible to measure power flows that are considerably lower than the reactive power in a structure. This is due to what has been termed residual intensity, a power flow that is measured where none exists. This is related to the strength of the reactive power in the structure the measurement is being performed on and, for the materials tested, was found to lie approximately 10 dB below this. Provided the active power flow was not less than 10 dB below the reactive power, measurement of the intensity was possible. If the active power was less, the residual intensity was measured. Within this restraint it was possible to use the technique to measure CLFs of plates coupled at points (as in the case of wall ties) and plates coupled along lines (two parallel plates that were coupled along one edge).

Using the intensity technique it was possible to measure the contribution that each tie made to the total power flow across the cavity. This was found to vary quite considerably at some frequencies and is due to the discrete nature of each tie position. The amount of power that a mode is able to transmit across a tie is related to the strength of its response at the tie location. This will differ at each tie location and so the power flow across them will differ. For walls with few ties, therefore, some fluctuation in the measured CLF would be expected, this diminishing as the number of ties increases and the dominance of any single tie becomes less. This was borne out in the change in the measured CLF as the number of ties was increased.
Chapter 10
Additional transmission paths across cavity walls

10.1 Introduction

Previous chapters identified several frequency regions where poor agreement was observed between measured and predicted data. This chapter examines these in more detail in an attempt to improve the accuracy of the predictions.

In the region of critical frequency, predicted data consistently overestimates the strength of transmission paths which involve the excitation of, or radiation from, the test wall. The radiation of sound, particularly at critical frequency, is examined. Standard equations predict a sharp dip in transmission loss that does not occur for real walls. A simple equation is presented which gives better agreement than the standard radiation efficiency equation.

In the region of the mass-spring-mass (MSM) resonance, dips observed in the measured data had a significant effect on the overall wall performance. This path was not included in the SEA model, resulting in poor agreement between the measured data and the predictions. The transmission of sound in the region of the MSM resonance generally results in a dip in transmission loss at low frequencies. An equation is given that enables the mechanism to be incorporated into an SEA model as a non-resonant path.

In addition to these paths, coupling at foundations is examined. The study on wall ties showed that it is possible to predict and measure, very high level differences. These high levels of sound insulation are, however, very rarely obtained in real buildings. Chapter 7 examined one transmission path that can be responsible for this, the path
due to line coupling that occurs at door and window openings. This chapter studies another path caused by coupling at foundations. The two leaves of a cavity wall usually share a common foundation and this provides a structural path for sound in one leaf of the wall to pass to the second leaf. In addition to the coupling that takes place between the bottom edges of the wall at the foundation, it is also common to fill the bottom of the cavity with concrete to prevent soil pressure pushing the two leaves of the wall in and to prevent water from ponding. This serves to further couple the two leaves of the wall and results in a strong transmission path.

10.2 Radiation at critical frequency

Radiation efficiency plays an important role in predicting the sound insulation of walls. The equations commonly used to determine the radiation efficiency of plates, at and below critical frequency, are approximate and generally agree well with measured data. One case where agreement tends to be poor, however, is in the region of critical frequency of walls made from masonry. In order to improve predictions in this region, the theory of radiation efficiency was examined to see if the assumptions and approximations were valid and appropriate.

Approximate expressions

The equations commonly used to determine radiation efficiency are approximations based on equations derived by Maidanik [12]. These are given by Beranek [28] in eqn(2.29). When these expressions are used to predict the performance of both single and double walls, dips occur in the airborne level difference in the region of critical frequency. The depth of these is determined by the expression in eqn(2.29) at $f = f_c$.

For panels that have high critical frequencies (e.g., windows, metal panels, plasterboard panels, etc), the agreement between measured and predicted data at $f_c$ is better than for masonry panels. For masonry panels, which typically have low critical frequencies, a dip in the measured level difference is rarely obtained and the
agreement with predicted results is usually poor in this region.

Fig 10.1 shows the measured and predicted airborne level difference for a single leaf wall. It measured 4.0 x 3.0 x 0.1 m, and was made from concrete blocks that had a density of 2010 Kg/m³ and a longitudinal wavespeed of 2200 m/s \( (f_c = 297 \text{ Hz}) \). The agreement between the measured and predicted curves is reasonable except at \( f_c \), where the sharp predicted dip is not measured. This problem has been encountered with double masonry walls tested in previous chapters and has been identified by other authors eg Elmallawany [51].

**Exact expressions**

The theory for radiation from plates was examined in more detail to arrive at an expression for radiation efficiency at critical frequency that would show better agreement with measured data for masonry walls.

**Maidanik**

Equation (2.29) is an approximation of an exact expression that Maidanik [12] obtained by considering the particle velocity and acoustic pressure on the surface of a vibrating plate.

For a plate, which is assumed to lie in the x-y plane, with length \( l_x \) and width \( l_y \), Maidanik showed that the radiation efficiency of an individual mode can be given by,

\[
\sigma = \frac{64k^2}{S\pi^2} \int_0^1 I_x I_y \, d\beta
\]

(10.1)

where,
Fig. 10.1 Measured and predicted airborne level differences for a single leaf concrete block wall. (Prediction made using Maidanik's [12] approximate radiation efficiency equations).
\[ I_x = -\frac{k_x^2}{\sin^2} \left[ \frac{1}{2} \beta k_o I_x \right] \]
\[ \frac{\cos^2}{\sin^2} \left[ \frac{1}{2} \beta k_o I_x \right] \]
\[ \left[ \beta^2 k_o^2 - k_x^2 \right] \]  
(10.2)

and,

\[ I_y = \frac{k_y^2}{k_o^4} - \int_0^{\frac{1}{2}\pi} \left[ \frac{1}{2} \gamma k_o I_y \sin \theta \right] \frac{\cos^2}{\sin^2} \left[ \frac{1}{2} \beta k_o I_y \sin \theta \right] \left[ (k_y/k_o)^2 - (\gamma \sin \theta)^2 \right] d\theta \]
(10.3)

In these equations,

\[ \gamma^2 = 1 - \beta^2 \]
(10.4)

where,

\[ \gamma = \sqrt{\frac{f}{f_c}} \]
(10.5)

In eqn (10.2) and (10.3), \( k_o \) is the wavenumber of the radiated sound wave, and \( k_x \) and \( k_y \) are the \( x \) and \( y \) components of the bending wavenumber \( k_b \). The \( \sin^2 \) function is used for odd modes in either the \( x \) or the \( y \) direction (modes that consist of an odd number of half wavelengths) and the \( \cos^2 \) function is used for even modes (modes that have an even number of half wavelengths).

Fig 10.2 shows the radiation efficiency of individual modes for the single wall
Fig. 10.2  Predictions of the radiation efficiency of a concrete block wall.
described above, evaluated using eqn(10.1). Shown also is the radiation efficiency obtained using eqn(2.29) and the band averages for the two curves. The agreement between the exact expression and the approximate expression is good below and above critical frequency. In the region of critical frequency, however, eqn(2.29) is a poor approximation, the radiation efficiency obtained using eqn(10.1) being significantly lower.

Figure 10.3 shows the predicted level difference obtained when the band average values from eqn(10.1) were used to predict the performance of the single wall shown in Fig 10.1. Although the prediction is improved, there is still a dip at $f_\text{c}$ that does not occur in the measured data.

Wallace

Wallace [52] has also examined radiation from plates and derived expressions for the power radiated into the acoustic farfield through an arbitrary hemispherical measuring surface centred on a plate. From this, he determined the radiation efficiency of individual modes using,

$$
\sigma = \frac{64k^2l_xl_y}{\pi^2n_x^2n_y^2} \int_0^\frac{\pi}{2} \int_0^\frac{\pi}{2} \left[ \frac{\cos\left(\frac{\alpha}{2}\right) \cos\left(\frac{\beta}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)} \right] \sin\theta \, d\theta \, d\phi
$$

(10.6)

where $\theta$ is the angle of elevation of the observation point on the hemisphere, $\phi$ is the angle of azimuth and where,

$$
\alpha = k_x l_x \sin\theta \cos\phi
$$

$$
\beta = k_y l_y \sin\theta \sin\phi
$$

(10.7)
Fig. 10.3  Measured and predicted airborne level difference of a single leaf concrete block wall. (Prediction made using Maidanik's [12] exact equation).
Examples of Wallace's curves are shown on Fig 10.4. In the figure, \( \gamma \), is given by eqn(10.5). The graph shows the radiation efficiency of modes on a plate with dimensions 4.0 x 3.0 m. Each curve shows how the radiation efficiency of a given mode shape changes with frequency. The actual frequency at which the mode occurs and therefore it's radiation efficiency, is dependent on the material from which the plate is made and it's thickness.

An approximate expression for radiation efficiency at critical frequency
Wallace was able to approximate eqn(10.6) by expanding the integral into a power series and then integrating it to obtain expressions for the radiation efficiency of different types of modes below critical frequency. The first terms in these expressions are the same as Maidanik's approximations.

At frequencies below \( f_c \), the radiation efficiency of an odd-odd mode (a mode that is odd in the x and y directions) can be approximated by [52],

\[
\sigma = \frac{32}{n_x n_y \pi^3} \left( \frac{l_x n_y}{l_y n_x} + \frac{n_x l_y}{n_y l_x} \right) \gamma^2 \times 
\left[ 1 - \left( 1 - \frac{8}{(n_x \pi)^2} \right) \frac{l_x}{l_y} + \left( 1 - \frac{8}{(n_y \pi)^2} \right) \frac{l_y}{l_x} \left( \frac{l_x n_y}{n_x l_y} + \frac{n_x l_y}{l_x n_y} \right) n_x n_y \pi^2 \gamma^2 \right]
\]

(10.8)

If it is assumed that the fundamental mode, \((n_x=1, n_y=1)\), is responsible for transmission at low frequencies (this is a reasonable assumption for masonry walls because of the low critical frequency and the low modal density) and if it is further assumed that the wall is approximately square, \((l_x = l_y)\), then eqn(10.8) becomes [31],

\[
\sigma = 2\gamma^2(1 - 0.2 \gamma^2) \approx 2\gamma^2 - \frac{2f}{f_c}
\]

(10.9)
Fig. 10.4 Radiation efficiency curves for modes on a wall obtained using Wallace's theory [52].
When the frequency of interest is below \( f_c \), the radiation efficiency, \( \sigma_l \), is given by eqn(10.9). When the frequency is greater than critical frequency the radiation efficiency, \( \sigma_h \), is approximately equal to unity as shown on Fig 10.5.

These two curves can be combined using,

\[
\frac{1}{\sigma_t} = \frac{1}{\sigma_l} + \frac{1}{\sigma_h}
\]

(10.10)

where \( \sigma_t \) is the combined radiation efficiency obtained from the high and low frequency approximations. This gives a solution that is correct at low and high frequencies and is approximate at critical frequency. Using eqn(10.10) the radiation efficiency becomes,

\[
\sigma_t = \frac{2\gamma^2}{1 + 2\gamma^2}
\]

(10.11)

This curve is also shown on Fig 10.5 with the exact radiation efficiency curve for the fundamental mode. The two curves show reasonable agreement.

**Measured and predicted results**

Fig 10.6 shows a prediction made for a single leaf masonry wall using eqn(10.11) to determine the radiation efficiency. Agreement between the two curves is good at all frequencies.

Figure 10.7 shows a prediction for a masonry cavity wall with 16 replacement ties, described in chapter 5. The leaves of the wall were made from the same material as the single wall in Fig 10.1. At critical frequency the agreement has been improved
Fig. 10.5  Radiation efficiency obtained from an approximation to Wallace’s [52] expression for the radiation efficiency of the fundamental mode.
Fig. 10.6 Measured and predicted airborne level difference for a single leaf concrete block wall. (Prediction made using the approximation to Wallace's [52] equation for the radiation efficiency of the fundamental mode).
Fig. 10.7 Measured and predicted airborne level difference for a cavity wall with concrete block leaves. (Prediction made using the approximation to Wallace’s [52] equation for the radiation efficiency of the fundamental mode).
by using eqn(10.11). Well below critical frequency the agreement is poor, the prediction being significantly lower than the measured results. This lack of agreement is not, however, due to the radiation efficiency and is common to both predictions.

Discussion

This section has shown that the approximate equation given by Maidanik can be improved using a simple equation derived from an expression given by Wallace. This results in more accurate predictions at and around critical frequency.

10.3 Mass-spring-mass resonance

Beranek and Work's theory [1] for the transmission of sound through double walls predicts a dip in the level difference in the frequency region where single wall behaviour gives way to double wall behaviour. The frequency at which the dip occurs is the same as the frequency where two masses (each with a mass equal to the mass of a single leaf of the wall), connected by a spring (with a stiffness equal to that of the medium in the cavity), display a resonance. This is commonly referred to as the mass-spring-mass (MSM) resonance.

Measurements made on cavity walls, in chapters 5 and 6, showed that dips occurred in both the airborne and structural level difference at frequencies close to the predicted MSM resonance frequency. Figure 10.8 shows a typical measured result for a cavity party wall discussed in chapter 5. It had 32 replacement ties, both leaves had the same material and physical properties and the predicted MSM resonance frequency was 142 Hz. The SEA model that was used to predict the performance of this wall did not account for the MSM mechanism and as a result the agreement with the measured data is poor in this region.

The dip in the airborne level difference at MSM resonance can be explained simply. An increased response of the leaves of the wall, due to the resonance, results in
Fig. 10.8 Measured and predicted airborne and structural level difference of a concrete block cavity wall with 32 wall ties, (mass-spring-mass resonances unaccounted for).
increased transmission and consequently a drop in the level difference. The dip in the velocity level difference curve for the two leaves of the wall is more difficult to explain. For cavity walls with identical leaves, it would be expected that the velocity of each would be the same at resonance, hence the level difference should be zero. The measured structural level difference curves display a dip in the region of the MSM resonance where the data was negative. This indicates that the response of the leaf in the receiving room was greater than that of the leaf built in the room where the sound source was located.

Cremer's [14] theory on double walls has an expression that predicts a dip in the structural level difference provided the two leaves have different material and physical properties. If the leaves are identical, however, the theory predicts that both will have the same velocity level and the difference is zero.

Sound transmission at mass-spring-mass resonance

A theory based on two masses coupled by a spring can be used to provide a prediction that exhibits the type of behaviour obtained in the measured data. This is a non-resonant model, where the leaves of the wall are represented by two masses, \( m_1 \) and \( m_2 \), and the medium in the cavity by a stiffness, \( k \). This is more appropriate than Cremer's wave model as the MSM resonance usually occurs at a lower frequency than the fundamental mode on the wall. It's motion is therefore non-resonant and is not governed by the bending wave number. In addition, Cremer's theory is for infinite plates which are approximated by real walls only when they have high damping.

Adopting the same technique that was used in chapter 3 to examine tie stiffness, the frequency response between an applied force, \( F_I \), and the resulting acceleration of the source block, \( a_I \), for the system shown in Fig 10.9, is,
Fig. 10.9 Simple model of a cavity wall used to account for the mass-spring-mass resonance.
\[ \frac{a_1}{F_1} = \frac{m_1 \omega^2 - k + i \eta_1 m_1 \omega \omega}{m_1 m_2 \omega^2 - \eta_1 \eta_2 m_1 m_2 \omega^2 - k (m_1 + m_2) + i \omega \left( \eta_1 m_1 \omega \left( m_2 - \frac{k}{\omega^2} \right) + \eta_2 m_2 \omega \left( m_1 - \frac{k}{\omega^2} \right) \right)} \]  

(10.12)

where \( \eta_1 \) and \( \eta_2 \) represent the structural damping of the two leaves of the wall. For the receiving block, the frequency response is,

\[ \frac{a_2}{F_1} = \frac{k}{m_1 m_2 \omega^2 - \eta_1 \eta_2 m_1 m_2 \omega^2 - k (m_1 + m_2) + i \omega \left( \eta_1 m_1 \omega \left( m_2 - \frac{k}{\omega^2} \right) + \eta_2 m_2 \omega \left( m_1 - \frac{k}{\omega^2} \right) \right)} \]  

(10.13)

\( \omega_n \) is the resonant frequency for the system, which can be given by the equation for the undamped system,

\[ \omega_n = \sqrt{k \left( \frac{1}{m_1} + \frac{1}{m_2} \right)} \]  

(10.14)

For a sound wave incident on one square metre of wall, the relationship between the incident sound pressure, \( p_i \), and the response of the receiving leaf can be given from eqn(10.13) as [31],

\[ \frac{a_2}{2p_1} = \frac{k}{m_1 m_2 \omega^2 - \eta_1 \eta_2 m_1 m_2 \omega^2 - k (m_1 + m_2) + i \omega \left( \eta_1 m_1 \omega \left( m_2 - \frac{k}{\omega^2} \right) + \eta_2 m_2 \omega \left( m_1 - \frac{k}{\omega^2} \right) \right)} \]  

(10.15)

where pressure doubling on the face of the source block was assumed to occur as a
result of a reflected wave with approximately equal amplitude. The relationship between the acceleration of the receiving block and the pressure, \( p_r \), of the transmitted sound wave is given by,

\[
a_2^2 = \left( \frac{\omega p_r}{\rho_o c_o} \right)^2
\]

(10.16)

from which the sound reduction index for the system becomes [31],

\[
10 \log \left| \frac{p_f}{p_i} \right| = \left| \log \left( \frac{m_1 m_2 \omega^2 - \eta_1 m_1 \omega^2}{2 \rho_f c_f} \right) + \frac{\omega}{\omega_1} \left( m_1 - \frac{k}{\omega^2} \right) + \frac{\omega}{\omega_2} \left( m_2 - \frac{k}{\omega^2} \right) \right|
\]

(10.17)

If it is assumed that there is no damping and if \( m_1 \) is equal to \( m_2 \), this expression reduces to the mass law equation for a single wall with mass 2 \( m \) given by Beranek [28]. Figure 10.10 shows a comparison between eqn(10.17) and Beranek and Work’s expression for the SRI of a double wall [1]. The difference at MSM resonance is due to the existence of damping in eqn(10.17) and the difference at high frequencies arises because the model described here does not include terms for cross cavity resonances.

From eqn(10.12) and eqn(10.13) the structural level difference can be written as,

\[
10 \log \left| \frac{a_1}{a_2} \right| = 10 \log \left| \frac{v_1}{v_2} \right| + 10 \log \left( \frac{m_2 \omega^2 - k + i \eta_2 m_2 \omega \omega^2}{k} \right)
\]

(10.18)

The level difference curve obtained using this equation will (for a wall with two identical leaves) display a dip below the region of MSM resonance that has a negative
Fig. 10.10 A comparison between the SRI of a cavity wall predicted using the simple model of a cavity wall and predicted after Beranek and Work [1].
level difference, similar to the behaviour observed in the measured data. The dip is not, however, due to the resonance between the two blocks but occurs at a frequency that is \( \sqrt{2} \) below the resonance frequency. This is illustrated on Fig 10.11, which shows the two frequency responses obtained from eqn(10.12) and eqn(10.13) and the resulting level difference obtained from eqn(10.18). The dip in level difference corresponds to an anti-resonance on the source block. At the MSM frequency, the responses of both blocks are identical and the level difference is zero.

**Measured and predicted results**

The results from the wall with 32 replacement ties, described in chapter 5, were used to provide data to compare with the predictions from the model above. The leaves of the wall were made from concrete blocks that had a density of 2010 Kg/m\(^3\) and a longitudinal wavespeed of 2200 m/s, giving the it a critical frequency of 297 Hz. The stiffness of each tie as \( 30 \times 10^6 \) N/m giving the predicted MSM resonance as 142 Hz. In the prediction the values for \( \eta_1 \) and \( \eta_2 \) were obtained from the sum of the coupling loss factors for the leaves of the test wall plus an internal loss factor of 0.008. The predicted transmission due to the resonance was combined with the predicted transmission from the full SEA model of the test wall and chambers described in chapter 3.

The structural results are shown in Fig 10.12. The top part shows third octave data and the lower part is narrowband data (with a constant bandwidth of 2 Hz), for the same wall. The addition of the path due to the resonance has caused a dip in the predicted data at 100 Hz, \( \sqrt{2} \) below the resonance frequency. The position of this dip and the range of frequencies over which the level difference is negative, shows good agreement with the measured results. The depth of the dip has, however, been overestimated. At frequencies above the MSM resonance this path is not the dominant transmission mechanism and transmission across the ties becomes important.

The measured and predicted airborne data is shown in Fig 10.13. For airborne transmission the predicted dip is caused by the increased response that occurs at the
Fig. 10.11 The predicted frequency response of the simple cavity wall model and the resulting structural level difference.

---

Level difference.

Frequency Response.

Response of receiving block.

Response of source block.

Frequency (Hz).
Fig. 10.12 Measured and predicted third octave and narrowband structural level difference of a concrete block cavity wall with 32 replacement wall ties.
Fig. 10.13  Measured and predicted third octave and narrowband airborne level difference of a concrete block cavity wall with 32 replacement wall ties.
MSM resonance frequency. It can be seen that the position of the dip is predicted with reasonable accuracy, however, despite the overestimate in the structural level difference, the airborne prediction underestimates the strength of transmission. This is due, in part, to the fact that in the SEA model, the test wall is not the dominant radiating surface. The floor of the receiving room dominates airborne transmission in this region and so the full impact of the resonance on the direct path through the wall can not be seen. It should be noted, however, that the measured data indicates that the actual strength of this path is far stronger than the predicted strength.

Discussion

The affect of the MSM resonance on overall wall performance was predicted by combining the results from two models of the wall. In the SEA model, the behaviour of the wall was dominated by coupling between the resonant modes on the two leaves, due to the ties. The interaction between the wall and the adjoining rooms was therefore controlled by the radiation efficiency of the test wall. In the model for predicting the behaviour of the MSM resonance, the ties coupled the non-resonant wavefields on the two leaves of the wall. For this model, the radiation and response was assumed to be uniform at all frequencies.

This treatment is akin to representing each leaf of the test wall with two subsystems, one resonant and one non-resonant, with the ties providing two parallel transmission paths for sound to pass through. The consequences of this model are described in more detail in chapter 11.

The tie coupling between the two resonant subsystems and the interaction between these and the two rooms will be modelled correctly. For the two non-resonant subsystems the tie coupling will again be modelled correctly, hence the reasonable agreement with the measured data. The interaction with the rooms is, however, based on a normal incidence model and this probably leads to the poor agreement between the measured and predicted airborne data. As with Beranek and Work's theory [1], the normal incidence solution will underestimate the strength of this path causing the
predicted level difference to be higher than the measured result.

Rewriting the above theory to allow for oblique incidence and integrating this to obtain a random incidence solution, would increase the strength of the airborne path whilst leaving the structural path unaffected.

10.4 Transmission across foundations

In order to prevent a wall from over-stressing the ground it is built off, it is necessary to spread it’s load over a greater area. This is commonly achieved by the use of a strip foundation. This is a thin concrete beam, slightly wider than the wall, which is cast into the trench that the wall is built out of. If the wall is a cavity wall, the two leaves will usually share the same foundation. This has the effect of coupling the two leaves along their bottom edge and provides a transmission path for sound to pass from one leaf to the other. In addition to this coupling, it is usual to fill the cavity with concrete to prevent water from ponding and to prevent soil pressure from caving the wall in.

Modelling a joint of this type is difficult. The strip foundation resists the lateral motion of the wall produced by the forces and the soil beneath the foundation resists the rocking motion caused by the bending moments. The nature of this coupling is different from the joints described in chapter 7, this is the reason foundations were not discussed there.

This section presents the results from measurements that were performed to investigate this path. Tests were performed on a double leaf concrete wall built in a transmission suite. The two leaves were built off the floor slabs of the chamber and were initially isolated from each other because of the gap in the test aperture. The effect of the foundation was achieved by coupling the floor slabs in each room, by filling the base of the cavity with concrete. This simulates the effect of the strip foundation, however, it does not include the effect of the soil. From Fig 3.1 it can be seen that one of the floor slabs is of suspended construction and the other is cast
on a thick sheet of polystyrene. Both would therefore be free to undergo bending and so provide little extra resistance to the bending moments on the test wall. The results do, however, compare favourably with data obtained from a second test wall built off a floor slab cast on the ground.

The test wall

The test wall that was used to study foundations was described in chapter 6 in the section on butterfly ties. It consisted of two 4.0 x 3.0 m leaves of 100 mm thick concrete blockwork, which had a surface density of 201 Kg/m² and a longitudinal wavespeed of 2200 m/s, giving the critical frequency as 297 Hz. After the completion of the tests to study its behaviour with 25 butterfly ties, the wall was modified to investigate the effect that coupling at foundation level had on sound transmission. A sketch of the modification is shown in Fig 10.14. Five replacement wall ties were inserted into the bottom course of blockwork. Three blocks were removed from the second course of one of the two leaves and the bottom of the cavity was filled with concrete to a depth of 215 mm. The blocks were then replaced and grouted solidly in place. The open textured nature of the blockwork afforded a good key to the concrete and the addition of the ties ensured the bases of the two walls were coupled strongly.

Measured results

Airborne and structural level difference measurements were made on the wall. Fig 10.15 shows the airborne level difference for the wall before the leaves were joined together and the level difference after the cavity fill was introduced. It can be seen that joining the two leaves resulted in a drop of between 10 and 18 dB over most of the frequency range. The only exceptions to this occurred at the low and high frequencies. Drying shrinkage of the free standing wall resulted in damage to part of the mastic seal at the wall perimeter. Sound was therefore able to travel directly from the cavity into the receiving room. This is probably what caused the level difference, for the wall with ties only, to drop off at frequencies above 1 KHz. Were it not for
Fig. 10.14  Section through the base of the test wall designed to study foundation coupling.
Fig. 10.15 Normalised airborne level difference for a cavity wall with 25 butterfly ties and for a cavity wall with ties and cavity fill.
this flanking path, the change in performance obtained at high frequencies by the
addition of the concrete would have been greater.

At low frequencies there is little difference between the results suggesting that the
dominant transmission path is not through the concrete connection. It was not possible
to remove the butterfly ties during the conversion of the wall so not only were the
leaves coupled at their base by the concrete, they were also coupled over their area
by the ties. From the results it appears that in the low frequency region it is coupling
across the ties that dominated, resulting in the two sets of data being very similar.

Fig 10.16 shows the structural level difference between the two leaves of the test wall
with and without coupling at the base. As with the airborne results this shows that
joining the two leaves together resulted in a large drop in the level difference. The
two curves are very similar below 100 Hz, which is the frequency region where the
transmission across the ties was dominant. Above this frequency the data for the two
leaves connected at their base, levels off at a value of about 8 dB. The data for the
wall with just ties continues to rise to a value of about 30 dB at 630 Hz before it too
levels off. The addition of the cavity fill, therefore, resulted in a drop in the structural
level difference that increased with increasing frequency above 100 Hz to a maximum
change of about 20 dB at 500 Hz.

Both the airborne and structural curves displayed a drop in insulation with the
addition of the cavity fill. The exception to this was at low frequencies where the
strong coupling across the ties was the dominant transmission path and where the
addition of the fill resulted in very little change in performance. For the structural
data the change occurs after 125 Hz, however, for the airborne data it starts after 63
Hz. This is because sound is being radiated into the receiving room from the chamber
floor and is discussed later.

Predicted results

Two predictions were made to provide data for comparison with the measured results.
Fig. 10.16  Velocity level difference for a cavity wall with 25 butterfly ties and for a cavity wall with 25 butterfly ties and cavity fill.
Approximate expressions given by Vinokur [10], for the airborne transmission loss for two walls coupled along an edge, were used to obtain the first prediction. An SEA model of the test wall and transmission suite was used to provide the second set of predicted data.

**Vinokur’s model**

Vinokur [10], identified two main paths through a double wall coupled along an edge. An airborne path through the air in the cavity and a structure-borne path from one leaf of the wall to the other, via the coupled edges. An approximate expression was given for the airborne transmission loss, $R_z$, of the path via the edge connection. This was combined with the transmission loss of the direct path through the double wall, $R_1$, to give the total airborne transmission loss. Below the critical frequency, $f_c$, of the double wall, $R_z$ is given by,

$$ R_z = R_0 + 5 \log \frac{f}{f_c} + 10 \log \eta + 15 \log \left(1 - \frac{f}{f_c}\right) + 20 \log \frac{f_c \pi S}{c l} + \Delta R_f + 12 $$

(10.19)

and at frequencies an octave above $f_c$, $R_z$ is given by,

$$ R_z = R_0 + \Delta R_f + 6 $$

(10.20)

where $R_0$ is the transmission loss of a single leaf of the double wall, $S$ is its surface area and $\eta$ is the damping given by eqn(2.91). In these equations $\Delta R_f$ is given by,

$$ \Delta R_f = \left[1 + \left(\frac{\pi^3 m S \eta f_c f}{2 l \rho c^2}\right)^2\right] $$

(10.21)
where \( \rho \) is the surface density of a single leaf of the double wall, \( l \) is the length of the joint between the two leaves of the double wall and \( m \) is the mass per unit length of the structural bridge. For a double wall sitting on a floor slab, \( m \) is given by,

\[
m = \rho h_l(h_1 + h_2 + h_3)
\]

(10.22)

where \( \rho \) is the density of the floor slab and \( h_l \) is it’s thickness. \( h_2 \) and \( h_3 \) are the thickness of a single leaf of the wall and the cavity width respectively.

The predicted transmission loss for the test wall (before the concrete was added to the cavity) and the predicted transmission loss for a single leaf of the wall were obtained from an SEA model used for \( R_l \) and \( R_o \) in the above equations. The predicted curve from eqn(10.20), is shown on Fig 10.17. Below \( f_c \), the agreement between the prediction and the measured data is reasonable, the prediction being around 5 dB higher. Above \( f_c \) the predicted curve is around 20 dB too high. Vinokur performed measurements on double glazed windows and obtained good agreement between the results and his predicted data. It is possible that some of the assumptions made in deriving his approximate expression cease to be valid for heavy forms of construction.

**SEA model**

In order to predict the coupling between plates that are coupled at the base of a cavity wall, cross joint theory was used. Two SEA models were used to provide the predicted data for the wall. The first was a small model consisting of the two leaves of the test wall and the two floor slabs. This was used to study the behaviour of different types of joint and select the one that best matched the performance of the test wall. The second SEA model was larger and included all of the transmission suite and the coupling obtained from the first model.

The two leaves of the test wall and the two chamber floor slabs form the joint as shown in the top part of Fig 10.18. This is identical to the wall shown at the bottom of the figure, where one of the leaves of the test wall is rotated through 180° to form
Predicted level difference from Vinokur's model.

Predicted level difference from SEA model.

Measured level difference.

Fig. 10.17 Measured and predicted normalised airborne level difference of the cavity wall with cavity fill. Predictions made using Vinokur's [10] theory and using the SEA model.
Plates forming the joint at the base of the test wall.

Equivalent cross joint.

Fig. 10.18 Plate numbering convention for the test wall and floor slabs.
a cross joint. With this joint configuration the transmission coefficient and hence the CLFs can be computed.

The simplest condition is to consider bending waves only, using the theories given in chapter 2. A refinement is to allow displacement of the joint and hence allow in-plane waves to be generated. The mass of the concrete at the centre of the joint can also be modelled as a beam using the boundary conditions given by Steel [53], to give the most accurate model.

The SEA model shown in Fig 10.19 was used to examine the behaviour of these joints. The leaf of the test wall in the source chamber and the two floor slabs were assumed to have a TLF given by eqn(2.91) and the leaf of the test wall in the receiving room was assumed to have a TLF equal to the sum of the CLFs and an ILF of 0.008. The model was solved for a power input into the leaf of the wall built in the source room (subsystem 2 in Fig 10.19). The predicted velocity level difference between the two leaves of the test wall, based on the three sets of boundary conditions, are shown in Fig 10.20. The coupling due to the ties was omitted from the predictions to allow the effect of the different boundary conditions to be seen clearly. The predictions based on the simple joint model and the joint model permitting in-plane motion give poor agreement with the measured data. The prediction that includes the effect of a beam gave much better agreement with the measured data, in both level and general shape of the curve. The predicted curve is about 4 dB higher than the measured data but uncertainties over the physical properties of the beam and it's location relative to the centre of the joint could, in part, be responsible for some of the disagreement.

The full SEA model of the test chambers, described in chapter 3, was used to make the predictions for comparison with the measured data. The CLFs for the beam joint were used to couple the two leaves of the test wall and the two floor slabs. The beam is not represented as a subsystem in the model, instead when calculating the transmission coefficients for the joint, it is treated as an impedance which is obtained from it's material and physical properties. The coupling across the ties and the air in the cavity was the same as the values used in chapter 6 for the wall with butterfly
Fig. 10.19 The important subsystems in the SEA model of a cavity wall with ties and coupling at its base.
Fig. 10.20 Predicted structural level difference using various cross joints.
ties. A single CLF for coupling between the leaves of the test wall was obtained by adding the CLFs for transmission across the wall ties and the air in the cavity, to the cross joint CLF as shown in Fig 10.21. At low frequencies transmission between the two leaves is dominated by coupling across the cavity and above 100 Hz the path around the base of the wall dominates transmission.

Measured TLFs were used for the two rooms. For the rest of the model the sum of the CLFs plus an ILF was used to obtain the TLF. For the structure of the test chambers the ILF was assumed to be 0.015. For the test walls 0.008 was used, a value obtained from measurements of structural damping. As the leaf in the source chamber was coupled to several other subsystems around it’s perimeter, the predicted value of total loss factor showed reasonable agreement with the measured values. The free standing leaf was only coupled along it’s base and as a result it’s predicted total loss factor was low, up to 6 dB lower than the measured values. This can be seen in Fig 10.22. The measured values correspond to the average value for the chamber and not the test wall. As with the prediction for the wall with 25 butterfly ties the predicted value was used in the model.

The measured and predicted structural level difference is shown in Fig 10.23. The inclusion of the transmission across the air and ties in the cavity improved the agreement with the measured data at low frequencies. At frequencies above 100 Hz, where the path via the bottom of the cavity was dominant, the prediction is about 4 dB higher than the measured data. Part of the difference between the measured and predicted data is probably due to uncertainties in the exact nature of the coupling at the base of the wall, however, the assumption that it behaves as a cross joint with a beam at it’s centre provides predicted results which show reasonable agreement with the measured data. The curve showing the result of additional bonding is discussed later.

The two leaves of the test wall were assumed to behave as two plates in a cross joint with the floor slabs. It was therefore useful to perform measurements from the floor slabs of the chamber to the test wall. Fig 10.24 and Fig 10.25 show the measured and predicted results. The difference between the two predicted curves is due the
Fig. 10.21  The predicted CLF for the test wall with tie coupling and coupling along its base.
Fig. 10.22 Measured and predicted damping for the two leaves of the cavity wall.
Fig. 10.23  Measured and predicted velocity level difference for transmission from the built in leaf to the free standing leaf of the test wall.
Fig. 10.24 Measured and predicted velocity level difference for transmission from the source room floor slab to the leaves of the test wall.
Fig. 10.25  Measured and predicted velocity level difference for transmission from the receiving room floor slab to the leaves of the test wall.
difference in the damping of the two leaves of the test wall. The agreement between the measured and predicted data is reasonable at the mid frequencies in Fig 10.24 and at the low frequencies in Fig 10.25.

The measured and predicted airborne level difference is shown in Fig 10.17. There is good agreement between the two curves, though the prediction underestimates the level difference below the critical frequency of the wall.

The results from the airborne prediction help to explain the measured airborne results in Fig 10.15 and the structural level difference on Fig 10.16. These figures show how the performance of the wall changed upon the addition of the cavity fill. The airborne data showed a drop in level difference which started from 63 Hz whilst for the structural data, the cavity fill only affected the data above 100 Hz. Fig 10.26 shows the predicted contributions from the two dominant surfaces which radiated into the receiving room. Since the critical frequency of the floor slab, (100 Hz) was lower than the critical frequency of the test wall (297 Hz) there was a region between these frequencies where the floor slab was radiating sound efficiently and the test wall was not. Increasing the coupling to the receiving room floor slab by the formation of the cross joint, increased it's energy level and hence the power it radiated. For the predictions made, both before and after the cavity fill was introduced, the floor was the dominant radiator of sound in this frequency region. However, the increased coupling between the floor slabs caused by the cavity fill increased the importance of this path. Since the structural level difference between the leaves of the test wall is not affected by flanking to the same extent, no change in level difference occurred in this frequency region.

The purpose of coupling the two leaves of the test wall was to examine how transmission across the foundation affects the sound insulation of a double wall. For the experiment, the two floor slabs provided the constraining effect that the foundation would have on the base of a real wall. For a real wall, the foundation is below ground level and so would not radiate sound into the rooms separated by the cavity wall. The contributions from the floor slabs of the test rooms would not, therefore, be present on a real wall and the data in the frequency regions where
Total sound pressure level in the receiving room.

Contribution from the free standing leaf of the test wall.

Contribution from the receiving room floor slab.

Fig. 10.26 Contributions to the receiving room sound pressure level from the test wall and the chamber floor slab.
radiation from these surfaces is dominant are not representative of the behaviour of a real wall. Fortunately the floors only dominate transmission over a narrow frequency range and over the rest of the frequencies the test wall is the dominant radiating surface.

Due to the nature of the construction of the test chambers, the joint between the edges of the two floor slabs did not run along the centre of the cavity. As can be seen from Fig 10.14, the gap is closer to the base of the free standing leaf of the test wall. It is possible, therefore, that the bond between the free standing leaf of the test wall and the reverberation room floor slab, (plates 2 and 4 on Fig 10.18), might be weaker than the bond between the built in leaf of the test wall and the source room floor slab, (plates 1 and 3 on Fig 10.18), due to the smaller amount of cavity fill in contact with it. This would be a problem if cracks had formed along the mortar joint at the base of the free standing leaf. If the bond between the floor slab and wall was broken then the joint between the remaining plates would be a Tee joint instead of a cross joint and would result in stronger coupling and lower level difference.

To see whether this was the case, the effect of increasing the bonding of the reverberant room floor slab to the free standing leaf of the test wall was examined. Fig 10.27 shows how this was achieved. A course of dense concrete blocks was laid on the reverberant room floor slab, 100 m away from the free standing partition. The gap between these was then filled with concrete. The structural level difference measurement between the leaves of the test wall was then repeated.

The measured structural level difference for the wall after the extra bonding with the receiving room floor was added is shown in Fig 10.23. The addition of the extra bonding has caused the level difference to rise by about 3 dB for the frequencies above 160 Hz and shows good agreement with the predicted data. Below this frequency there was little change in the measured level difference, except for the large peak at 63 Hz. Little change would be expected below 100 Hz because transmission across the wall ties was the dominant path in this frequency region and this path would be unaffected by the coupling at the base of the wall.
Receiving room.
Source room.

Concrete

200 mm

215 mm

Receiving room floor slab.
Source room floor slab.

Replacement wall tie.
Cavity fill

ΔΔΔΔ

ΔΔΔΔ

ΔΔΔΔ

ΔΔΔΔ

ΔΔΔΔ

ΔΔΔΔ

ΔΔΔΔ

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ΔΔΔΔ

ΔΔΔΔ

ΔΔΔΔ

Leaf bonded along one vertical edge to another wall.
Leaf built free standing.
Strip foundation.
Floor slab

(Both leaves 3 m long).

Fig 10.27 Extra bonding at the base of the test wall.

Fig 10.28 The small test wall on a strip foundation.
In addition to the tests performed on the test wall built in the transmission suite, tests were also performed on a smaller cavity wall. This measured 3.0 x 1.5 m and was built on a strip foundation cast on top of a floor slab supported on soil. One of the two leaves of the wall was built free standing and the second leaf was butted up along one edge to a concrete wall. A section through the wall is shown on Fig 10.28. Only structural tests were performed on this wall as it was not built between two rooms. The cavity was 75 m wide and the top and one edge were left open.

Measurements were made on the wall to examine how some of the other mechanisms present at the foundation level, affect the behaviour of the wall. Tests were performed to examine how the addition of coupling across the cavity via a wall tie affected performance and also how the loading of the faces of the test wall by soil, which is present when the foundation trench is backfilled, affected performance.

Fig 10.29 shows the results from two sets of structural level difference measurements made on the wall. For the first measurement that was performed, the only structural transmission path was via the foundation. The measurement was then repeated after a single replacement wall tie was inserted into the test wall. For the test with the tie, the level difference rises from a low value at low frequencies, where transmission across the ties dominated and then levels off over the remainder of the frequency range at about 8 dB. The behaviour at low frequencies shows large fluctuations, probably due to the small size and hence low modal density of the leaves of the wall. For the same wall without the tie there was not a drop off in level difference at low frequencies as the path via the tie was not present. Above 400 Hz there was no change in the performance of the wall suggesting that in this frequency region the path via the foundation dominated transmission. The predicted curves for the wall were obtained using the same joint that was used for the first test wall. The agreement between both predictions and the measured data is reasonable.

Fig 10.30 shows the results for the wall (with foundation coupling only), plotted with the results from the measurement performed to study the effect of backfill on
Measured level difference for the wall with foundation and tie coupling.

Predicted level difference for the wall with foundation and tie coupling.

Measured level difference for the wall with foundation coupling only.

Predicted level difference for the wall with foundation coupling only.

Fig. 10.29 Measured and predicted structural level difference for the small test wall, with and without, tie coupling.
Fig. 10.30 Structural level difference for the small test wall, with and without, backfill.
transmission. To perform this measurement sand was heaped up against the faces of the two walls to a height of 540 m on one side and 340 m on the other side. It can be seen that the effect of the soil loading is to increase the level difference at frequencies above 400 Hz by between 4 and 5 dB. Below this frequency, the addition of the backfill did not result in any significant change in the level difference which suggests that in this frequency region the backfill had little effect.

The results from this wall are surprisingly similar to those obtained in the transmission suite. Fig 10.31 shows the level difference for the wall tested in the transmission suite, with the results obtained from the smaller test wall with one tie present. Although these results are not directly comparable, the trends are clearly the same. At low frequencies transmission across the wall ties dominated and both curves show a general rise in level difference with increasing frequency as the strength of this path diminishes. At higher frequencies the path via the base of the wall is dominant for both walls.

Discussion

The predictions made in this section are purely empirical and the test wall built in the transmission suite is a very idealised representation of a real foundation. The results obtained by examining the behaviour of this joint under controlled conditions are however, a reasonable first attempt towards understanding its behaviour. The agreement they showed with the results from a wall built on a concrete slab cast on the ground were encouraging. However, to fully observe the behaviour that occurs, measurements would have to be made on test walls built off strip foundations cast in trenches. This would allow the restraining effect that the soil has on the forces and moments imposed on the foundation by the leaves of the wall to be modelled correctly. In addition, it would allow the effect that backfill has on transmission, to be observed. It is likely that all these effects would serve to reduce transmission.

To arrive at a more satisfactory method of predicting the performance of such models would require a study of the different wave types that propagate in semi-infinite
Fig. 10.31 Comparison between the measured structural level difference for the large and small test walls.
media. This would allow expressions for force and moment impedances for the soil to be determined. These would allow more accurate predictions to be made and would remove the need for the empirical approach adopted here. The numerous different types of wave that can occur may, however, make this approach difficult.

10.5 Conclusions

The transmission via three paths present in cavity walls was examined in this chapter.

In previous chapters, predictions for paths that involve wall-room coupling, in the region of critical frequency, were found to be unreliable. The radiation efficiency obtained from the commonly used equation, derived by Maidanik, was found to show poor agreement with measured results from masonry walls. A simple expression based on the radiation efficiency of the fundamental mode was presented. This showed better agreement with the results from masonry walls and hence resulted in improved predictions for these paths.

An expression was presented that predicts the performance of a double wall in the region of the mass-spring-mass resonance. The theory predicts that dips in airborne data are due to increased structural response and hence increased transmission at resonance. The dip in the predicted structural data is due to a structural anti-resonance which occurs at a frequency $\sqrt{2}$ below the airborne dip.

Tests were performed on the walls to study the effect of the coupling at the base of a cavity wall caused by the foundation. Measurements performed in a transmission suite on a cavity wall with coupling at it's base showed that the effect of the coupling was to cause a large reduction in the sound insulation of the wall. The only region where the performance of the wall was unaffected was at low frequencies where coupling across the air and ties in the cavity dominated.

Coupling the two leaves of the test wall at their base resulted in the formation of a cross joint between these two walls and the two floor slabs of the test chambers. The
prediction obtained by assuming the joint between the test wall and floor slabs behaved as a cross joint with beam at its centre gave the best agreement with the measured structural data. The airborne predictions showed that, except at the critical frequency of the floor slabs, the test walls were the dominant radiating surfaces. The results from this wall should therefore provide an indication as to the strength of the path across the foundation. Test results from a cavity wall built on a concrete slab in contact with the ground suggested that using this method to predict the performance of real foundations may give reasonable predicted data. The theory is not, however, based on the true boundary conditions at a real foundation and so only gives an indication as to the type of behaviour that may be expected.
Chapter 11
Conclusions

11.1 Introduction

The first section in this chapter draws together the important findings and conclusions from this thesis. This is followed by a brief discussion of the implications that these have for the performance of common forms of building construction. The final part of the chapter gives proposals for further research.

11.2 Conclusions

The aim of this thesis was to examine sound transmission across cavity walls. The approach adopted was to identify and then examine the behaviour of individual transmission paths. Statistical energy analysis (SEA) was used to provide predicted data to compare with measured results obtained from test walls designed to highlight specific paths or groups of paths. This provided a check for the theory and allowed the importance of the paths to be assessed.

A basic description of the procedure involved in using SEA to model a structure was given in chapter 2, along with the theory necessary to predict it’s performance using the technique. In addition to the theory necessary to model general building type structures, this chapter also examined some of the existing theories specific to transmission through cavity walls.

It is necessary to know some of the basic physical and material properties of a
structure to enable the theories in chapter 2 to be used. Chapter 3 described the existing non-destructive methods for determining these in addition to methods for measuring structural damping and the damping of cavities. A technique for measuring the stiffness of wall ties was presented. This involves casting a concrete cube onto each end of a wall tie and exciting the system along its longitudinal axis. The resonance frequency of the system is measured and provided the mass of the cubes is known, the tie stiffness can be determined. This property is important in determining the coupling between the two leaves of a cavity wall due to the wall ties. Also described in chapter 2 were the measurement techniques used to determine the airborne and structural performance of the test walls. It was necessary to perform these measurements to a high level of accuracy as some of the changes made to the test walls resulted in only minor changes in performance. Most of the third octave airborne and structural measurements were made to a 95% confidence interval of less than ± 1 dB.

The review of existing work in chapter 1, revealed that many transmission paths exist across the air in the cavity between the two leaves of a cavity wall. Chapter 4 examined the relative importance of these for masonry cavity walls. One of the paths that was highlighted in chapter 1, was transmission due to the stiffness of the air in the cavity, path 1-2-[5]-3-4 (where the notation described in chapter 1 has been used). This was found to dominate performance in the region above the critical frequency of the cavity wall. A convenient technique was presented for modelling the transmission via this mechanism. It assumes that the stiffness of the air can be concentrated at a single point and uses an existing theory for metal tie coupling to obtain a coupling loss factor (CLF) for an "airtie". At frequencies above the critical frequency of the cavity wall, predictions made using this theory showed good agreement with predictions made using classical theories. There was also good agreement between the predictions and the measured structural level difference between the leaves of the test walls. Below critical frequency, however, the "airtie" overestimated the strength of the coupling across the cavity and the agreement was poor. This is probably a result of the hydrodynamic short circuit which occurs on the surfaces of the test wall below critical frequency. If the air is able to undergo lateral motion its stiffness is reduced and the coupling will be weaker. Despite the good
agreement between the measured and predicted structural data, the airborne level
difference showed poor agreement, the prediction being higher than the measured
results. There was, however, evidence to suggest that the measured data for the walls
with weak cavity coupling, was affected by flanking transmission caused by a fault
in the construction of the wall.

Measurements were also made of the sound pressure level (SPL) in the cavity of one
of the test walls. This allowed the accuracy of the expressions for predicting cavity
coupling to be assessed. The predicted SPL showed good agreement with the
measured results and suggests that for masonry walls, paths via the cavity have been
predicted correctly. In addition, the cavity SPL displayed evidence of cross cavity
modal behaviour which occurred at the same frequencies where dips were observed
in the measured level difference data. Very high level differences were being
measured at these frequencies and the resonances only had a small affect on the
overall performance of the wall.

The results from measurements to examine the transmission across steel wall ties
were presented in chapters 5 and 6. The effects of varying the number and stiffness
of the ties was examined, both theoretically and experimentally. The theoretical study
showed that for every doubling of the number of a given type of tie, the coupling will
rise by 3 dB. The airborne and structural level difference will therefore drop by the
same amount. Doubling the stiffness of a fixed number of ties was shown to cause
a 6 dB drop in the airborne and structural performance of the wall. These effects
were borne out in the measured data for walls where the path across the ties was
dominant. In addition, an envelope was identified, within which all the measured
results for a wall with a fixed number of ties of arbitrary stiffness would be expected
to lie. The upper band of this envelope is set by the performance of the wall with
only air coupling in the cavity. The lower band is set by the performance of the wall
with infinitely stiff ties. Most of the measured data was found to fall within this
envelope. The only exceptions occurred for walls with soft ties. These were sensitive
to variations in the strength of the airborne path via the cavity, however, when
measured values of air coupling were used to account for this path, the prediction
showed good agreement with the measured results.
The measured results showed some evidence of the change in performance that is predicted to occur in a cavity wall at the mass-spring-mass (MSM) frequency. The theory for cavity walls predicts that, below the MSM resonance the air in the cavity is very stiff and the wall behaves as a single subsystem. Above the resonance, the air coupling is much weaker and the two leaves of the wall act independently. Measurements of the structural response of the test walls indicated that an increase in mobility occurred when passing from the low, to the high frequencies, through this region. This suggests that the behaviour of the wall changed from that of a stiff structure to that of a more flexible structure and is consistent with the predicted performance. The measurement also showed that, as more ties are added to the wall, the size of this mobility change increases. When there is only air present in the cavity, a slip plane will exist between the two leaves of the wall and the stiffness will equal the sum of the stiffnesses of each leaf. The measurement indicated that as ties are added, the slip plane becomes less effective until a point is reached where it is totally absent. The behaviour is then that of a single, very stiff wall, which for the measurement performed was around twenty-three times stiffer than a single leaf. This has implications on the way in which a cavity wall is modelled below the MSM resonance frequency. For walls with no ties or very soft ties existing theory can be used. This assumes that a slip plane exists and makes a correction that allows a two subsystem SEA model to predict the performance of the wall above and below the MSM resonance. Walls with stiff ties, however, have to be modelled using two separate models. The existing theory is suitable for predicting the performance that occurs above the MSM resonance frequency, however, a second low frequency model is necessary below the MSM resonance, where the wall must be modelled as a single stiff subsystem.

Chapter 7 examined the transmission that occurs in a cavity wall when the two leaves are coupled along a line, either along an edge or at their centres. A wave model was used to obtain the transmission coefficients for joints where the coupling between the two leaves was rigid. This provided predicted data which showed good agreement with measured results obtained from a test wall built to examine the performance of this type of joint. The results showed that the coupling is strong and can result in significant transmission. This theory has applications for the joints that occur around
doors and windows in external cavity walls and also for dry lined walls where plasterboard is fixed to a heavier core wall using timber battens or plaster dabs.

The performance of dry lined walls was examined in chapter 8. For this type of construction, the dominant transmission through the air in the cavity occurs via path 1-2-5-[3]-4 and involves resonant transmission through the core wall into the cavity and then non-resonant transmission from the cavity through the dry lining. The addition of absorbent quilt to the cavity was found to result in improvements of up to 10 dB in the airborne performance of the wall. It proved possible to predict the airborne performance of the wall with a reasonable degree of accuracy, however, predicting the structural performance was less successful. The resonant coupling via the cavity overestimated the transmission between the two leaves of the wall, suggesting that for walls of this nature, there may be limitations to the existing theory. The "airtie" prediction also overestimated the coupling, though this was probably caused by the high critical frequency of the dry lining. Chapter 4 showed that, at some frequencies the "airtie" overestimated the stiffness of the air in the cavity. This was attributed to the hydrodynamic short circuit that occurs on the surfaces of the cavity wall below critical frequency, which allows the air to undergo lateral motion and reduces its stiffness. The dry lining had a high critical frequency and the use of the "airtie" below this frequency would be expected to overestimate the coupling. The effects of metal ties and of line coupling were also investigated. Metal ties were found to have little affect on the airborne performance of the wall as the airborne path via the cavity was dominant. They did, however, affect the structural results, and above the MSM resonance frequency, the predicted structural data showed good agreement with the measured results. Line coupling is much stronger than tie coupling and was found to have an affect on the airborne performance of the wall, the dominant transmission mechanism being nearfield radiation from the dry lining in the region around the structural joint. The structural performance of the wall with battens was overestimated slightly by the prediction.

Direct power flow measurements were used in chapter 9 to examine the performance of individual wall ties. An instrumented wall tie was built into a wall and was used to measure the power flow. A two accelerometer technique for measuring structural
intensity was used to measure the power flow across additional ties that were added to the wall during the course of the experiment. The measurements made using the instrumented tie showed no significant variations in the power flow as the number of ties was increased. This supports the assumption made in deriving the expression for tie coupling, that the power flow across individual ties is uncorrelated. The measurements made using the tie also provided evidence that suggests that some of the modes on the source leaf of the wall are more successful at transmitting power than others. The discrete nature of the structural coupling at a tie means that the ability of any given mode to transmit power depends upon the strength of it's response at the tie location, modes exhibiting strong responses transmitting more power than modes that exhibit a weak response. Further evidence of this type of behaviour was found from the measurements made using the structural intensity technique. These showed that there were variations in the power flowing across different ties, corresponding to a difference in their position relative to the modes on the source wall. As ties are added to a cavity wall, the ability of any individual tie to influence the overall power flow will diminish. This was reflected in the tie CLF measured using the intensity technique. As ties were added to the wall the measured CLF showed smaller fluctuations. This agrees with the behaviour observed in the narrowband structural level difference data in chapter 5, which shows that with the addition of ties to a wall, the level difference curve becomes smoother as the effects of the transmission of discrete modes becomes less important.

Chapter 10 examined three transmission mechanisms to assess the importance of the paths they formed a part of. These were wall/room coupling in the region of critical frequency, the effect of MSM resonance on the performance of a cavity wall and the transmission that occurs at the foundation of a cavity wall.

All the predictions made in the thesis, for transmission paths that involved wall/room coupling, showed large dips in the region of critical frequency that were not observed in the measured results. The dips in the prediction were caused by an overestimation of the radiation efficiency made by Maidanik's [12] approximate expression for this frequency region. An alternative approximate expression was presented, based on the radiation efficiency of the fundamental mode on a plate. This was found to provide
predictions that showed improved agreement with the results from both single and double walls.

Expressions were presented that predict the airborne and structural transmission that occurs as a result of the MSM mechanism, path 1-[2]-[5]-[3]-4. These are based on a model of two damped masses coupled by a spring. The theory predicts a dip in the airborne level difference at MSM resonance, caused by the increased response of the leaves of the cavity wall. A dip is also predicted in the structural level difference, however, this occurs at a frequency $\sqrt{2}$ below the MSM resonance and is caused by an anti-resonance on the receiving leaf of the cavity wall. Evidence for this type of behaviour was found in the measured results from the test wall examined in chapter 5. Dips were observed in the structural level difference at frequencies close to the predicted anti-resonances. The dips observed in the measured airborne results occurred at higher frequencies, close to the predicted MSM resonance. Using this theory to predict the structural transmission which occurs via this path results in a slight overestimate in the size of the dip in the level difference. The airborne prediction underestimates the strength of the transmission at the resonance frequency. The theory, as presented, is limited to normal incidence. Modifying it to account for obliquely incident sound waves and integrating to obtain a random incidence solution would result in stronger predicted airborne transmission and hence better agreement with the measured data.

The final path examined in chapter 10 was the path that occurs at the foundation of a cavity wall. Measurements were made on a cavity wall built in a transmission suite which had the base of the cavity filled with concrete. This had the effect of coupling the base of the two leaves along with the floor slabs off which they were built and simulated the constraining effect that would be imposed on a cavity wall by a strip foundation. This results in a large reduction in the performance of the wall and implies that the transmission via this path is very strong. Predictions of an empirical nature were obtained by modelling the coupling as a cross joint with a beam positioned at its centre. This showed reasonable agreement with the measured results. Measurements were also made on a small test wall built on a concrete slab cast on the ground. These allowed some of the effects that the soil would be expected to exert
on the foundation, to be assessed. The results from these measurements were similar to those for the test wall tested in the transmission suite and also showed good agreement with the cross joint prediction. This suggests that the effects of the ground were insignificant compared with the constraining effect of the foundation. These results are not conclusive, however, as the nature of the coupling between the floor slab and the ground was unknown. For a real wall, the coupling at this joint would be expected to be weaker. The measurements performed in this thesis did not account for the full effects of the soil on the foundation, or the effects of soil loading on the faces of the wall below floor level. The effects that ground floor slabs cast against the base of the cavity wall were also neglected. These will reduce coupling and hence reduce the strength of this path.

This thesis has identified and examined the important transmission paths through three different types of cavity wall. Data from test walls designed to highlight specific paths or groups of paths has been used to verify existing theories for predicting their performance. Where these were found to be inappropriate, alternative theories have been proposed. Combining these theories within the framework of SEA will allow the overall performance of a cavity wall to be predicted, whilst still enabling the performance of the individual paths to be examined. In buildings, many other types of double and multi leafed construction are commonly encountered eg timber floors, stud partitions, metal clad walls, double and triple windows etc. Many of the paths examined in this thesis will be common to these types of structure and should go some way to predicting their behaviour. Determining which paths are important allows attention to be concentrated at specific parts of the wall’s design and provides an opportunity to design structures with improved sound insulation.

11.3 Discussion

The work on examining the behaviour of transmission paths allows some general conclusions to be drawn on the behaviour of different types of construction.

In chapter 8 the implications that the results from the dry lined wall have on the
behaviour of similar types of construction were discussed. Four types of construction were examined and these can be divided into two groups based on their behaviour.

The first group of structures were masonry walls finished by the direct application of plasterboard, either on dabs or on battens. The high air stiffness resulting from the narrow cavities and the lightweight nature of the dry linings on these walls, means that the MSM resonance occurs at a high frequency. For typical walls, this falls well within the building acoustics range of frequencies and could result in poor performance. Single wall behaviour occurs below the resonance and at these frequencies the wall behaves as if it were hard plastered. Above the resonance, nearfield radiation from the dry lining in the region around the dabs or battens dominates transmission.

The second group of structures were characterised by having wide cavities and weak structural coupling across the cavity. The two forms of construction discussed were concrete floors with an isolated timber walking surface and independent plasterboard partitions. The increased width of the cavity in these forms of construction results in the MSM resonance occurring at a lower frequency than it does for the dry lined walls. For the floor, a resilient inter-layer is positioned between the structural concrete slab and the timber walking surface resulting in weak structural coupling between the two. For the independent plasterboard partition, the dry lining is fixed to a frame that is built independently from the core wall and as a result, the two leaves are structurally isolated from each other. The dominant transmission path therefore occurs through the cavity, via path 1-2-5-[3]-4. To minimise transmission via this path, it is important that the cavity is highly absorbent and this is normally achieved by building a glass fibre quilt into this region.

The behaviour of masonry cavity walls differs from that of dry lined construction. In general for this type of construction, coupling due to wall ties dominates transmission at low frequencies and coupling around doors and windows or at foundation level will dominate at higher frequencies. At low frequencies, both the air in the cavity and any cavity wall ties that might be present are very stiff and single wall behaviour occurs. The improvements in wall performance that can be achieved by reducing the tie
stiffness is therefore limited, as the benefits of reducing tie stiffness will cease to accrue once the ties are softer than the air in the cavity. As the frequency rises, the coupling across the air in the cavity and across the ties weakens and high level differences can be achieved for walls tested under controlled conditions. For walls in real buildings, transmission from other paths will be present. This occurs at the perimeters of doors and windows in external walls and at the foundation of all walls. Measurements made in the laboratory to examine these paths showed that this transmission is strong and it is the existence of these paths that prevents the high sound insulation offered by cavity construction from being fully achieved. Where high performance might be achieved, however, is in tall buildings. For rooms that are several stories above ground level, the path via the foundation involves transmission past several floor slabs. These result in significant attenuation and provided transmission via the external wall is weak, the performance of the cavity party wall might begin to approach that of an idealised wall with only the air in the cavity and the wall ties coupling the two leaves.

11.4 Suggestions for further research

During the course of this research, several areas of study were encountered that warrant further investigation.

The work on double walls with line coupling was restricted to forms of construction where the joint was rigid. The theory could be extended to account for the stiffness and mass effects of the structural bridge. This would be useful for modelling the behaviour of concrete party floors where resilient materials are placed between the structural slab and a timber walking surface. Stud partitions and timber floors were not studied in this thesis but they do possess joints similar in nature to the dry lined walls. There is, however, a large difference between the properties of the leaves of these structures and the stiff framework onto which they are fixed. To provide reliable predictions will probably require that the mass and stiffness effects of the frame are incorporated into the model for the joint.
The behaviour of sound in the cavities of double walls would also benefit from a more detailed examination. In real buildings the cavities in the party and external walls are much longer and taller than the individual walls that radiate into them. It is unlikely that the cavity will be excited into a truly reverberant state and as a result the distribution of the energy within the cavity will not be uniform. To model this as a subsystem using SEA, may necessitate that it is divided into several smaller subsystems. CLFs will be required to allow the transmission between these sub-cavities to be determined. This is a problem that will also be encountered when modelling the external leaf of an external cavity wall and is a problem that is commonly encountered when using SEA to model large subsystems, eg corridors, concrete floor slabs in open plan buildings etc.

The relationship between the absorption in a cavity and the associated damping of the subsystem also requires further study. Existing theory assumes that only the absorption present at the reveals of the cavity is effective at providing damping. For walls with cavities that have little absorption, however, the measured value of cavity damping is higher than would be predicted, based on the amount of absorption present at the reveals. This suggests that absorption present elsewhere in the cavity can provide damping. This is a problem which is closely linked to the question of where absorption should be placed for best effect and currently there is no consensus in the literature to provide an answer.

The coupling between the cavity and the leaves of a double wall also requires further study. Existing theory assumes that radiation into a cavity is the same as radiation into a quarter space. Predictions obtained using this theory show reasonable agreement with measured data from masonry walls, however, they overestimate the coupling for dry lined walls. This may be due to a limitation on the range of angles over which sound is able to radiate into a cavity, imposed by it's narrow width. Further investigation into the interaction between structures and cavities might provide a more accurate means of predicting this coupling.

Finally, the study made in this thesis, on the coupling that occurs at a foundation can be considered a reasonable first step towards understanding the behaviour of this
joint. The predictions were, however, of an empirical nature and it would be desirable to examine this joint further to determine the boundary conditions necessary to produce exact predictions. This will involve an examination of the interaction between the strip foundation and the soil it is cast onto to arrive at expressions for the force and moment impedances. In addition, the effects of soil loading on the faces of the wall and the effects of ground floor slabs cast up against the foot of the wall, also need to be considered. This joint will be present at the base of most of the cavity walls encountered in real buildings and unlike the path via the perimeter of doors and windows, reducing transmission by the introduction of an inter-layer will probably be impractical. If the mid and high frequency performance of real cavity walls is to be predicted with a reasonable degree of accuracy, the coupling at this joint must be determined.
REFERENCES


[31] Communication from R.J.M. Craik.


ADDENDUM

The SEA model used to provide the predicted data in this thesis included not only the double walls being studied but also the transmission suite in which they were tested. This allows the effects of flanking transmission resulting from the interaction between the test walls and the transmission suite to be accounted for. The transmission lab affects some of the airborne results but does not affect structural data.

In each of the figures listed below, the sum of the direct paths is considerably less than the sum of all paths. Typically the difference is,

| Freq. (Hz) | 50  | 63  | 80  | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1K  | 1.6K | 2K  | 2.5K |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Diff. (dB) | 11  | 12  | 14  | 14  | 11  | 14  | 13  | 12  | 14  | 14  | 14  | 14  | 14  | 14  | 13  | 12  | 11  |

The figures affected are,

Fig 4.4, Fig 4.7, Fig 4.8.
(difference between the sum of all the paths and the "airtie" path).

Fig 5.8, Fig 5.13.
(difference between the sum of all the paths and the path across the airtie plus the metal ties).

Fig 6.7, Fig 6.11, Fig 6.14, Fig 6.16, Fig 6.18, Fig 6.2.
(difference between the sum of all the paths and the path across the airtie plus the metal ties).

Fig 7.10.
(difference between the sum of all the paths and the path across the "airtie" for the curve showing the performance of the wall before the addition of the sound bridge and the difference between the sum of all the paths and the path across the line connection for the curve for the wall with the sound bridge).

Fig 10.7, Fig 10.8, Fig 10.13
(difference between the sum of all the paths and the path across the airtie plus the metal ties).

ERRATUM

In Fig 4.4 the curves with the line types, .....

and in Figs 4.5, 4.6 and 4.7 the curve with line type, .....

are energy level differences. For these to be comparable with the remaining curves on the figures, which are sound pressure level differences, they must be increased by 4.1 dB.