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The Acoustic Design of Factory Built Homes

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Declaration

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

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Abstract

A general approach to investigate the problems associated with residential noise issues is described. This research combines knowledge of the evolving nature of the governmental legislation used to control the finished quality of modularly constructed building products with small scale laboratory testing, full scale on-site testing, and surveys performed on a population sample resident in modularly constructed dwellings. Due to the time and expense associated with full scale testing of every possible design, the clear need for the development of a reliable and accurate method to predict the acoustics performance of building elements has been explored.

Laboratory experimental work has yielded results that correspond well with that of large scale on-site testing. The results obtained have been vigorously examined in an attempt to understand the factors and parameters involved in the sound transmission through building elements. An attempt to simulate the test environment of reverberation chambers has been made, through the development of a mathematical model that predicts and assesses the acoustic behaviour of potential partition designs exposed to airborne sound, therefore reducing the need to construct and test small or large scale prototypes. Approximation methods have been investigated and found to accurately resemble test data within certain parameters. Limitations as to this type of methodology have been discussed.

Issues allied with the complexity of assessing the acoustic performance of various building methods have been considered and reviewed. A survey on a population sample has highlighted and characterised frequencies associated with perceived noise annoyance within the modular construction industry, and this work has been found to be in good agreement with other works in this field, further contributing to the continued understanding of the need for a method of determining acoustic performance by a single figure rating.

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Aims & Objectives

With the notion in mind that light steel framing, with its inherent lack of mass, is known to present significant challenges to overcome in terms of its resistance to low frequency sound transmission, several aims and objectives were set out at the concept stage of this research project in order to test/confirm this hypothesis.

The aims of this research therefore were to:

- Perform sociological survey to investigate the perceived noise related issues associated with modular construction
- Investigate the damping effect of coating on various grades of steel specimens in the lower end of the frequency range.
- Design and construct prototype floor and ceiling panels for reverberation testing and comparison with on site full scale testing.
- Within a suitable modeling framework, develop a mathematical model to predict the acoustic performance of single layer partitions over the British Standard 717 1/3 Octave band range
- Investigate the accuracy of known approximations and their relationship to measured sound reduction index values.

It is anticipated that through exploring several avenues of research techniques and ideologies, the acoustic behaviour of building elements at the lower end of the frequency range can be greater understood.

Chapter 1 Introduction

As peoples' expectations as to acceptable standards of living are rapidly increasing, so are the government regulations tightening to force construction companies to meet consumer demands. Over the last 10 years, the UK government has underlined its desire for urban regeneration in an attempt to revitalise the central districts of our cities, whilst highlighting areas in need of urgent re-development within the existing housing stock. This progress cannot be realised without overcoming the significant challenges associated with city central sites such as tight working conditions, speed of construction, massive financial implications, whilst achieving a quality design that can meet the requirements of the Building Regulations particularly in such high density residential accommodation.

The Egan Report, a definitive report on UK construction industry (Egan, 1998), concluded that more efforts must be made within the industry itself to streamline the processes involved in order to meet the increasing demands placed on the quality of the finished products. Over the last decade, the industry has therefore turned its attention to lightweight steel framing systems in place of the traditional timber building methods to construct pre-fabricated modular units. Of course, this type of construction is not without its problems. Pre-fabricated residential dwellings have long been operational, with early successes dating back to the first decade of the 20th Century in the United States. However, the poor pre-conception of this type of construction within British society, has forever placed a limitation on its potential, with the most damaging period proceeding World War II in which concrete and steel were abundantly used to provide a rapid solution to replace housing stock and provide large scale accommodation to encourage people to move to certain areas or for people who had found themselves homeless. Lightweight steel construction is by definition devoid of a mass comparable to more traditional construction methods such as masonry, and would therefore harbour noise related issues more readily due to this reduction in mass. It is therefore of great importance that methods are developed to overcome this issue.

Currently, environmental issues such as noise complaints are some of the most high profile challenges that dominate local authorities' agendas, which in turn focuses the attention on construction companies to develop and deliver viable solutions to the problem of unwanted noise, addressing such issues and the health problems that can arise as a result, with the ultimate goal of achieving consumer satisfaction. This research attempts to investigate the evolving nature of the legislation in place, tracing the development of the Building Regulations from their inception through to the current requirements. Due to the complexity of this subject, it has become increasingly difficult to be able to accurately assess the acoustic performance of building elements and make viable comparisons between various construction methods. By understanding the nature of noise complaints, highlighting frequencies associated with perceived noise annoyance within the modular construction industry, it is hoped to contribute to the knowledge and practice that currently exists in this field of research and gain further insight into the need for a method of determining acoustic performance by a single figure rating.

This thesis describes my experiences of on-site airborne sound transmission testing on full scale residential modules to gain a better understanding of the test methodology necessary to ascertain the acoustic performance of modular construction developed within Corus. To facilitate this process, and to highlight areas of success and improvement within residential modules, it was necessary to perform oral surveys on a population sample living in this environment. Evaluations and comparisons of various survey techniques are discussed in detail, and the chosen method executed on a population sample. By characterising various domestic noises and establishing their frequency ranges, this research highlights the audibility of such sounds, representing their impact on the occupiers of residential dwellings in terms of the annoyance perceived by the subject.

The reduction of sound through building elements is reliant on factors such as mass, damping, and stiffness. A section of this research therefore investigates the damping effect of coating on galvanized steel specimens in an attempt to measure, through a simple experimental set-up, to what extent various coatings may or may not impact upon the ability of several grades of steel specimens to withstand vibration. Through successful measurements, it is hoped that the damping coefficients of such specimens can be obtained and predictions made of the acoustic performance of full scale modules using this type of framing.

The final section of this research describes the construction and testing of a floor and ceiling element, and the laboratory testing that proceeded. Through detailed analysis of the results and expanding on theoretical equations, a mathematical model has been constructed to simulate the sound transmission though single-leaf partitions. This model has been used to create a test environment that, with further development, can be utilised to virtually construct complete building elements, tested across the 1/3 octave band frequency range to obtain an ISO-717 single figure rating, therefore accurately predicting the acoustic performance of modular construction elements, eliminating the costly and time-consuming necessity for proto-type testing. Through research in the field of work that unites noise pollution and construction, further understanding and knowledge can be achieved creating greater opportunities to tackle issues of residential noise complaints at the design stage of such constructions.

For Corus, a leading manufacturer of steel products worldwide, the construction industry represents a significant share of the company's annual turnover, approximately 30%. The automotive and packaging industries within Corus account for 16% and 15% of its turnover respectively. With this considerable contribution from the construction industry within Corus, it is critical that Corus maintains or increases its market share through developing its technologies to exceed that of its competitors. Corus stands face to face with significant challenges within the construction sector, with enormous opportunities to influence the construction industry itself whilst meeting the challenge of creating homes and commercial buildings that will shape communities and societies for generations to come. It is therefore vital that Corus equips itself to develop and expand its existing knowledge and technologies in the construction sector to meet the necessary regulations that are tightening as consumer demands increase, achieving customer satisfaction though innovative, durable and superior designs.

Chapter 2 Human Reaction to Noise

'More than two thirds of all complaints received by local environmental health officers relate to some form of domestic noise - that's twice the number generated by disturbance from business and leisure activities, construction work, vehicles and street equipment put together.' (Government news release 05/07/02)

2.1 Increasing importance of noise 'nuisance'

In the society in which we live, the expectations people have as to what is an acceptable environment to live in have greatly increased. Noise, whether it is wanted or unwanted, can have a significant impact on people's well being, and for this reason it receives a lot of attention from the source, through the transmission medium, to the recipients.

In contrast to many other environmental issues, issues associated with noise pollution continue to grow. This is evident in the number of complaints received by Local Authorities regarding domestic noise. In the home, there are several noise sources that commonly become a complaint, with road traffic noise being a dominant source (Berglund, Lindvall and Schwela, 1999). Population growth, urbanization and also technological development are seen to be the main driving forces, and the continued expansion of road networks, regional and international airports, and railway systems will only add to the problem. On a global scale, this growth in urban environmental noise pollution is unsustainable as it not only has a detrimental cumulative impact upon the health of a population, it also plays an important role in a reduced health of future generations, by degrading the social, residential and learning environments, resulting in potential economic losses (Berglund and Lindvall, 1995).

2.2 Human reaction to noise

In terms of human reaction to noise, the World Health Organisation (WHO) has defined health as being:

‘*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*’,

Present day sound perception theory is based on the development of psychometric methods linked to an increasing understanding of auditory anatomy and physiology. These psychometric methods attempt to provide objective quantification of sensations and perceptions that are inherently subjective. Because of the nature of this complex transition from subjective response to objective results, the history of psychometry is riddled with blind alleys and controversy. It is therefore apparent that when performing experimental analysis in this field, great care must be taken when inferring general principles from limited experimental data.

Sound is perceived in many different ways within any given population sample and it is important to understand the varying sound sources that exist in daily noise exposure and the consequent sound pressures that the human ear experiences. When measuring sound pressures, and because of the variation in humans’ sensitivity to sound throughout the frequency range, it is essential to incorporate various *‘weighting filters’,* the characteristics of which approximate to the sensitivity of the ear at various levels and frequencies, based on the Fletcher Munson curves. The most common weighting used is the *‘A weighting’*, which has the greatest sensitivity in the 1 kHz-5 kHz range. This is known to most closely correspond to the sensitivity of the human ear, and is therefore a more accurate measuring tool to understand the human ear’s response to sound levels. Less common weightings are B, C, and D. The B and C weightings have similar responses to the mid-frequency range of the human ear, but have greater sensitivity at the lower frequencies. These other weightings were originally intended to imitate the behaviour of the human ear at higher sound levels, but are now used to characterise noise within a more industrial setting. Due to the subjective nature of the perception of sound, noise can be perceived as both wanted, and unwanted. Music can be pleasurable to many people at the right time and place, but can similarly drive others to distraction at the wrong time and place. Sound can be a useful tool in the conveyance of information about the environment, various messages and speech communications, but at the same time can be harmful to the those exposed to it by interfering with these very same processes, disturbing rest, relaxation and sleep, changing people's behaviour through annoyance, and in extreme cases damaging the hearing mechanism itself. This perception of sound is an important subject, as it defines normal hearing capabilities. Achievements such as engineering noise control is only worthwhile if it leads to a measurable benefit, for example either against written standards, discussed in Chapter 3, or perhaps more importantly in terms of human perception.

Much research has been carried out by a significant number of research groups within this field of work, and the knowledge gained as a result is widespread. A leading research group, The London Health Observatory (www.lho.org.uk), have indicated that intermittent, higher frequency, short duration, intense sounds have a greater effect on a person's well being than continuous low frequency, long duration, low intensity sounds. It was also found that when exposed to these types of sounds, the level of disturbance or annoyance varied between the population samples. It therefore becomes apparent that it is not possible to make objective measurements of perception in the same way that objective measurements can be made of sound pressure level and frequency content as an objective measurement cannot be distorted by emotion, memory or personal bias, whereas a subjective measurement is directly related to perception and is therefore likely to be susceptible to such bias.

In order to gain a deeper understanding into the effects of unwanted noise, it is important to gain an insight into the processes involved from the sound source through the sensations within the ear to the way in which sound is then perceived. Firstly there is an infinite array of sounds or acoustic signals that humans are exposed to. However, it is by no means conclusive that all subjectively discriminable differences can be explained using existing objective measurement techniques. Secondly, acoustic signals can create auditory sensations if they are within the hearing range of the subject. Finally, these sensations can lead to a perception of the auditory surroundings around the subject, or of the information present within these signals. It is important, therefore, to realize that sound perception need not correspond precisely to the acoustic signals present at the subject's ear.

2.3 Health and behavioural effects

It has been found that annoyance levels as a result of exposure to unwanted sound within a dwelling can affect day to day life and can cause serious health problems in the most extreme cases (World Health Organisation, WHO). The sort of noise levels that are typically encountered within domestic properties, such as road traffic, music, speech, footsteps can lead to a wide array of health problems such as:

- Annoyance
- Psycho-physiological effects
- Mental health problems
- High blood pressure
- Stress
- Learning difficulties in children
- Pre-term birth in pregnant women

Annoyance, as a result of noise, can usually be attributed to a specific source of noise. However, the fundamental contributory mechanisms are not always clear (Porter, Flindell and Berry, 1998). There are many research studies available in this area, but are often found to be quite vague in terms of whether specific or general effects are being described. This is evident on the fact that the perceived annoyance of a specific sound source may substantially exceed that of the aggregate or entire annoyance to the overall noise levels that exist in the studied environment. Researchers have historically concentrated on the perceived annoyance that specific sound interferences can have on speech, communication, concentration, sleep, or task performance, but the fundamental relationships are found to vary between studies (Noise & Nuisance Policy, 2004).

The two most common effects of unwanted noise within domestic dwellings are sleep disturbance and speech interference (The Noise Act, 1996). Communication by speech is a vital ingredient in society and is easily adversely affected by masking noise. The degree of interference with speech communication can be measured using subjective response methods such as rating scales, or objectively by measuring the number of words as a percentage, or sentences correctly understood, known as true speech intelligibility measures. Environmental noise, especially noise which varies in loudness or frequency, can interfere with many activities involving speech. However, the extent to which speech can be interfered with, therefore contributing to increased stress levels in different situations is not particularly well understood at present.

Sleep patterns vary considerably between different people and therefore, sleep disturbance can occur as a result of many different causes (The Noise Act, 1996). In either case, lack of sleep can have a significant impact on the health and wellbeing of an individual, resulting in increased stress levels and the problems associated with it. Sleep disturbance can be measured subjectively using methods such as questionnaires, or objectively using physiological indicators. However, problems occur when taking measurements as instruments can often be disturbing to the subject, particularly within a laboratory setting, and significant differences between results obtained in sleep laboratories and in own-home experiments are commonplace. Laboratory studies can be well controlled, particularly with regards to the stimuli used, but on the negative side, it may take time for subjects to get used to the laboratory surroundings. Studies performed in subjects' familiar environments are difficult in terms of instrumentation, and problems arise in terms of controlling the pattern of stimuli that actually occur on instrumented nights.

In the most severe cases, mental health problems can occur or even noise induced hearing loss. These however, are rare and there is very limited research available in such extreme cases.

2.4 Sound power measurement

The sensation of sound is the response of the human ear to changes in air pressure. The ear has an extremely large sensitivity range, responding to pressure changes at the ear, between the frequencies 20Hz to 20,000Hz. (Kinsler and Frey, 1982) In the absence of sound, the ear drum remains stationary held steady by atmospheric pressure of the air which reaches it on one side from the ear canal and on the other side from the mouth. When a sound waves travels along the ear canal, the pressure fluctuation causes the ear drum to vibrate and sends signals to the brain. The level of sound heard by the ear can be evaluated subjectively and very small changes in sound pressure level are generally considered to be significant. However, it is also evident that not everyone's hearing is identical, but for simplicity, we can define 0dB as being the point at which we begin to hear sound, the threshold of hearing (Kinsler and Frey, 1982).

In order to obtain an absolute evaluation of sound pressure, measurements are taken using a sound level meter. However in this instant, background noise can adversely impact upon the assessment of a sources sound level, and it therefore becomes difficult to measure the sound pressure level of a source if this background noise is less than 10dB below the sound pressure level of the source itself.

A *noise level* or *sound pressure level* is a measure of the small dynamic pressure fluctuations in the air that are in addition to the normal static atmospheric pressure. Sound power level, therefore, is the measurement of the total noise radiated by a source in all directions, and is independent of the environment in which measurements are taken. A variety of factors need to be taken into consideration when determining the sound pressure amplitude such as the sound power, proximity, reflections prevalent within both the source and measuring environments, sound source direction, and the presence of other sources of sound within the immediate environment, known as ambient noise.

2.4.1 Measuring Sound Pressure

Sound level meters give a numerical value of the sound pressure level at the exact position of measurement. The sound level however, will vary depending on the measuring environment, and the distance between the meter and the sound source. When using the same sound source, there will always be a distinct difference in the sound level readings between a room containing soft furnishings, and that of a bare room with hard walls as these furnishings provide varying absorption and reflection characteristics. Information gained from measurements within these types of environments is important as they relate to the loudness of the sounds and highlight the potential effects the sounds have on the quality of life of the inhabitants of within these dwellings.

2.4.2 Calculating Sound Pressure Levels

Within the threshold of hearing, sound perception is highly non-linear. In the mid-range frequencies, the ear is at its most sensitive, corresponding to the region associated with vowel sounds in normal speech.

The sound pressure level (SPL) or loudness (L_p) is calculated in decibels (dB) using the following formula (Fahy and Walker, 1998):

$$SPL = 20\log_{10} (p/p_{ref}) \qquad \text{eq.2.1}$$

Where p = actual root mean square (rms) sound pressure

$p_{ref} = 2\times10^{-5}$ N/m^2 (rms), which corresponds approximately to the threshold of human hearing

When $p = p_{ref}$, the sound is just audible to the human ear, and has a sound pressure level of 0dB. At the opposite end of the spectrum, a sound pressure level of 140dB is at the point of instantaneous damage ($p=p_{ref}x10^7$).

It is evident in this formula that humans' perception of the loudness of sound operates on an exponential scale, as with all human sensory systems. That is to say if a series of sounds are heard which humans perceive as having increased in loudness, the corresponding sound waves are in fact a factor of multiplication in their amplitudes. It is therefore more convenient to use a logarithmic scale to measure loudness.

The above formula can also be expressed in the following way (Fahy and Walker, 1998):

$$L_p = 20log\ (p/p_0) = 10log\ (p^2/p_0^2) \qquad \text{eq. 2.2}$$

Where the reference pressure amplitude $P_0 = p_{ref}$.

The ratio p/p_0 is dimensionless and indicates what factor is needed to multiply the reference pressure amplitude in order to obtain the amplitude of a given sound wave. L_p is defined in terms of p^2/p_0^2 in order to correspond to the sound intensity level, as the energy and intensity of a sound wave is proportional to the square of the amplitude of the wave oscillation (p^2).

The minimum change in pressure which is just detectible to the human ear is approximately 2×10^{-11} N/m^2. The pressure changes of the ear, along with the energies associated with these changes are many orders of magnitude less than other variables studied in building physics such as transmission loss and thermal values, and therefore very small amounts of kinetic energy experienced by the ear have the potential of generating significant noise problems to the listener.

2.5 The Search for a Single Number Rating for Buildings

As discussed in section 2.2, the subjective nature of sound perception has for many years presented a problem when trying to achieve some sort of definition as to what is an acceptable level of sound that an individual should be exposed to. As a result, the task of obtaining an accurate method of quantifying the acoustic performance of any given building element based on the subjective response of individuals has found to be impossible. So as to overcome this issue, scientists and researchers have developed many methods to achieve some form of uniformity and consistency in the way we evaluate the acoustic performance of single building elements such as partition walls and floors.

2.5.1 Single Figure Ratings and EN-ISO 717 Standard

Sound, or indeed noise, is present at the interface between a room and the sound source. This sound is then reflected, absorbed and transmitted through the building element into the adjacent room, through the airborne and structure borne methods, and some sound is also transmitted via flanking transmission. These methods are discussed in more depth in Chapter 5. The sound level that is evident in the receiving room is controlled by many different factors such as absorption, reflections and the reverberation present in the source room. It is therefore clear that the sound paths present create a complex issue that requires significant understanding in an attempt to calculate a room's acoustic performance.

To allocate a single figure rating to a partition wall, site testing must usually take place. The sound insulation value measured on site relates to the sound pressure level reduction between adjacent rooms and the reverberation time of the receiving room. (Buzzi, Courne, Moulinier and Tisseyre, 1997). This value is termed the Standardised Level Difference (D_{nT}). The general testing method to calculate the D_{nT} values of a room are as follows.

- Sound is generated in one room and the sound pressure level (L_1) is measured.
- The sound pressure level is also measured in the adjacent room (L_2) so that the reduction can be calculated.

- Additionally, the reverberation time measurements (T) are taken in the receiving room in order to normalize any sound absorption effects.

Once this information is known, the D_{nT} value can then be calculated using equation 2.3 (Fahy and Walker, 1998):

$$D_{nT} = L_1 - L_2 + 10\log_{10}\frac{T}{0.5} \qquad \text{eq.2.3}$$

For both laboratory and site experiments, measurements are carried out in one third octave bands over a frequency range between 100Hz and 5000Hz, allowing a graph of sound insulation verses frequency to be plotted. Figure 6.1 shows the test results for on site airborne sound transmission testing at Shotton using the above theory, and is further discussed in Chapter 6.

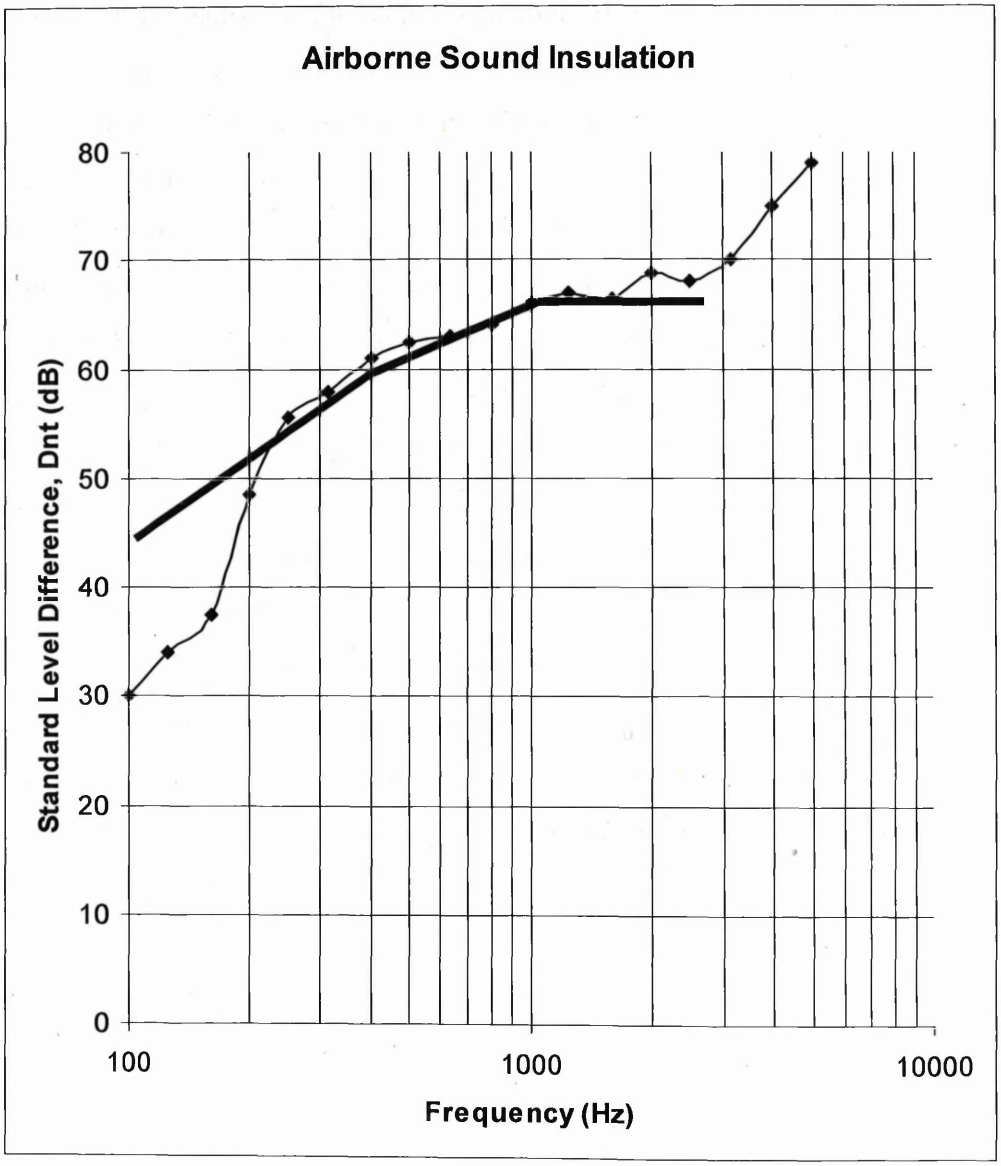


Figure 6.1 Graph showing the results of the modularly constructed Unit Type A, tested in Shotton, North Wales. The solid bold line shows the reference curve used to calculate the negative deviation.

However, to simplify the data presentation and therefore provide a valid method of comparison between various structures ranging from partition walls within dwellings to separating elements between dwellings, a single figure rating method has been devised which calculates a single figure from the measured test results, as set out in the building regulations. (Part E of the Building Regulations; BS EN ISO 717). A typical graph showing test results for the sound insulation of a separating element between two self contained dwellings is shown in figure 6.1 (Also displayed in Chapter 6). As very low rating values can be disguised at certain frequencies, simply obtaining the mean value for the 16 one third octave bands is generally not representative. The method set out in EN ISO 717 (parts 1 and 2) compares the set of 16 measured results with a set of 16 reference results, known as a reference curve. By considering only the measurements which fall short of the reference curve and choosing a reference curve where the sum of the negative deviations (over the 16 measured octave bands) is as large as possible but not greater than 32dB, a single figure rating can be obtained, being the Sound Reduction Index value (R) at 500Hz. This can be seen in figure 6.1 where the reference curve is on a vertical sliding scale and the sound reduction index reading at 500Hz provides the single figure rating for the partition. For laboratory tests, this single figure rating is termed the Weighted Sound Reduction Index (R_w), indicating the amount of sound energy being stopped by a separating building element when tested in isolation in the absence of any flanking paths. For site tests the single figure rating is termed the Weighted Standardised Level Difference ($D_{nT,w}$), giving the airborne sound insulation performance between two adjacent rooms within a building. Being a site measurement the result achieved is affected not only by the separating element but also by the surrounding structure and junction details.

2.6 Pink Noise and Spectrum Adaptation Terms

Due to the uncertainty that historically has existed in the measurement of low frequency sound transmission, it has become necessary to expand the range that measurements have traditionally been performed, though standards such as ISO 717. These standards were revised during the 1990s and measurements incorporating weighting filters at centre frequency bands 50Hz, 63Hz and 80Hz have now become possible. All spectrum adaptation terms C and C_{tr}, discussed below, are available for airborne sound insulation between rooms, as well as for airborne sound insulation against outdoor sound. The results are plotted as single figure ratings curves, reflecting the way in which sound is perceived by the human ear. ISO 717-1:1997 uses Spectrum Adaptation Terms in order to account for different spectra of noise and to assess sound insulation curves with these very low values in a single frequency band. For airborne sound, two spectrum adaptation terms are defined below:

- C (Pink noise) relates to everyday living noise sources such as children playing and highway road traffic noises (>80km/h) and has each octave of noise throughout the frequency range possessing the same amount of power. It is usually found to be a small negative number. Pink noise is a wide band of random noise with a level decreasing by 3dB per octave. This attenuation allows a constant energy to be transmitted through a filter with a bandwidth which increases in width for each octave increase.

- C_{tr} relates to an urban road traffic spectrum incorporating a low frequency weighting to the D_{nTw} value and can equally be applied to noises such as slow speed railway noises and music. In a poor performance construction, the C_{tr} value becomes a larger negative number in the low frequency range.

With regards to impact sound, EN ISO 717-2 uses the spectrum adaptation terms for typical noises generated by activities such as walking, known as C_i. At low frequencies however, lightweight constructions tend to be weaker, and may therefore have inferior values of C, C_{tr} and C_i. It should be noted that some European countries including England and Sweden have introduced or are in the process of introducing spectrum adaptation terms as part of their building regulations.

The sound insulation properties of a wall or a floor are dependent on the frequency of the noise in question. At present, there is concern over noise sources such as heavy beat music, footsteps, and road traffic. All these noise sources have a low frequency energy concentration. However, sound transmission in any given structure, is attenuated better at certain frequencies than at other frequencies, and this is discussed in further detail later in this investigation.

Chapter 3 Building Regulations and Standards

Unwanted sound has been identified as an irritant to the human race and something that should be reduced or eradicated particularly when exposed to it on an everyday basis whether in the work place or at home (ODPM, 2004). As discussed in chapter 2 the level of annoyance suffered by a subject varies throughout a population sample and this is evident by the broad subjective responses displayed in the results of my own survey, presented in chapter 6, and other research into this field where sounds with different frequencies are considered to be more, or less, annoying throughout a population sample. This characteristic presents a problem when trying to characterise these sounds in order to accomplish a design of building that can achieve a higher level of satisfaction for the greatest number of people.

To try and overcome this problem and achieve some sort of standard in which to assess the acoustic performance of any given room, the government have set guidelines in which, when followed during the design and construction of building elements, some level of consistency can be achieved in terms of quantifying its sound insulation levels.

3.1 Acceptable Environments and the History of the Regulations

To address the issues of sound insulation between dwellings that are evident in our culture, the government created a set of regulations that tackle these issues at the design stage. Under these regulations, the construction industry is required to build homes which satisfy the regulations in every aspect, thus improving the standard of living for its inhabitants.

Early standards produced by the government can be traced back to the 1950s where the guidelines stated that, at that time, a 225mm thick solid masonry wall and solid concrete floor offered a reasonable standard of sound insulation. As it seemed reasonable to assume that the results of a test of a particular type of construction would hold true with any other similar constructions, the performance values that were obtained for the constructions in the 1950s were used as the basis for determining which types of constructions would be included in the 'deemed-to-satisfy' list that was incorporated within the 1965 Regulations. After some alterations, this list was also included in the Approved Document E of the 1985 and 1992 Regulations.

Over the last 50 years, there have been significant improvements in living standards as a result of tightening building regulations. One of the main reasons for these changes is an increase in the quality of life that occupiers demand. Other potential reasons might include reduced contact with neighbours, perhaps creating a more 'frosty' atmosphere; an increase in the amount of people working from home, resulting in noise being produced for longer periods of the day; and a general increase in expectations resulting in a decrease in tolerance to noise disturbances. Perhaps another small but maybe significant factor is an increase in public awareness of such issues due to the media spotlight focusing on noise problems and the creation of television programs such as *'Neighbours from Hell'* which go a long way in highlighting complaints that seem commonplace.

3.2 Need for Change

A survey by the Chartered Institute of Environmental Health (CIEH) has indicated that the level of complaints of domestic noise has risen over the last twelve years. It is reported that there are now over 5000 per million population complaints about domestic noise, and that in the 10 year period from 1986 – 1996, the total number of complaints trebled, primarily due to the reasons discussed above.

The 1996 English House Condition Survey (EHCS) has also published results indicating that over a third of households, which is approximately 7 millions homes, experienced noise disturbances in that year. The survey also highlighted the fact that 4.7 million households, which is around one quarter of the total households in the U.K, thought that the noise originated from external sources such as road traffic, aircraft, or neighbours. The remaining 2.7 million households felt the cause of their complaint was a result of their neighbours' behaviour. Around 3.4% of households who were bothered from noise disturbance from their neighbours stated that in their opinion, it was a result solely of poor acoustic design of their home or a combination of poor design and neighbours behaviour.

The data obtained from the EHCS also suggested that people who live in flats (10.9%) reported a larger number of complaints as a result of their immediate neighbours than those people who lived in houses (4.9%). The highest number of complaints lodged by people living in houses was from occupants of terraced houses (6.1%), closely followed by semi-detached houses (5.3%) and detached houses as 2.5%. It was also found that the age of the dwellings did not appear to be a significant factor in determining the effect of the extent of reported problems (pre/post 1980).

It is regarded by many that the definitive survey on the subjective acceptability of sound insulation through partition walls was performed by Langdon et al (1981). It was found that poor insulation was mentioned spontaneously by 20% of respondents, and that 24% of respondents living in dwellings deemed to be at or below the target standard rated poor sound insulation as the most important when presented with a list of about 9 different housing deficiencies. When posed with another question, approximately one quarter of respondent living in dwellings that actually attained the target standards, rated the insulation as poor or very poor. An additional 25% rated the insulation as fair. The survey also suggested that impact sounds in adjacent dwellings such as footsteps and slamming doors were deemed considerably annoying, and interestingly the annoyance from these impact sounds became more common as the airborne sound insulation was improved.

Between 1992 and 1994, a study was undertaken by BRE to investigate complaints about sound insulation between dwellings that had been approved under Building Regulations. These buildings complied with the relevant design guidance given in Approved Document E. It was found that the complainants were, on the whole, living in dwellings that did not meet the target sound insulation requirements set out as 'reasonable' in the Building Regulations. The main causes of complaints were sound sources such as hi-fi systems, television, and domestic appliances particularly washing machines, vacuum cleaners and telephones. Footsteps, slamming doors and water pipes could all also be heard. Again, this survey found that some complainant's occupied dwellings which actually satisfied current standards, although it must be noted that most of these complaints were concerned with impact sounds such as banging doors and, at the time, such noises were not controlled by the regulations. As a result of this increase in noise related complaints, government buildings regulations are tightening, forcing building construction companies to raise the quality of their buildings in this area. BRE estimated that in newly constructed dwellings, up to 40% of separating floors and 25% of separating walls may fail to satisfy the standards set in Building Regulations 2000.

Although the study by BRE provides some evidence of non-compliance with standards resulting in sound insulation issues, it was confined to dwellings in which the occupants were dissatisfied and it cannot therefore indicate to what extent the total population are dissatisfied with the standard of sound insulation within their homes. Similarly, it does not provide information as to the proportion of domestic noise complaints that are a result of poor sound insulation within the dwellings.

3.3 The Building Regulations 2000

There are many regulations and laws that are in place allowing greater control over external noise sources and their effects. Examples of these include the Environmental Protection Act 1990, the Noise and Statutory Nuisance Act 1993, and the Control of Pollution Act 1974, and these acts have a direct relevance in the control of noise.

The Building Regulations 2000 are enforceable on any significant building work within England and Wales, and are primarily concerned with the health and safety of people within or around buildings. Examples of construction work that is exempt from these regulations are minor constructions such as conservatories and porches which meet certain criteria such as having a minimum footprint of 15m^2. In order to provide guidance on some of the more common situations that occur in construction and compliance with the Regulations and Standards, the Secretary of State produces Approved Documents. Construction companies are not obliged to follow any design guidelines contained within these Approved Documents, provided that the requirements themselves are met in any other alternative way. For guidance on the resistance to the passage of sound between dwellings, Approved document E should be consulted. It is vital for the person responsible for the acoustic performance of a building, that the designers and construction workers follow the laws of best practice. A 'bad' design of a building will almost certainly lead to or increase a noise problem, and so the Building Act 1984 provides a framework of acceptable construction techniques in relation to noise, and in particular airborne and impact sounds.

Whilst there are no mandatory Building Regulations requiring specified levels of acoustic insulation in industrial and general commercial buildings, there are circumstances in which some resistance is required. Three obvious cases are buildings at or near busy roads and motorways, airports, where the sound heard from aircraft taking off and landing needs to be reduced or eliminated, and where an internal process is so noisy that the sound must be contained, e.g. engine test houses.

Under Part E of Schedule 1 of the Building Regulations 2000, there are three requirements:

- Regulation E1 states that:

  'A wall which:

  (i) 'separates a dwelling from another building or from another dwelling, or

  (ii) separates a habitable room or kitchen within a dwelling from another part of the same building which is not used exclusively with the dwelling

  shall resist the transmission of airborne sound.'

- Regulation E2 states that:

  'A floor or stair which separates a dwelling from another dwelling, or from another part of the same building which is not used exclusively as part of the dwelling, shall resist the transmission of airborne sound.'

- Regulation E3 states that:

  'A floor or a stair above a dwelling which separates it from another dwelling, or from another part of the same building which is not used exclusively as part of the dwelling, shall resist the transmission of impact sound.'

These three regulations make up the approved documents on insulation requirements in relation to sound.

3.4 Governments Target for high-rise

As the population of the U.K continues to increase, so too does the demand for housing. The U.K housing stock is in urgent need of renovation, and new-builds are often seen as a better alternative. A recent survey by the Steel Construction Institute (SCI) suggests that in the U.K alone there is a predicted demand for approximately 4.4 million homes to be built between the years 1999-2016. It also states, mainly due to the culture we now live in, that around 80% of these new homes will be single occupancy. This figure may seem large. However, should this be the case, it is clear that this demand for small scale accommodation will provide the construction industry with many challenges and great opportunities to develop the technology to new levels. In 2002, the government stated its drive for urban regeneration, instilling a new sense of activity within the city and town centres of the U.K. This target of high-density living is evident in the fact that over 40% of new homes built in 2004 were apartments, which signals a large increase (up from 17% in 1999) in apartment construction over the last 5 years. As discussed in section 3.2, apartment construction produces the largest percentage of occupiers dissatisfied with the sound insulation of their properties and so presents both the construction industry and the government standards agency with a challenging array of issues that must be addressed.

It now becomes clear that the issue of noise pollution, particularly sound transmission of low frequency sounds such as the bass frequencies of music, within domestic dwellings presents a problem that both needs to, and will need to be addressed for many years to come. There would appear to be a correlation between improvements in living standards, changes in social attitudes and lifestyles and an increase in complaints about noise. Social surveys have found that the problem may have several causes, some of which being:

- The activities and lifestyles that neighbours live out
- Current target values are set too low
- The quality of the building design and even the workmanship in construction is not meeting the required standards.

3.5 Changes to the Building Regulations

In a move designed to deal with the problems associated with noisy neighbours, the ever increasing rise in living standards, and to clear up any confusion that was present in the old regulations, the new Part E of the Building Regulations (2003) requires more acoustically robust building standards to improve soundproofing in new homes and schools, through the consolidation of requirements E1, E2, and E3 into a single, more general requirement that dwellings should provide reasonable insulation against sound produced in adjoining dwellings. It is hoped that these new changes, incorporating the various low frequency weighting filters, will combat the noise issues associated with modern day living discussed earlier in this chapter. The proposed changes apply to new build or conversions of buildings that are to be used as dwellings, or residential accommodation where people either live or sleep. Consequently, hotels, hostels, halls of residence as well as houses and apartments, will be affected. The regulations are applicable throughout the UK except Scotland which has its own technical standards. The regulations set requirements for the transmission of noise between separating wall and floor constructions within the dwelling rather than elimination of external noise penetrating the external walls as in the old legislation.

3.5.1 The New Requirements

The new index that has been applied in the new Requirement E1 against airborne sound has been changed from $D_{nT,w}$ to $D_{nTw}+C_{tr}$ and is defined in BS EN ISO 171-1:1997 and discussed in chapter 3 (section 3.6). In these cases, sound is measured over the same frequency range as $D_{nT,w}$ but incorporates a greater weighting on the low frequency spectrum, which appears to be more of an issue over the last few years. The new changes have also provided the opportunity to increase the target standard by 3dB. However, in reality, the actual target values are lower than previous requirements due to the way the new rating index works. Under the old regulations, the target value was 49dB. The new regulations have increased this target to 52dB, but because of the added C_{tr} low frequency weighting, 5dB has been subtracted, followed by a further reduction of 2dB to allow for measurement accuracy. The new target for new dwellings therefore now stands at 45dB for airborne sound insulation.

Performance requirements are set in the UK building regulations, but until recently, there have been no requirements to demonstrate that compliance to these regulations has been achieved after the design stage. Historically, buildings are only required to comply at the design stage. This, however does not take into consideration poor workmanship or in some cases minor changes to building design specifications, and can therefore result in a significant impact on the acoustic performance of the building, and the satisfaction of its occupants. This problem has been addressed in the new Part E of the Building Regulations 2003, in which pre-completion testing has been introduced.

Requirement E2 aims to increase sound insulation and privacy between a W.C and a living area e.g. dining room, bedroom. It also includes sound insulation requirements between bedrooms and other rooms. Although the bedroom section of this requirement is entirely new, the first section is based on NHBC and Zurich municipal standards. Pre-completion compliance testing is not a requirement.

Requirement E3 proposes to transfer responsibility of sound insulation of the complete building envelope from the planning authorities to the building control bodies. Protecting a dwelling from external noise will remain the responsibility of the planning system. This change allows the sound insulation (Part E) to be grouped with thermal insulation (Part L) and ventilation (Part F) within the building control regulations, which should provide a more consistent approach to building quality. Again, pre-completion compliance testing is not a requirement.

Requirement E4 is intended to restrict the type of noise that can reverberate along corridors and stairwells in the common part of flats and apartments. Pre-completion compliance testing is not a requirement.

In 21st Century Britain, acoustics in schools has become an important factor in providing a learning environment for children. Requirement E5 intends to bring this area under the control of the building regulations, aiming to increase the sound insulation between rooms, protect rooms from external sources of noise, and provide adequate reverberation levels to support good speech intelligibility. Pre-completion compliance testing is not a requirement.

3.5.2 Proposed changes to Part E

In summary, the most significant changes that are due to be made to Part E of the building regulations are listed below;

- *Protection against sound from adjoining dwellings or buildings. (Requirement E1)* *(i) Rooms for residential purposes are now covered.*

(ii) Introduction of an explicit (minimum) performance standard to replace the current need to infer the meaning of 'reasonable sound insulation'. This new level is set higher than the current level, to fall in line with European legislation. A new ratings method will be put in place, which will force improvements in the insulation of lower frequencies.

(iii) Technical changes to guidelines on separating and flanking constructions will be made.

(iv) Introduction of a pre-completion testing requirement, applying to all new dwellings

- *Protection against sound within a dwelling. (Requirement E2)*

  (i) New requirements based on current 'good practice', extended to protect bedrooms

  (ii) New guidance in the Approved Documents standardises and extends current good practice.

- *Protection against noise from external sources. (Requirement E3)*

  (i) Changes made to shift control of sound insulation measures from the planning regime to Building Regulations. Control of site matters will remain within the planning system.

  (ii) New guidance in the Approved Documents standardised and informs current good practice.

- *Reverberation in the common internal parts of buildings containing dwellings. (Regulation E4)*

  (i) New requirements based on current good practice.

(ii) *New guidance in the Approved Document standardises and informs current good practice.*

3.6 Robust Standard Details

Recent times have seen a shift away from pre-completion testing, with its reliance on workmanship and time associated with in-situ testing, in order to develop a viable alternative to this method. A concept known as Robust Details has been developed in which a design can be constructed and the performance is established on the mean result of 30 tests with a maximum of 8 of the tests being performed on the same site. Should the results be found to satisfy the requirements of Part E of the Building Regulations (assessed by Robust Details Ltd), the design can be deemed an approved robust detail. These designs can then be rolled out across the board, eliminating the need for further pre-completion testing. Certainly this technique would have significant time and cost benefits over that of pre-completion testing. The issue associated with workmanship would still present a problem in ensuring the 'deemed to satisfy' robust details are correctly incorporated within every new build. However, provided that the robust details are in fact built correctly, this will be acceptable by all building control bodies throughout England and Wales as evidence that the buildings are exempt from pre-completion testing. A range of details have been rigorously developed, of which Corus have made their contribution, to achieve the necessary acoustic performance requirements of Part E of the Building Regulations. These details are published by Robust Details Ltd.

3.7 Comparison of airborne sound insulation requirements in Europe

The EN ISO 717-1:19972 and EN ISO 717-2:19972 were introduced as an attempt to establish a methodology that resolves differences in alternative methods used in different European countries. In some European countries including the UK, Ireland and the Netherlands, single figure ratings D_{nTw} and L'_{nTw} are used to describe the acoustic performance of building elements. The weighted sound reduction index, R'_w, and the weighted normalised impact sound pressure level, L'$_{nw,}$ ratings are used in Scandinavia, Austria, Belgium, and Germany. These rating systems set higher standards for the reduction of sound than those used in the UK, having a single figure rating of 55dB for separating walls compared to 45dB for the UK when considering apartment buildings. However, the L'nw system does not incorporate the low frequency component of the proposed UK system. Some countries allow both methods to be used and a complete guide to the European target values can be viewed in tables D3.1-D3.4 (Appendix D)

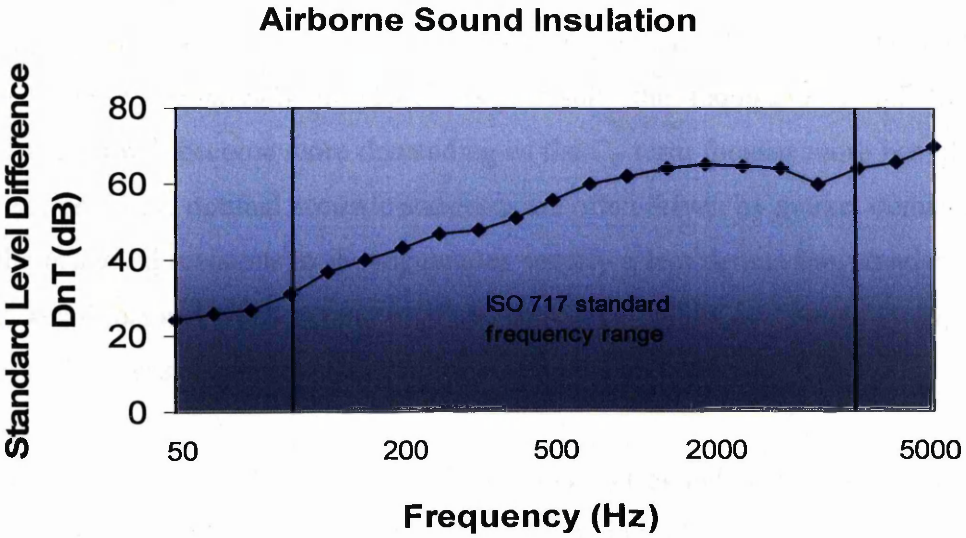


Figure 3.1 - *Airborne sound insulation of a light steel frame separating floor at 1/3 octave bands.*

When calculating the spectrum adaptation terms, the EN ISO 717 standard allows some flexibility over the frequency range. Like the D_{nTw}, the C and C_{tr} terms correspond to the 100Hz to 3150Hz frequency range. This frequency range is also specified in the regulations of most countries. However, this standard can be extended to cover the frequency range between 50 Hz and 5000Hz.

Lightweight constructions are particularly prone to problems with low frequencies, and in order to identify these problems, the frequency range is often extended down to 50Hz.

Difficulties occur however, when attempting to obtain accurate on-site low frequency measurements. This discourages European countries from extending the range down to 50Hz, and it is currently only Sweden that uses spectrum adaptation terms over a frequency range of 50 Hz to 3150Hz for airborne sound. A complete list of European countries and the various weighting systems and European Standard Acoustic Requirements in place can be viewed and compared in *tables A3.1-A3.4* in section D of the appendices.

The revisions to the regulations that have been proposed in England and Wales include the $D_{nTw} + C_{tr}$ and $L'_{nTw} + C_l$ and in the optimal enhanced acoustic standard, *'Quiet Homes'*, these are already in place. As a result, the requirements for lightweight constructions will become more demanding as the C_{tr} term focuses more heavily on low frequencies. These optimal acoustic standards are often driven by market demands. In the UK the proposed revisions to the regulations specify a less demanding standard for both separating floors and walls in renovated and converted buildings. *'Quiet Homes'* also sets an optimal increased acoustic standard for developers and clients to use.

It is clear from *tables A3.1 – A3.4* (Appendices) that Scandinavian targets are set at a higher level to that of the rest of Europe, and this would reflect the fact that Scandinavian countries boast some of the highest living standards in the world. The UK would seem to have some of the lowest sound insulation standards for the various building elements within Europe. However, the UK is one of the few countries that have attempted to confront the recent noise issue of low frequency domestic sound generation by incorporating the low frequency filters in an attempt to increase the standards over a larger frequency range than previous standards have accommodated. It would be reasonable to assume that the noise issues faced in the UK are evident throughout Europe and so it is anticipated that other European countries will shortly follows the UK's lead in combating low frequency sounds.

Chapter 4 Review of World Wide History of Modular Construction

4.1 Introduction

In 1998, Lord Egan carried out significant research within the construction industry, investigating the techniques that existed at that time, in order to produce the next generation of construction techniques. It was hoped that as a result of this landmark report the construction industry would become better equipped to deal with the ever increasing demands placed on it in terms of the need to become more efficient and increase the quality of the products, satisfying the consumer expectations in the market place. It was concluded that to accomplish the necessary changes within this industry, more efforts must be made to be innovative, streamlining the whole process of construction. As the world continues its rapid move towards a more sustainable society, so the construction industry must follow with the emphasis now being place on pre-fabricated units, off-site manufacturing and therefore increased program predictability. A principle target identified for all construction companies to attain to is to achieve a reduction in construction costs whilst meeting the quality expectations. A key milestone in achieving theses changes is to form partnerships with suppliers, establishing long lasting relationships.

4.2 Framed construction

Timber framed construction has long been utilised by building companies as a method of construction of many different building types. The reliance on timber frames provides excellent methods of structural support and strength. Timber framing has evolved over the years to become a modern innovative industry that promotes and encourages quality and sustainability. A report by the UK Timber Frame Association suggests that over 70% of the world's population live in timber framed dwellings, whilst over 90% of low rise buildings in the U.S.A and Canada are constructed using timber framed methods. In the

UK, it is reported that one in six new homes built is constructed using timber framing, making up 17% of the current market share.

However, this type of construction is not without its drawbacks. Accuracy levels in construction are not wholly predictable, giving rise to movement in the construction within weeks of erecting the framework, due to subsidence. The knock on effect results in cracks developing and the efficiency of the building therefore decreasing. Furthermore, whilst many countries are committed to re-forestation through actively replacing trees and forests that have been harvested for wood, there are serious implications resulting from the continued loss of forests throughout the world, and so alternatives methods that can sustain and increase accuracy and predictability in construction must be investigated.

4.3 Light Steel Framing

One of the principle construction techniques identified in the Egan Report is that of light steel framing (LSF). LSF is the structural component used in lightweight construction and meets the aspirations set out in the Egan Report which identified the house building sector as an important area that cross-fertilizes innovation with quality and standardization. LSF has come to the forefront of the construction industry and is now regarded as a technique that will play a very important role in delivering a more sustainable construction industry that will contribute to the improvement of the processes involved in construction, achieving quality products whilst minimizing waste.

LSF uses cold rolled steel sections, usually less than 2mm in thickness, that are galvanised in zinc before fabrication. This protects the steel in a more reliable way than paint. The coating makes the steel impassive, therefore becoming resistant to damage and, crucially within the construction industry, the corrosive effects of condensed moisture. The very nature of factory assembled components dictates that LSF can be manufactured to exact design specifications, as requested by the architects.

4.3.1 Uses of light steel framing

LSF has many uses, such as domestic, commercial or industrial type buildings, and due to its versatility, offers high levels of freedom to achieve creative and innovative features in such buildings. Extending the range already present for steel construction, it can be used for construction of components, known as stick-build construction, pre-assembled elements, or as volumetric modules. The stick-build approach offers more on site variation ability, but it requires fixings and cutting on site. It is therefore more time consuming and allows for less quality control during the manufacturing process. Pre-assembled construction involves factory made panels, walls, and floors that are then taken to a pre-prepared site. These panels are inserted into place in small units, with minimal amounts of labour required, and would usually have pre-attached fascia materials. Volumetric modules are constructed entirely within a factory environment. They are three-dimensional frames which are often fully fitted on arrival to the site and are usually standardized in size and shape, allowing mass production. As a result, the construction costs are dramatically reduced and high levels of dimensional accuracy is achieved. The modules act as the main structural component of the building, allowing the non-load bearing structures to be inserted in the periphery. This modular technology is now widely used throughout the world, particularly North America and Japan, and is therefore well established in the construction industry. As an example, there is now a demand of over 100,000 houses to be constructed per year using LSF in the USA alone. Over the last few years, LSF has made a rapid and significant impact in Europe.

4.3.2 Benefits of light steel framing

One of the major advantages of using LSF is its speed of construction. While the site is being prepared, the framing of the building can be built and cut to exact lengths in a factory and then delivered to the construction site as pre-fabricated structures with pre-punched holes are in place, ready for the services to be installed. This allows the internal structure of a building to be erected in a matter of weeks, which then provides a dry envelope for contractors and sub-contractors to work under. This whole process dramatically reduces the construction time of such buildings, particularly as the method allows for familiarity of construction to be achieved by the labourers. The reliability of using LSF in this way is immense as the construction method is totally independent of weather conditions, therefore eliminating unexpected delays. Construction using LSF has been found to be both dimensionally stable and accurate, minimizing the potential for future subsidence within the structure, with a large strength to weight ratio. It therefore offers competitive advantages over traditional construction methods in terms of design and durability. An important factor in deciding to use modular construction with light steel framing is the fact that it enhances the building's long-term useful life, which is of great value to the owner. Modular buildings are adaptable and can therefore respond more easily to changes in use that may be required in this changing society.

A reduction in construction time would clearly provide an earlier return on capital and improved cash-flow, resulting in an overall reduction in financing costs. It therefore becomes apparent that construction using light steel framing is ideally suited for both physically tight working conditions such as city centre sites and high rise buildings where the need for short term profit gain, therefore on-time completion, is essential. Light steel framing by its very nature is light in weight, resulting in foundation costs being kept to a minimum due to the alleviation of the need to produce complex and expensive substructure designs.

4.3.3 Value assessment of light steel framing

A research study was carried out by the Steel Construction Institute (Lawson and Rogan, 1998) in which a comparison was made between the construction and financing costs of houses built using '*Surebuild*' light steel framing, and houses built in the conventional manner of blocks and timber floors. Building type 1 was a detached house of 133m^2 floor area, and building type 2 was a semi-detached house of 77m^2 floor area. Both were constructed using standard repetitive components with relatively simple plan forms and elevations.

The motivation for this study was due to the release of a government paper entitled Opportunity for Change: Sustainable Construction, 1998, (www.sustainable-development.gov.uk) addressing all aspects of the construction process in search of attainable solutions for improvement of the construction industry within the UK. This paper states that the housing sector comprises more than a quarter of all UK construction, and suggests that a change in construction technique, resulting in a 1 per cent saving in construction cost, would equate to potentially 2000 new homes being built at no extra expenditure. Achieving this objective, while maintaining or increasing the level of quality, would provide the construction industry with vast opportunities and challenges.

The Steel Construction Institute study was performed in two sections, the first being a study in which detailed comparisons were made between the two construction techniques by considering detailed bills of quantities. The costs for all items in two house types were based on current practical experience. The findings were validated by the School of Economics, University of West of England, Bristol, and the results compared to building costs of recent projects constructed by major housing developers.

The second section of the study developed a comprehensive financial model that could determine the 'value', in financial terms, of the light steel frame used in these specific construction projects. The spread sheets were developed in consultation with a quantity surveyor, and derived the month by month financial costs. This model was based on the Nationwide Building Society's quarterly sales data and the Royal Institution of Chartered Surveyors' indices for regional building costs, incorporating regional variations. Two case studies were investigated. Case study 1 was a development comprising 10 building type 1 houses, and 10 building type 2 houses. Case study 2 used the same basic building types, but 25 of each were investigated.

It was concluded that the use of LSF would bring considerable benefits to the developer or builder in terms of construction speed and reliability. These benefits would in turn lead to savings in construction costs due to a reduction in preliminary costs and plant usage; no reliance on lintels as they are now incorporated within the frame; and a reduction in call-backs due to the minimisation of movement known as 'shrinkage' which is physically manifested as cracks in the plaster at the edges of rooms. The result of this reports once again show that housing constructed using LSF offers better all round quality and additional benefits for both developer and owner/occupier at no extra costs. It should also be noted that recent project involving LSF are being constructed with even cheaper costs, and these savings can therefore be filtered down to the client.

4.4 Modular Construction

Pre-assembled construction, particularly modular construction using light steel framing has evolved to the forefront of the construction industry over the last few years. The principles involved in modular construction, however, are not new. The origins of this type of technique can be traced back to the manufacturing of mobile homes. A company known as Sears pioneered the way in relation to modular construction, manufacturing over 100,000 timber framed modular homes between 1908 and 1940. 21st Century modular construction uses pre-engineered volumetric units that are built in a factory and transported to the site to be installed. In this type of construction, the client has direct influence over factors such as the speed of construction, fitted extras and quality. In addition, modular construction techniques can significantly increase the energy efficiency of a house, which again is becoming an ever more important issue for construction companies to consider. The use of light steel framing is ideally suited to modular construction as it is strong, light, accurate, long lasting, and is flexible in design, being used for a wide range of applications.

4.4.1 The general process

Generally, when dealing with mass produced factory built modular homes, a new house can be delivered and finished within six to eight weeks of the order taking place. By the time a house leaves the factory, all its fixtures and fittings are in place, the interior walls will be thermally and acoustically lined, and exterior cladding fitted. It is even possible to fit carpets and paint the interior prior to delivery taking place. From the point of leaving the factory, it takes on average a further three weeks before the building is ready for occupancy.

When using modular construction techniques with larger developments than domestic dwellings, such as school buildings, it has been found that a building of this type and scale can be designed and constructed within the time it takes to renovate an existing building of similar scale. Modular construction techniques can produce a new school in as little time as six months, which can be up to half the time it takes to build using conventional methods. As with domestic dwellings, the site is prepared while the actual school is being built in a controlled factory environment. When the site is ready, the school is then transported in sections sometimes as large as classrooms and put in place, fully equipped. Connections are then made between the each of the modular sections. At present, the technology exists to construct buildings up to a maximum of five or six storeys in height, as a higher number for storeys would result in structural compression due to the finite strength of the load bearing elements within the construction. Existing buildings don't need to be modular to be able to extend modularly. Classroom extensions can be achieved on conventionally built schools, with minimum disturbance to present activities. School construction using this technology can be built in phases to suit the particular school, allowing for pupil number variation, and modular buildings can be added, removed, or relocated at any time.

4.5 Market Review

Modular construction using light steel framing has a wide range of applications in the construction industry, particularly in residential buildings such as houses and hotels. In the 1990's, construction began to slow down, and timber prices rose. This resulted in an interest in using steel framing as an alternative. Although there is a large market for this type of construction, mainly in Japan and North America where steel's robustness to hurricanes and earthquakes is ideal, the demand for such construction techniques is only now making inroads in the UK.

4.5.1 USA and Japan

In the USA alone, there are nearly eight million single storey units manufactured, providing homes for around thirteen million people (American Iron and Steel Institute (AISI). Within the last 20 years, the modular construction industry has accounted for 25% of the annual, single-family house production. It has been calculated that the cost of a house built in this way is approx. 20-30% less than the same house built conventionally (AISI). Until recently, the market for modular construction in North America has been aimed at local market requirements. By cutting production costs whilst still improving quality, companies are now aiming to strengthen their position in the national housing markets. The American Iron and Steel Institute estimated in 1994 that there was between 50,000 and 75,000 houses built using steel that year, and that by the year 2000, 25% of all houses would be built using at least some steel. At present, there are around 100,000 houses being built in the USA using steel framing each year.

The major difference between modular housing in Japan and North America is that the market in Japan is dominated by high income, and middle to high-income families, whereas in the USA, the industry aims at low earners. The Japanese housing market is estimated at around 1.5 million houses per year, which is approx. eight times that of the UK, even though the population is only twice that of the UK (Clough and Ogden 1993).

4.5.2 Europe

With the exception of Japan and the USA, the early use of modular construction for residential purposes was slower than expected, considering the benefits of the technology (Lawson and Grubb, 1997). A possible reason for this is that until recently, European modular technology has been more associated with discrete architectural applications rather than a production driven market demand. There is, at present, a demand in the Scandinavian market to renovate and extend existing buildings, (usually built in the

1960's) using modular construction.

4.5.3 The United Kingdom

Although cold-formed steel sections have been in use in the UK since the 1920's, the use of modular construction first started in the late 1970's, but has recently enjoyed a rapid increase. This is mainly due to client demands in various well-defined construction sectors. The 1990's have raised wider social and environmental issues on the design of buildings (Popo-ola and Lawson, 2000). One of the major reasons for this growth is because of an increase in the demand of the clients for quick construction times, so as to receive early returns on investment, when the building becomes operational. With regard to residential buildings, modular construction is in demand due to its economy of scale, and the fact that modular construction reduces disruption within inner-city sites. The policies that exist for planning are constantly being updated, and at present, there is a need to build at much higher densities than ever before. As a result, a demand for multi-storey modular buildings has developed. The market has now become highly competitive, with each manufacturer developing and settling for their own section designs, to what they believe provides the maximum efficiency. There is around one million tonnes of cold-formed steel sections being used in the UK each year at present, which provides evidence of its excellent performance and economy (Lawson and Trebilcock, 1994). Over the last decade, the UK construction industry has turned its attention to using lightweight steel framing systems in place of the traditional timber building methods to construct pre-fabricated modular units (Makelainen and Hassinen, 1999). Many of the large hotel chains in the UK have built extensions to existing hotels, or even new hotels using this new technology. Up to the end of 1998, there were at least 30 hotels built in this way, with around 100 more planned (SCI).

4.6 The future and long-term useful life

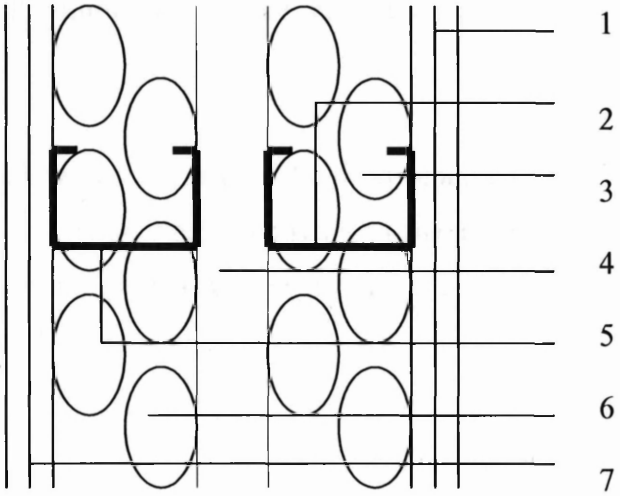
There is an international demand for affordable new houses to be built in the near future. The results of a recent survey suggest that in the UK alone there will need to be built 4.4 million homes between 1999 and 2016 (Popo-ola and Lawson, 2000). It was also discovered that around 80% of these new dwellings will be of single occupancy and that the total projected growth of single person households in all EU countries over the next 15 years is expected to reach 14 million. Making a crude estimation that each module constructed costs approximately £30000 to construct, it can be calculated that the market is worth a staggering £100 billion.

A recent survey performed by (Pinder and Price, 2003) provides a consensus of opinion as to the top six reasons given by office workers why their conventionally built office space fails to deliver an acceptable level of amenities and performance. The reasons given in this survey all add up to decrease the building's long-term useful life, again highlighting the need for acoustic advancement in terms of the quality of building design.

There is currently a large emphasis being placed on buildings in the commercial sector, which can incorporate information technology. The name given to this type of building is an 'intelligent building'. The architects DEGW defined an intelligent building as 'one that maximises the efficiency of its occupants while at the same time allowing effective management of resources with minimum life time costs', and in both the public and private sector, it is apparent that there is a rapid growth in demand for intelligent buildings.

4.7 Typical Prefabricated Units

The most common separating wall that is used in Europe is illustrated in *figure 4.1:*



1 - 2 layers of 15mm gypsum wall board
2 - 100mm deep steel frame with studs at 600mm centres
3 - 75mm thick rock wool insulation between studs (within one or both leaves)
4 - 20mm clear cavity
5 - 100mm deep steel frame (1.2mm thick steel) with studs at 600mm centres
6 - 75mm thick rock wool insulation between studs (within one or both leaves)
7 - 2 layers of 15mm of gypsum wall board

Figure 4.1 – *Typical characteristics of a light steel double stud separating wall (The Steel Construction Institute, 1998)*

Adding additional layers of gypsum board to the wall will result in an increase of mass, further improving the acoustic insulation. Generally, a mass of greater than about 20kg/m^2 for each wall is required for walls between dwellings (separating walls) (De Fonseca, Sas and Van Brussel, 2001). The gypsum board manufacturers produce acoustic boards that have a greater density and therefore improve sound insulation. Other enhancements include the addition of acoustic absorbent materials, usually rock wool or glass wool within the space between the two leaves or even within the frames themselves. Also, sheathing layers on the cavity side of each leaf can be added. Airborne sound insulation in lightweight floors can be achieved by various measures including achieving an appropriate mass in each layer, structural separation between layers, the addition of sound absorbent quilt within the structure, and minimizing the flanking transmission at wall-floor junctions.

Structural separation however, is more difficult to achieve in separating floors, although the same principles can be applied. This requires maximum separation between layers, thus separating floors are generally designed as a series of layers (*figure 4.2*) with resilient connections between them.

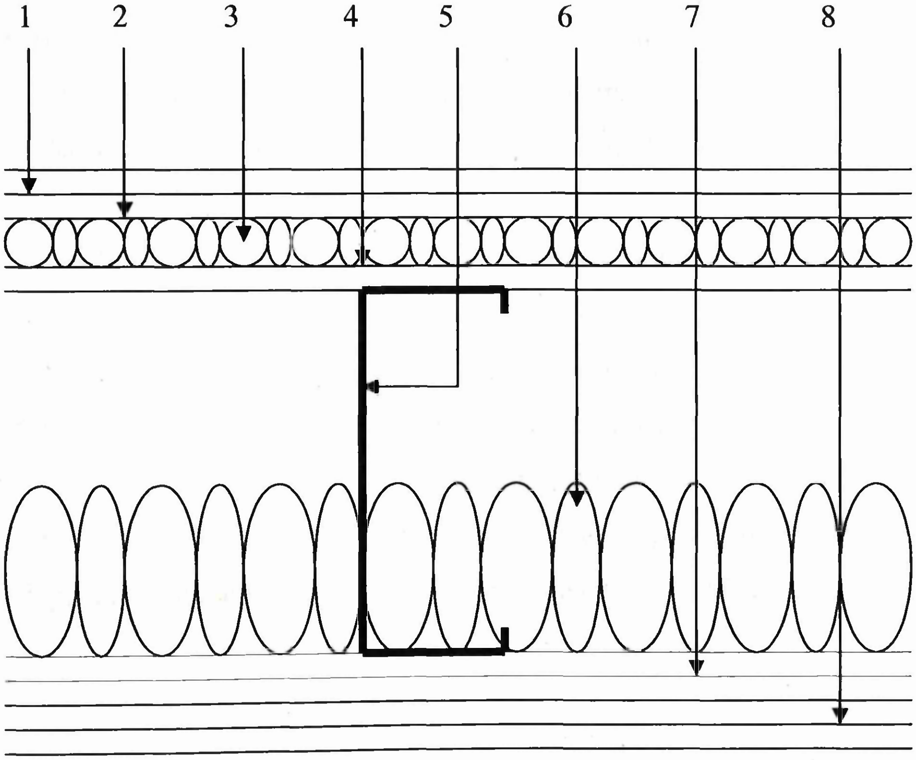


Figure 4.2 - *Typical characteristics of a light steel floor. (The Steel Construction Institute, 1998)*

1 – 18mm T&G chipboard adhesive bonded to layer below at 300mm centres

2 – 15mm gypsum wallboard

3 – 30mm rock wool or glass wool insulation board

4 – 22mm OSB Sterling Board screwed to top of joists

5 – 200mm deep steel joists (1.5mm thick steel) at 600mm centres

6 – 100mm thick rock wool or glass wool insulation between joists

7 – Resilient bars at 400mm centres

8 – 2 layers of 15mm gypsum wallboard

4.7.1 Floating Floors and Coverings

Usually, a layer of resilient material e.g. a dense mineral wool (60 to 100kg/m^3) is placed on the structural floor deck of a separating floor. A finish floor layer of chipboard or other sheathing material is then laid on top. In some floating floors, a layer of gypsum board is inserted under or on top of the resilient layer. The effect that a floating floor has on the impact sound insulation can be an improvement of up to 8dB. This type of floor also provides a significant improvement in airborne sound insulation.

Heavy floors have a greater improvement in impact sound insulation using soft floor coverings with a floating floor than that of light weight floors (Craik and Smith, 2000) Research has shown that soft floor coverings have a greater impact in absorbing high frequencies than low frequencies. Thus carpets have a positive effect on the absorption of frequencies above 200Hz, with improvements of up to around 10dB at certain frequencies. Overall, the impact sound rating $L_{nw} + C_{(50\text{-}200)}$ is improved by around 1.5dB - 2.5dB depending on the type of floor covering used (Craik and Smith, 2000).

Chapter 5 Acoustic design/quality of buildings

Chapter 2 discussed the issues associated with unwanted noise within residential dwellings, and it has become clear that people throughout the world, be it consciously or sub-consciously, are aware of sounds and noises to which they are subjected to on a daily basis. All sorts of rooms can display 'good' or 'bad' acoustics, e.g. offices, living rooms, and restaurants. Places such as staircases, corridors, factories, and airports all exhibit different acoustic properties, ranging from exceptionally quiet to very noisy, and this variation in the environment plays a significant role in the complexity of the sound field. At present, the level of understanding in many areas of room acoustics is somewhat incomplete. There may be several reasons for this, but the most important one would be the fact that in a closed space such as a room, there is a very complex sound field at work due to the large numbers of degrees of freedom. It is for this reason that the sound field in any particular room cannot be measured entirely accurately. Another major source of debate as to a room's acoustic performance is due to the fact that the finished product's performance is highly subjective and the variation throughout the subject responses dictates that the perceived annoyance levels of the noise also vary.

Of course, another factor in determining what measures should be taken into account when designing a room, is what will the main purpose of the room be? Will it be used for sports, singular offices, open-plan offices, music performances, or simply living accommodation? Each of these purposes requires different acoustic properties, each of which need to be considered, and calculated when the room is in its initial design stages.

5.1 Corus Interest

Lightweight construction, using materials such as cold-rolled steel sections, is more likely to present sound attenuation problems than traditional construction techniques as there is, due to its lightweight characteristics, an inherent lack of mass within the structure, leading to a direct reduction in sound insulation ability. This is of particular importance to Corus in the development of 'Living Solutions', the modular construction business, as the lightweight steel construction industry would already have a disadvantage, in terms of sound transmission reduction, to that of traditional building techniques such as masonry construction. Therefore research in this field is vital to the continued progression of the business moving downstream so as to be able to provide a viable alternative to traditional methods, particularly in today's market where there is an immediate demand for high quality, functional, and sustainable living accommodation. However, the acoustic performance of the modular industry is not the only hurdle that must be overcome in order to succeed. The resistance to change from traditional construction methods and the history of perceived failure from other modular companies, have all contributed to the reluctance of construction companies to embrace this method of construction, even though this technique has been to with incredible success in most other products (Edwards and Turrent, 1998). This aspect of the construction industry has been well documented in the Latham and Egan Reports and it is of paramount importance that the opportunity that is presented to Corus is investigated and exploited.

There are, however, a great variety of construction companies already present in the off-site manufacturing market, many of them well established as design and build contractors, albeit specialising in one sector, e.g. schools of student accommodation, and so Corus is faced with the issue of finding a niche in the market to expand within, by solely concentrating on manufacturing rather than contracting and acting as a supplier to the existing array of contractors and builders.

5.2 Sound propagation theory

5.2.1 Airborne Sound

As the title implies, airborne sound is generally regarded as sound that is transmitted mainly through air. Sounds such as musical instruments, speech or audio equipment are said to be sources which create *airborne sound.* Vibrations are set up in the surrounding air, which in turn impose themselves on the adjacent walls and floors. These are then set into motion, the vibration in which causes the air nearby to vibrate, therefore transmitting the sound through the air in the next room.

Air cannot sustain a shear force, and the only possible type of sound wave is a longitudinal one. Sound in a free field, radiates in a spherical fashion from a point source, and the intensity of the sound decreases with the square of the distance from the point source.

It is known that since the surface area of the sphere is proportional to the square of the radius and this is demonstrated in the following simple equation (Kinsler and Frey, 1982):

$$I \alpha \frac{1}{d^2} \therefore \frac{I_r}{I_R} \approx \frac{R^2}{r^2} \qquad \text{eq.5.1}$$

Where I_r = intensity at a distance r from the source

I_R = intensity at a distance R from the source

L_r = sound pressure level in decibels at a distance r from the source

d = diameter

$$\begin{aligned} L_r - L_R &= 10 \log_{10} I_r/I_R \\ &= 10 \log_{10} R^2/r^2 \\ &= 20 \log_{10} R/r \qquad \text{eq.5.2} \end{aligned}$$

It therefore becomes clear that for every doubling of distance from the source, there will be a reduction in sound pressure level of 6dB.

5.2.2 Impact sound

One of the major sources of noise disturbances in residential homes, particularly multi-story dwellings, is that of footsteps and closing doors (DEFRA), a result which is backed up by the results discussed in Chapter 6 These are structure-borne sounds and are known as impact sounds. It is widely known that in order to reduce the effect of impact sounds between the sound source, or point of impact, and the surface responsible for the radiation of sound such as walls or floors, a large enough impedance must be created. This is most commonly achieved by adding extra mass to the structure or developing technologies to allow for more resilient materials to be used in construction.

The important factor in measuring the level of impact sound is the actual noise heard in the receiving room, not the level of noise produced at the source. The most common method in determining acceptable levels of impact noise within dwellings is to create a constant impact noise at the source using a tapping device or footstep machine, whilst measuring the levels in the receiving room. The levels recorded can then be compared with values that are known to be acceptable.

5.3 Sound Transmission

When dealing with construction of any type of building, both impact and airborne sound must be minimised in order to comply with the strict regulations put in place, particularly in residential construction, in the United Kingdom. In order to establish whether a sound is airborne or impact is dependant on who is actually listening to it *(figure 5.1)*. Consider the following diagram of a multi-storey dwelling:

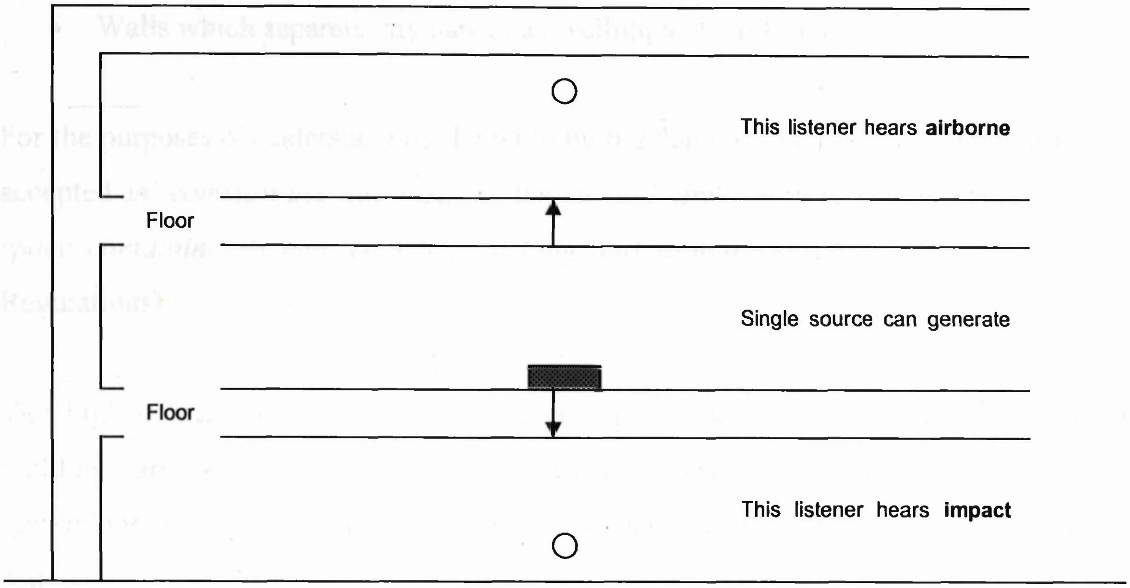


Figure 5.1 *Illustration of two sound paths perceived by two listeners.*

In figure 5.1, it is apparent that the listener in the room above the source room hears the sound as airborne, while the listener below the source room hears the same sound as impact. For this reason, the building regulations distinguish between airborne and impact sound.

5.3.1 Transmission through walls and floors

The walls in which some level of airborne sound resistance is required, according to former building regulations (Part E, schedule 1, 1991), are:

- Walls which separate a dwelling and another dwelling; or another building.
- Walls which separate a habitable room and any other part of the same building which is not in the same dwelling; or machinery room or tank room; a place used for any other purpose unless it is only occasionally used for maintenance and repair

- Walls which separate any part of a dwelling and a refuse chute.

For the purposes of understanding the building regulations, the term dwelling is generally accepted as *'common use that restricts the current application to a self-contained living space containing its own cooking, washing and sanitary facilities.'* (Part E, Building Regulations)

The highest standards of sound insulation required in construction of multi-dwelling buildings are concerned with separating floors. These floors must meet the building regulations standards by achieving good insulation against both airborne *and* impact sounds.

Floors which are expected to meet building regulations regarding airborne sound are:

- Floors which separate a dwelling above and another dwelling; or part of the same building which is not in the same dwelling including a machinery or tank room.

- Floors which separate a dwelling below and another dwelling; or part of the same building which is not in the same dwelling including a machinery or tank room.

The following floors are required to satisfy building regulations regarding impact sound.

- Floors which separate a dwelling below and another dwelling; or part of the same building which is not in the same dwelling including a machinery or tank room.

There are several ways in which impact sound can be significantly reduced. The problem of noisy pipe-work can be reduced by using simple isolation techniques. The best and most cost-effective method is to locate and isolate the source of the vibration, in this case the pipe mountings (Lawson and Grubb, 1997). However, such isolation methods will be ineffective if solid sound bridges between the partitions such as pipes, power sockets, nails, etc are present.

5.4 Acoustic and Sound insulation Techniques

Sound, and indeed noise, can be transmitted between walls and floors through the air or through a structure (i.e. airborne and impact). Separating partition walls are excited by the source, and the consequent vibration directly radiates the sound through to the receiving room. There is a dependence on several parameters such as frequency of the source, mass of the partition, methods of connecting building components and therefore the resonant frequencies of the partition. Consequently the amount of attenuation can be controlled. Walls other than the one directly between the source and receiving room may become excited by the same airborne sound. In this instance, energy is transmitted through the structure and re-radiated though another partition wall. Finally, other walls can be set to vibrate by the partition directly separating the source and the receiving room i.e. not directly by the airborne sound.

It must be noted however, that sound traveling between different storeys within flats are not exclusively dependant on the standard of insulation of the floors (Beranek, 1960). The insulation of the floors is affected by sounds traveling through adjacent walls, or openings such as windows, or even cracks. These are known as flanking sounds. Simply increasing the level of insulation in the floor will result in the flanking sounds becoming dominant. Therefore the improvement to the floor insulation will become unproductive. Improvements must be made to both the floor insulation and wall quality to satisfy the requirements of the building regulations.

Typically, a single stud light steel wall has three possible paths for the transmission of sound. A simple representation of the behaviour of such systems can be seen in *figure 5.2*, showing the three basic transmission paths.

1 - *Direct transmission*
2 - *Transmission through the partition and supporting structure*
3 - *Flanking transmission*

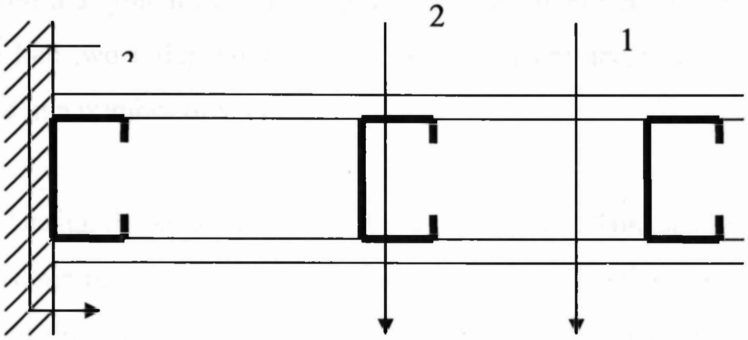


Figure 5.2 – *Sound transmission paths through light steel frame walls.*

Direct transmission – Sound is directly transmitted through the partition. Using heavy or stiff materials will help in the reduction of sound transmission, as these are not set into vibration easily. A gap between double layer walls will also prove effective. This technique relies on the principle of structural isolation. However, this method will only prove effective using materials that are as heavy as masonry construction, as the lower stiffness in the cavity walls usually offsets the benefit of isolation.

Flanking transmission – Sound is transmitted via flanking elements i.e. walls and floors adjoining the sound-resisting element. It is possible for sound to travel via solid elements or cavities at junction points in the construction, therefore sufficient attention to these junctions is necessary to reduce the amount of flanking transmission. At these locations, added mass will provide resistance to sound waves.

5.5 Achieving good insulation

Generally, the most significant problems occur due to the transmission of sound through the studs within a wall. In order to achieve higher acoustic performance, the structural links within a typical modularly constructed element need to be reduced so the wall will behave like two independent leaves (Smith, Peters and Owen, 1996). Achieving this is possible in a number of ways:

- Design the studs to reduce the sound transfer. This can be achieved by introducing some resilience within the frame itself, e.g. bracing, or by considering the design of the shape of the steel framing elements to provide a more acoustically robust structure.

- Include a small cavity between the separate parallel walls (20-50mm). This allows minimal structural connection, thus the gypsum boards act as two independent walls and almost the doubling of the acoustic separation can be achieved.

- Use resilient connections between the gypsum board lining and the steel sections, allowing some flexibility and reducing the sound transmission. This can be achieved by the use of lightweight galvanised steel channels called resilient bars or acoustic profiles that have a corrugated web. These are then fixed perpendicular to the studs and to which the gypsum board is fixed.

The frequency above which these sound reducing methods has an effect has been found to be approximately 50Hz, and increases with increasing frequency (Gorgolewski and Lawson, 1999), or, at higher frequencies, the effect of the sound reduction techniques is amplified. The use of resilient elements such as channels inserted between the traditional building materials and the steel joists can improve both airborne and impact sound insulation by around 10dB, compared to gypsum boards fixed directly to the joists themselves. However, at levels close to the natural resonant frequencies of the floor, resilient ceilings actually amplify the sound pressure levels, which occur at around 25-50 Hz. So generally, resilient ceilings decrease impact sound insulation below approx.50Hz – the frequencies generated by walking. This presents a clear problem to the construction industry as subjective response surveys, as discussed in Chapter 6, highlight the sound source of footsteps above a residential dwelling as the major contributor to the health and enjoyment of the occupiers of the dwellings below such sound sources.

For a single partition, the insulation can be calculated approximately, using the following formula (Gorgolewski & Lawson, 2001):

$$R_{av} = 10 + 14.5\log_{10}m \qquad \text{eq.5.3}$$

Where R_{av} = average sound reduction in dB

m = mass/unit area in kg/m^2

It can therefore be said that the greater the mass of the partition, the greater the amount of insulation provided.

The 'completeness' of a partition wall also plays an important role in how well insulation can be achieved. It is essential to ensure there are no air gaps between doors and windows. When using a perforated false ceiling, there are inevitably holes needed to allow for services to be installed and maintained. As a direct result of an incomplete ceiling, a reduction in insulation of around 10dB or more can occur.

5.6 Mass Law

Generally, sound transmission across a solid element is approximated by the 'mass law'. In principle this suggests that in order to achieve a reduction in sound transmission to a quarter, the mass of the solid element should be doubled (Warnock and Fasold, 1997). In other words, the sound insulation of a solid element increases by 6dB for each doubling of mass. In can also be said therefore, that the doubling of the frequency should in theory, be accompanied by a 6dB loss in sound transmission. In practical situations however the increase has been found to be less than 6dB at frequencies below approximately 1000Hz.

However, better standards of sound insulation can be achieved using light steel framing than the mass law would suggest, aided by incorporating as wide an air gap as possible between each element of a double layered wall. Essentially, this allows the two wall elements to act independently of each other. When using lightweight panels, the use of a double-layered partition can provide measurable improvements in the level of insulation. However in order for this to be achieved, certain criteria must be met (The Steel Construction Institute, 1998):

- The gap is greater than 50mm
- The two panels are a different weight
- There is sound absorbent material in between the two panels
- There are no air gaps present through the material
- There is no coupling present between the panels

As can be seen in *Figure 5.3*, the acoustic insulation of separating elements within a double layer wall usually combine together in a simple cumulative linear relationship, providing the two layers are structurally separate. Generally speaking, the overall performance of a double skin wall is determined by simply adding together the sound insulation ratings of each of its constituent parts. In this way, two comparatively lightweight walls of 30dB sound reduction index can be combined to create an acoustically enhanced wall with a sound reduction index approaching 60dB. The same sections when applied to the mass law would only suggest an improvement of 6dB.

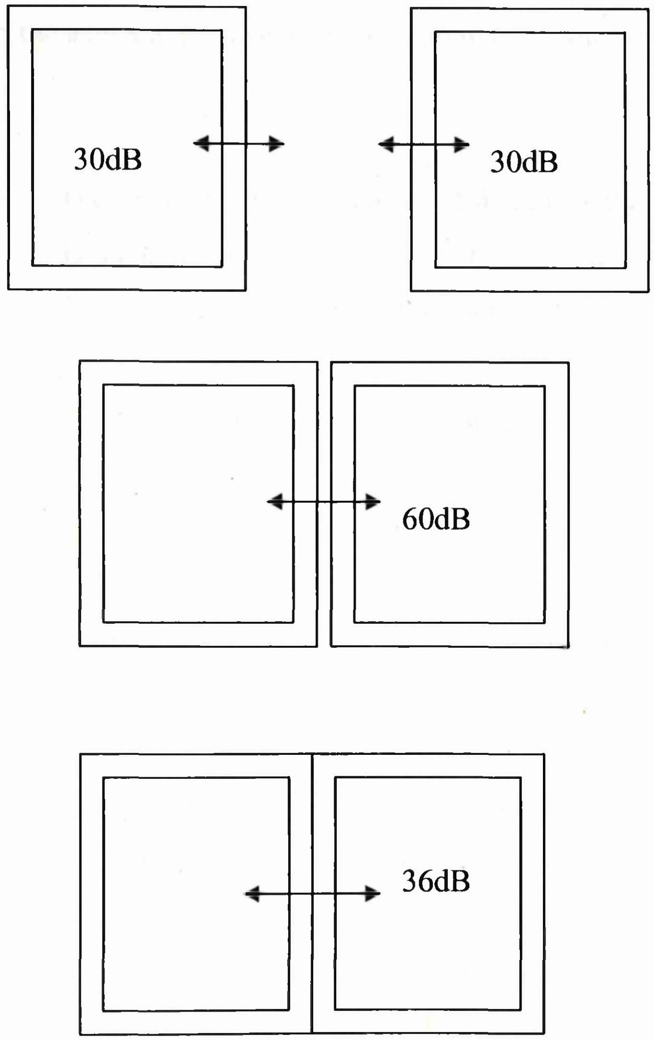


Figure 5.3 – *Schematic diagram illustrating the double layer construction principle.*

When two layers of a partition are firmly attached together they behave like one layer, and superior sound insulation can be achieved (De Man, Francois and Preumont, 2003) However, the apparent further increase in the acoustic performance of two layers as a result of providing an air cavity the between two layers is dependant on frequency, and the consequent standing waves within the cavity leading to acoustic coupling.

5.7 Acoustic Measuring Techniques

When determining the acoustic performance of a room, the acoustician is faced with two problems:

(i) The relationship between the structural features of the room, such as the materials used, the shape and geometry of the room, and the frequency and intensity of the sound sources present.

(ii) The determination of the existing sound field that occurs within it.

The latter of the two problems is perhaps the most complicated, as it deals with the differences in the objective and subjective sound field parameters, i.e. measurable and perceived sounds.

The measurement of the acoustics of any particular room can be performed in two ways. Objective measurements: The techniques used in this method are accurate and are completely objective providing a useful calculation or prediction as to how a room will perform. To obtain measurements of airborne sound involves producing a suitable sound source on one side of a panel. The reduction in sound pressure level is then measured in the receiving side of the panel. In order to completely eliminate differences in sound levels due to the modes present on the room, broadband frequencies are used, e.g. white noise. Using this form of noise allows the measurements to be performed in one-third octave bands (100, 125, 160, 200, 250, 315, 400, 500, 640, 800, 1000, 1250, 1600, 2000, 2500, 3150 Hz). The exact measurement can be calculated by finding the average sound pressure level difference between the receiving room and the source room. The simplest method of achieving this is to use two microphones connected directly to a level recorder, reading the difference shown.

There are several other scientific methods that can be used to perform acoustic measurements.

(i) **Free field measurements** – This technique measures the sound radiated from the source and must not, in any way, be affected by any reflected sound. An example of this type of environment is in an anechoic chamber, or outdoors in an open area.

(ii) **Sound intensity measurements** – An intensity meter is required for this technique. This piece of equipment is sensitive to the sound energy's direction. A sound intensity meter measures the sound power levels in non-anechoic areas, i.e. normal environments.

(iii) **Reverberant measurements** – These are carried out in the specialist test conditions of a reverberant room.

(iv) **Substitution measurements** – This technique requires a calibrated sound source.

Perhaps the most important method to be used in the determination of a room's acoustic quality is through questioning its users, as the relative success or failure of a room's acoustic performance is ultimately decided by the collective judgment of its users. This is known as subjective measurement. A general consensus of opinion needs to be formed, and an average taken so as to determine how well a room performs acoustically.

5.8 Standard Measurement Methods

The human ear experiences sound over a large frequency range and most sounds that we can hear incorporate several different frequencies. However, the sound insulation properties of separating floors and walls vary with varying frequencies, and so certain frequencies within any sound are likely to be attenuated more effectively then others by any given separating element. Low frequencies are generally attenuated less than high frequency, particularly in lightweight steel constructions. With this in mind, sound insulation characteristics of floors and walls are usually measured using a wide range of frequencies across the human audible range, normally 16 bands from 100Hz to 3150Hz (one third octave bands). This measuring technique is well-suited to aid in the achievement of meeting the minimum requirements set out in the new Approved Document E, discussed in Chapter 3. Even though progress has been made in the need to improve the acoustic performance of residential dwellings through the tightening of the legislation in place, there is still some level of concern regarding the importance of low frequencies. This is because everyday noise disturbances for example traffic noise and loud music are dominant at the low frequencies and there is little legislation in place to combat noise produced from outside the building envelop. Again, subjective response surveys have highlighted this as a potential irritant to occupiers of dwelling exposed to high levels of external sound sources and so, there is a clear need to address this issue in future legislation.

The measurement of low frequencies is problematic, but many countries have shown willingness to introduce regulations that more accurately reflect the performance of walls and floors at low frequencies (under approx. 100Hz.)

5.8.1 Airborne Sound Measurements

As discussed in Chapter 3, U.K building regulations require airborne sound insulation between separating walls, and both airborne and impact sound insulation between separating floors. Some European countries also include requirements for walls and floors within dwellings. EN ISO 140 sets out the requirements for performing acoustic measurements of this type.

By generating a steady sound at a particular frequency, the airborne sound insulation between rooms can be measured. The sound level in the source room can be compared with the sound level in the receiving room. The difference in level, D, that is found is simply the difference between the source and the receiving room. This difference in level is influenced by the acoustic absorption in the receiving room. This is measured by the reverberation time T, which, is the time taken for a reverberant noise to decay by 60dB. The Standardised Level Difference D_{nT} normalises the measurements for a reverberation time of 0.5 seconds. D_{nT} is a site based rating and is dependant on conditions such as room size, workmanship and edge detailing.

R, the sound reduction index is a property of the building construction, and is independent of its area and the acoustics of the receiving room. It can usually be obtained by laboratory measurements.

5.8.2 Impact Sound Measurements

The problem of impact sound transmission is most relevant when trying to understand sound transmission through floors. When measuring impact sounds, the most common method is to use a mechanical tapping machine to impact the floor. This simulates the action of footsteps traveling across a room. The impact sound pressure level L is measured in the room directly below that of the source room. The measurements taken can be standardised to a reverberation time of 0.5 seconds, thus giving the Standardised Impact Sound Pressure Level L'nT of the room in which the experiments were performed. When conducted in a laboratory, tests results are normalised for both absorption and area in order to achieve the Normalised Impact Sound Pressure Level Ln.

5.9 Transmission Loss and Sound Reduction Index

In order to be able to compare the acoustic performance of various building element constructions, and make a judgement using a standardised method of obtaining a single figure rating as to how well any given building element performs, it is important to know the sound *transmission loss* (TL) of these structures. The transmission loss of any given partition depends not only on the frequency of the sound source but also the physical properties of the partition. It becomes clear that any noise reduction (NR) apparent between two rooms decreases as the area (S) of the separating partition increases. Similarly, the noise reduction increases as the absorptivity (A) of the receiving room increases.

It also becomes apparent that the transmission loss of a partition is related to the noise reduction and is represented by the following equation (Fahy, 1985):

$$TL = NR + 10\log\frac{S}{A} \qquad eq.5.4$$

where transmission loss (TL) is measured in 1/3 octave bands.

Once this vital information is known, important factors can be determined such as the acoustic privacy between separate rooms, likely level of disturbance from outdoor noise sources e.g. traffic noise, and to provide information to allow for the engineering of optimum solutions for noise control problems.

However, it has become conventional to express the transmission loss of any given partition in terms of the transmission coefficient (t). The transmission coefficient is best described as the fraction of incident energy directed on a partition that is transmitted through the partition and into the receiving room. Chapter 8 deals more fully with the mathematics behind the calculation of the transmission losses of various materials used in the construction of partition walls.

The transmission loss of a partition can be calculated in terms of the transmission coefficient by taking the inverse log of the *transmission coefficient* (t) as shown below (Fahy, 1985):

$$TL = 10 \times \log_{10}\left(\frac{1}{t}\right) \qquad \text{eq.5.5}$$

The transmission loss, or sound reduction index (R), between two rooms is dependant on all of the elements of the structure separating them, and therefore all of the sound transmission paths need to be considered when assessing the total sound reduction. Once the transmission loss, or sound reduction index of a partition has been calculated, accurate comparisons can be made between building elements which provides an invaluable tool in the design and construction of modular buildings.

During the third year of my research program I spent some time in Shotton, north Wales to attend the acoustic testing of the full scale prototype modules that had been constructed by Living Solutions. To continue my progression through the research project, it was vital that I not only gained an understanding of the academic background of the earlier chapters, and the theoretical knowledge discussed in latter chapters, but also obtain first hand experience of full scale commercial testing. By being involved in such work, I have gained a deeper insight into construction techniques, and the methods required to test such structures on-site, using up to date legislation and data obtaining techniques, within a commercial, business orientated environment.

In this chapter, I also discuss the surveys I conducted on a population sample resident in modularly constructed buildings. Again, the importance of this type of work is essential in the understanding of the acoustic behaviour of modular structures in order to develop the construction techniques within the industry to meet the ever increasing targets put in place by the Governments legislation. By gaining this experience of surveying a population sample, it was hoped that an understanding of the acoustic performance perceived by residents of modularly constructed could be gained, which could in turn be related back to the design of such buildings so as to advise architects and designers of methods to overcome 'real-life' problems.

6.1 Shotton Unit Type A and B Tests

During May 2003, Corus Living Solutions performed acoustic testing on prototype modules for which I was present. Measurements of the airborne sound insulation and impact sound transmission of a separating floor between two types of two storey modular units were conducted at Shotton, Flintshire, on 29th May 2003.

Standardized Level Difference (D_{nT}) and Standard Impact Sound Pressure Level (L'_{nT}) measurements were carried out in accordance with British Standards BS EN ISO 140-4:1998 (ref 1) and BS EN ISO 140-7:1998 (ref 1). Single figure ratings of airborne sound insulation performance ($D_{nT,w}$), and impact sound transmission performance ($L'_{nT,w}$), discussed in chapter 2, are derived from these measurements in accordance with British Standards BS EN ISO 717-1:1997 (ref 2) and BS EN ISO 717-2:1997 (ref 2). The results of the measurements are also compared with the performance standard given in Section 3 of Approved Document E to The Building Regulations 1991 (ref 3).

6.2 Method of Measurement

For both unit type A and unit type B, the following method was used to measure the airborne and impact sound insulation, using BS EN ISO 140-4:1998 and BS EN ISO 717-2:1997.

The airborne sound insulation measurements were performed according to a prescribed procedure that specifies the sound generated in the source room shall be steady and have a continuous spectrum in the frequency bands of interest.

T is the average reverberation time of the receiving room (seconds)

T_0 is the reference reverberation time of 0.5 seconds

The Weighted Standardized Impact Sound Pressure Level ($L'_{nT,w}$) in decibels (dB) and the Spectrum Adaptation Term (C_I), also in decibels, are calculated in accordance with BS EN ISO 717-2:1997 by comparison of the sixteen values of Standardized Impact Sound Pressure Level from 100 Hz to 3150 Hz with the relevant reference curves.

Airborne Sound Insulation

Test 1 – Living room/kitchen, Unit Type A and B (first floor) to
Living room/kitchen, Unit Type A and B (ground floor)

Impact Sound Transmission

Test 2 – Living room/kitchen, Unit Type A and B (first floor) to
Living room/kitchen, Unit Type A and B (ground floor)

All windows were closed for the test and all hung doors were taped shut. Where doors were not hung, the entrance and internal doors were boarded up and taped shut. The dwellings were unfurnished and the floor surface was exposed.

Measurements of the sound levels were made in both the source room and receiving room at the one-third octave intervals from 100Hz to 5000Hz as recommended in the Standard. The measurements were taken using a microphone attached to a rotating boom in order to obtain a good average of the sound pressure level in each room. The reverberation time measurements were also made in the receiving room following the procedures set out in the International Standard ISO 354:1985.

6.3 Construction of Separating Elements Between Each Unit

So as to understand better the methods of construction that were employed in the construction of each of the Unit Types used in this experiment, and be able to provide a valuable discussion of potential explanations for the acoustic behaviour of each of the Unit Type, detailed knowledge of the materials used and overall structure of the modules must be known. Architects plans of the layout of each of the test rooms are displayed in Appendix A (figure A1).

6.3.1 Unit Type A

The separating floor in the main living areas consisted of 18mm chipboard, 40mm *Rockfloor* insulation, laid onto 19mm plasterboard plank on an 18mm chipboard floor deck. This was then fixed to a 350mm deep Box Beam floor joists. The ceilings within the main living areas consisted of two layers of 12.5mm plasterboard fixed to 22mm deep x 82mm wide trapezoidal steel sections fixed to the underside of joists. 100mm insulation was placed between the joists at first floor level. The estimated mass of the finished separating floor between the living areas was 70 kg/m^2. This type of construction incorporated the use of air gaps in which to reduce the transmission of sound through the complete partition. A diagram of the details of construction of Unit Type A can be viewed in Appendix A (figure A2).

Within the kitchen modules, the separating floors consisted of 11mm OSB, 40mm Rockfloor laid onto 19mm plasterboard plank on an 18mm chipboard floor deck fixed to 150mm deep steel floor frame. An 11mm OSB layer was fixed 110mm below the floor frame and attached to a 100mm deep steel ceiling frame supporting 12.5mm plasterboard ceilings below. The floor in the kitchen was overlaid with vinyl covered MDF floor tiles. The estimated mass of the finished separating floor between the kitchens was 60 kg/m^2.

The nominal room volumes and common floor separating floor area were:

Table 6.1 – *Unit Type A Room Volumes*

Source Room Volume, m^3	Receiving Room Volume, m^3	Common Floor Area, m^2
135	132	54.3

6.3.2 Unit Type B

The separating floor in the main living areas consisted of 18mm chipboard, 40mm Rockfloor, laid onto 19mm plasterboard plank on an 18mm chipboard floor deck, fixed to 350mm deep Lattice Struss steel floor joists. The ceilings within the main living areas consisted of two layers of 12.5mm plasterboard fixed to 22mm deep x 82mm wide trapezoidal steel sections fixed to the underside of joists. 100mm insulation was placed between the joists at first floor level. The estimated mass of the finished separating floor between the living areas is 70 kg/m^2. Again, air gaps were incorporated in this design.

Within the kitchen modules, the separating floors consisted of 11mm OSB, 40mm Rockfloor laid onto 19mm plasterboard plank on an 18mm chipboard floor deck fixed to 150mm deep steel floor frame. An 11mm OSB layer was fixed 110mm below the floor frame and attached to a 100mm deep steel ceiling frame supporting 12.5mm plasterboard ceilings below. The estimated mass of the finished separating floor between the kitchens is 60 kg/m^2.

The nominal room volumes and common floor separating floor area were:

Table 6.2 - Unit Type B Room Volumes

Source Room Volume, m^3	Receiving Room Volume, m^3	Common Floor Area, m^2
135	58	23.9

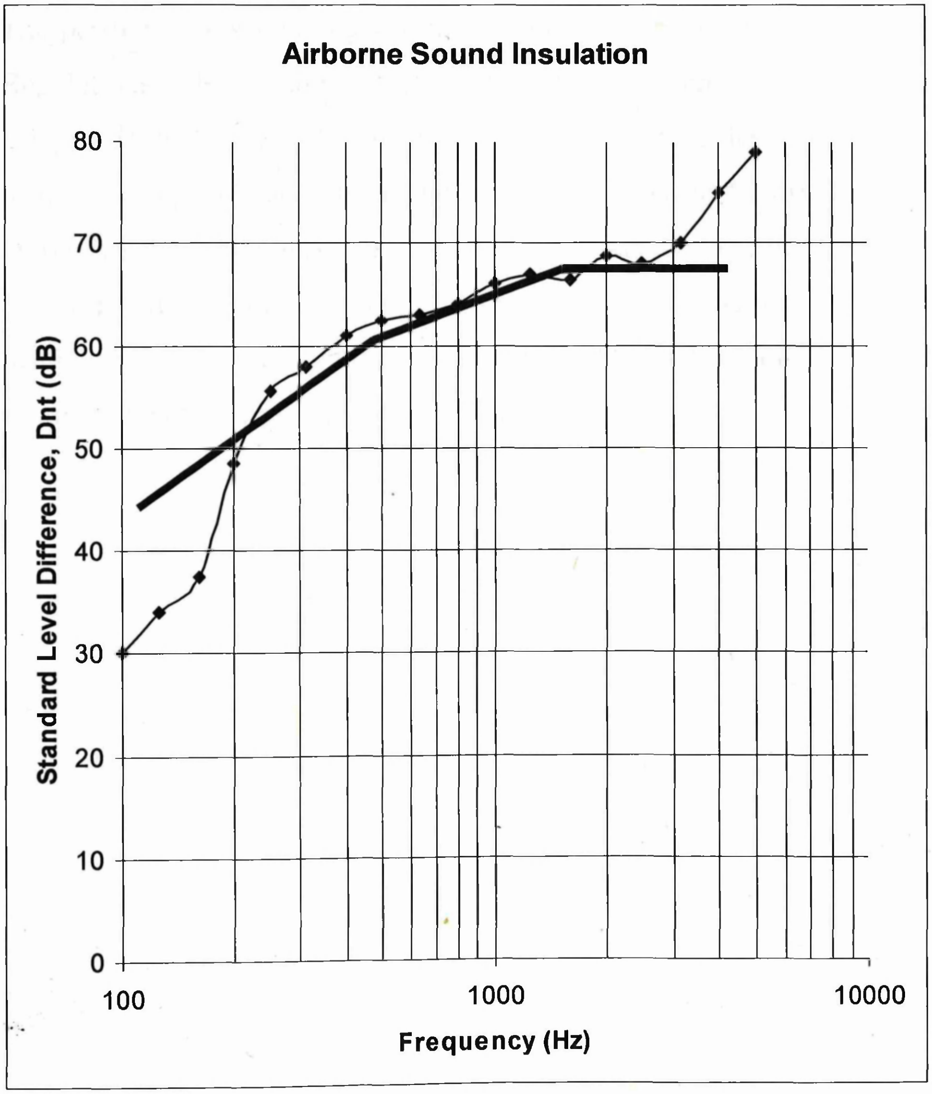
Table 6 .3 - *Specifications for each of the floors and ceilings for unit types A and B*

	Unit Type A				Unit Type B			
MATERIALS	Living area		Kitchen		Living area		Kitchen	
	Floor	Ceiling	Floor	Ceiling	Floor	Ceiling	Floor	Ceiling
Chipboard	18mm (x2)	***n***	18mm	***n***	18mm (x2)	***n***	18mm	***n***
Rockfloor	40mm	***n***	40mm	***n***	40mm	***n***	40mm	***n***
Plasterboard	19mm	12.5mm (x2)	19mm	12.5mm	19mm	12.5mm (x2)	19mm	12.5mm
OSB Board	***n***	***n***	***n***	11mm	***n***	***n***	11mm	11mm
Box beam joists	350mm deep	***n***	***n***	***n***	***n***	***n***	***n***	***n***
Steel floor frame	***n***	***n***	150mm deep	100mm deep	***n***	***n***	150mm deep	150mm deep
Vinyl	***n***	***n***	***y***	***n***	***n***	***n***	***n***	***n***
MDF floor tiles	***n***	***n***	***y***	***n***	***n***	***n***	***n***	***n***
Lattice Struss steel floor joists	***n***	***n***	***n***	***n***	350mm deep	***n***	***n***	***n***
Trapezoidal steel sections	***n***	22mm deep	***n***	***n***	***n***	22mm deep	***n***	***n***
Insulation	***n***	100mm	***n***	***n***	***n***	100mm	***n***	***n***

The floors in the living areas of both the Unit Types are very similar with the only difference being Unit Type A uses a 350mm deep box beam joist as the main structural component, whereas Unit Type B uses a 350mm deep lattice struss steel floor joists. The ceilings in the both living areas and kitchens of the Unit Type A and B are of identical constructions.

6.4 Shotton Results

Figure 6.1 shows the results of the airborne sound insulation between the living room/kitchen of the first floor of Unit type A to the living room/kitchen of the ground floor of Unit type A



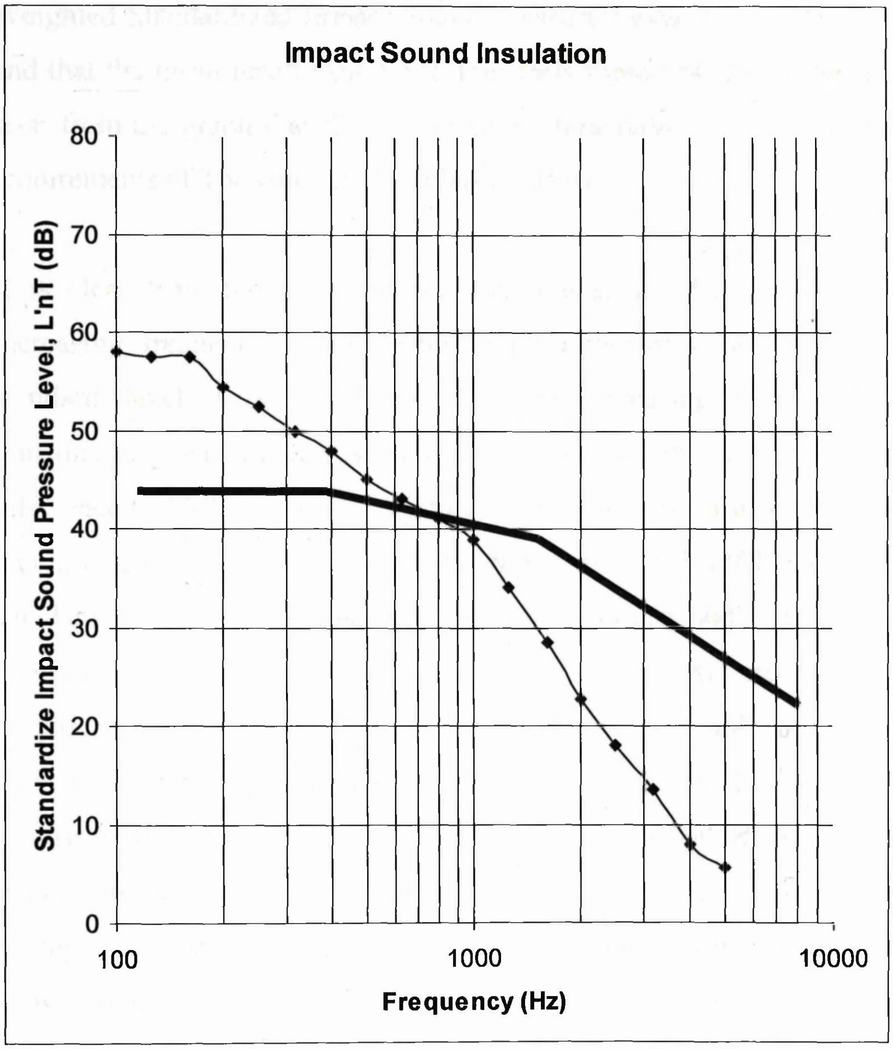
▬ Reference curve, D_{nt},W = 60 dB (BS EN ISO 717-1:1997)

Figure 6.1 *Airborne Sound Insulation between living/kitchen areas of Unit Type A (ground floor)*

The airborne sound insulation test carried out between rooms in a modular building at Shotton Works, Flintshire achieved the following results:

$D_{nT,w}$	60dB
C_{tr}	-12dB
$D_{nT,w} + C_{tr}$	48dB

The performance standard given in section 3 of Approved Document E to The Building Regulations 1991 requires that each individual separating floor should achieve a Weighted Standardized Level Difference ($D_{nT,w}$) of at least 48 dB and that the mean result from up to four tests should be at least equal to 52 dB. It can be seen from the graph that the airborne sound insulation result satisfies the performance requirements of The Building Regulations 1991. *Figure 6.2* shows the results of the impact sound insulation between the living room/kitchen of the first floor of Unit type A to the living room/kitchen of the ground floor of Unit type A.



▬ Reference curve, L'nT,w = 48 dB (BS EN ISO 717-2:1997)

Figure 6.2 *Impact sound insulation between living/kitchen areas of Unit Type A (Ground Floor)*

The impact sound transmission test carried out between rooms in a modular building at Shotton Works, Flintshire has achieved a Weighted Standardized Impact Sound Pressure Level ($L'_{nT,w}$) of 48 dB.

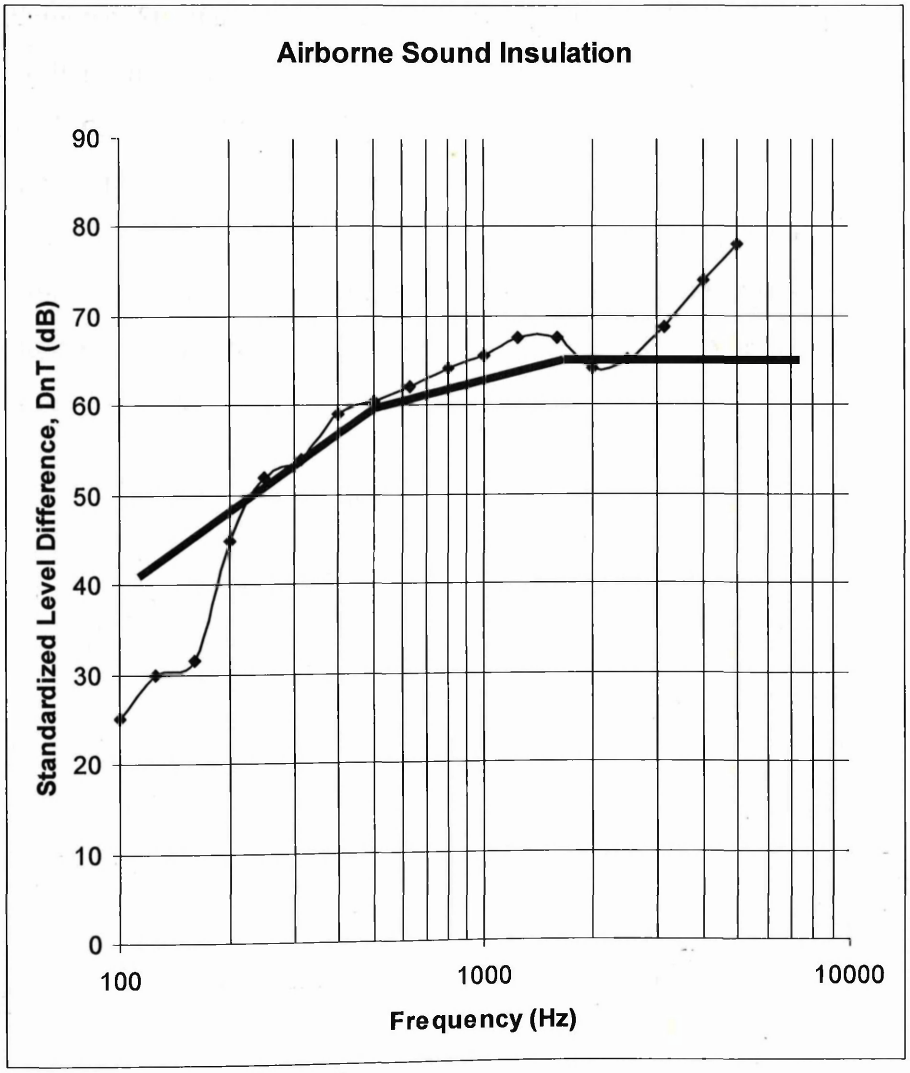
The performance standard given in Section 3 of Approved Document E to The Building Regulations 1991 requires that each individual separating floor should achieve a

Weighted Standardized Impact Sound Pressure Level ($L'_{nT,w}$) of no greater than 65 dB and that the mean result from up to four tests should be no greater than 61 dB. It can be seen from the graph that the impact sound transmission result satisfies the performance requirements of The Building Regulations 1991.

It is clear from the above graphs that the standard level difference increases with increasing frequency when dealing with airborne sound transmission, whereas the standard level difference decreases with increasing frequency for impact sound transmission. At the lowest frequency (100Hz) the airborne sound standard level difference is 30dB, rising steeply to approximately 60dB at 400Hz, with a more gradual increase as the frequency increases to approximately 3000Hz. Above this frequency, the standard level difference increases rapidly to almost 80dB. This would imply that this type of construction does not perform well when exposed to airborne sound in the frequency range 100-300Hz, the speech frequencies, highlighted in further work in this chapter. In relation to the impact sound insulation, the results show that at 100Hz the standardized impact sound pressure level is almost 60dB, and this decibel level falls steeply to as low as approximately 5dB at 5000Hz. These results suggest that the ceiling/floor system of Unit Type A is more capable of resisting the passage of sound at high frequencies than at lower frequencies when exposed airborne sound whereas the same system is more capable of resisting the passage of sound at lower frequencies when exposed to impact sound.

High frequencies are more likely to be attenuated when forced through materials, particularly porous, soft materials such as plasterboard, MDF, and insulation used in the construction of these building elements. This is certainly evident in the results described above, in which large levels of low frequency sounds are transmitted through the building elements, relative to higher frequencies (figure 6.1). The large levels of impact sound reduction evident in figure 6.2 at low frequencies (100-300Hz) can be explained due to the sound produced as a result of the method of creating an impact (dropping sand bags from a height of 1m on to the floor). In this case, the sound source is produced directly onto the surface of the floor itself, and it transmitted directly into the structure of the building element. Due to the quality of construction and the stiffness of the structure, low frequency sounds are easily contained and absorbed, and the passage of sound is resisted at a very early stage. As the frequency increases, the structure's ability to withstand the sound transmission is limited, and the highest frequencies are transmitted relatively restriction free, through to the living space below.

Figure 6.3 shows the results of the airborne sound insulation between the living room/kitchen of the first floor of Unit type B to the living room/kitchen of the ground floor of Unit type B.



▬ Reference curve, DnT,w = 55 dB (BS EN ISO 717-1:1997)

Figure 6.3 *Airborne sound insulation between the living room/kitchen area of Unit type B (ground floor)*

The airborne sound insulation test carried out between rooms in a modular building at Shotton Works, Flintshire have achieved the following results:

$D_{nT,w}$	55dB
C_{tr}	-12dB
$D_{nT,w} + C_{tr}$	43dB

The performance standard given in section 3 of Approved Document E to The Building Regulations 1991 requires that each individual separating floor should achieve a Weighted Standardized Level Difference ($D_{nT,w}$) of at least 48 dB and that the mean result from up to four tests should be at least equal to 52 dB. It can be seen from the graph that the airborne sound insulation result satisfies the performance requirements of The Building Regulations 1991.

Figure 6.4 shows the results of the impact sound insulation between the living room/kitchen of the first floor of Unit type B to the living room/kitchen of the ground floor of Unit type B.

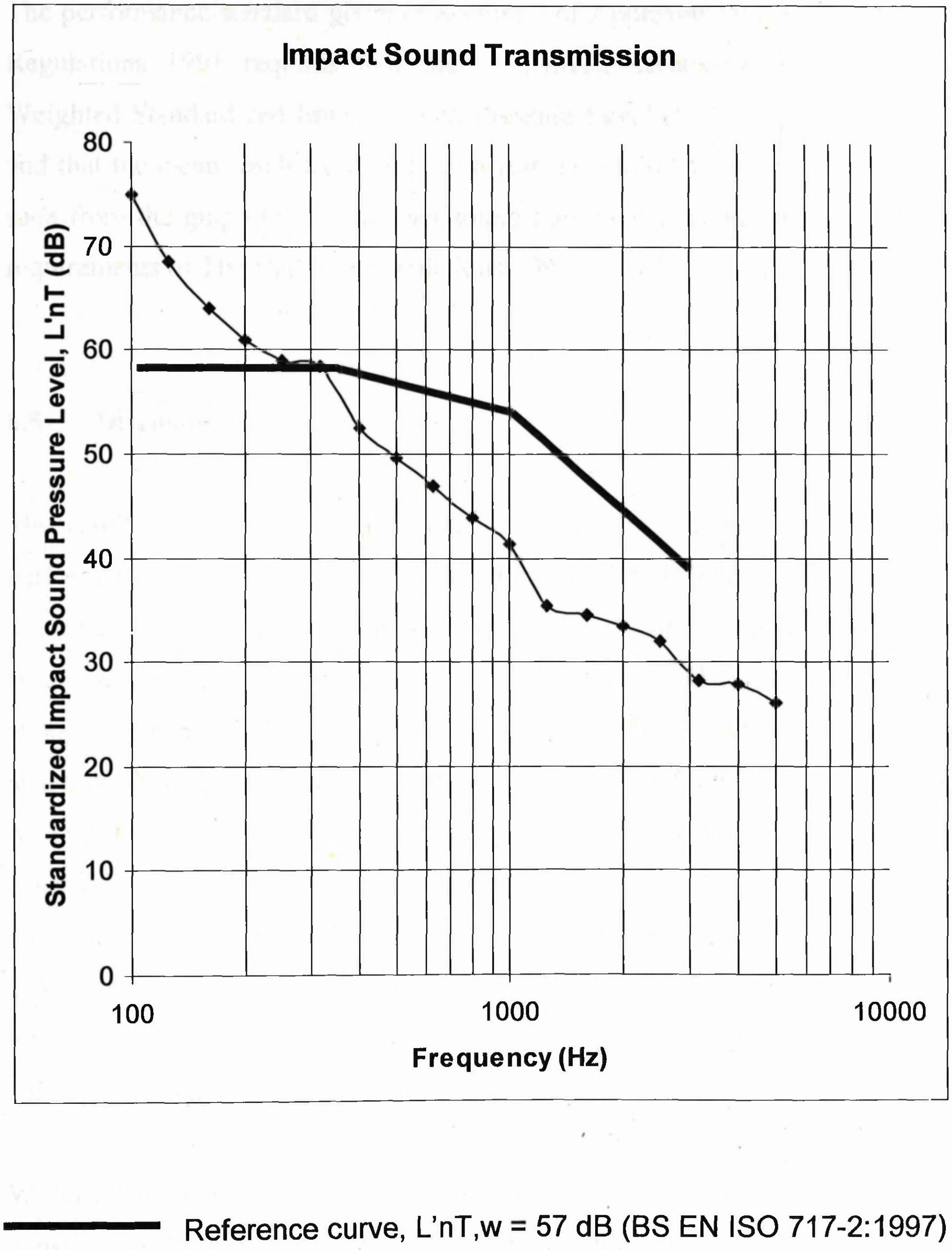


Figure 6.4 *Impact sound insulation between the living room/kitchen Unit type B (first floor)*

The impact sound transmission test carried out between rooms in a modular building at Shotton Works, Flintshire has achieved a Weighted Standardized Impact Sound Pressure Level ($L'_{nT,w}$) of 48 dB.

The performance standard given in Section 3 of Approved Document E to The Building Regulations 1991 requires that each individual separating floor should achieve a Weighted Standardized Impact Sound Pressure Level ($L'_{nT,w}$) of no greater than 65 dB and that the mean result from up to four tests should be no greater than 61 dB. It can be seen from the graph that the impact sound transmission result satisfies the performance requirements of The Building Regulations 1991.

6.5 Discussion

The results obtained, whilst showing similar shaped curves, suggest that the acoustic performance of the airborne sound insulation of Unit Type A is superior to that of Unit Type B, having a standardized level difference of 60 dB compared to 55dB for unit type B. In the case of Unit Type B, a significant dip in the level of sound reduction was found at approximately 2000Hz, to around 64dB, with the D_{nT} values increasing to almost 80dB at the highest value of the frequency range (5000Hz). Unit Type B also performed the worst at the lowest end of the frequency scale, having a standardised level difference of approximately 25dB compared to 30dB for Unit Type A. The only difference in the construction between the two units types was the Unit Type A contained 350mm deep box beam joists within the floor, with Adhesive and floor tiles in the kitchen area, whereas Unit Type B comprised of 350mm deep lattice struss floor joists, having no adhesive or tiling in the kitchen area.

Without having access to the completed modules, nor samples of the materials used in construction for laboratory testing, it would be impossible to emphatically conclude the reasons why Unit Type A performed better than B. However, it would be reasonable to assume that the box beam floor joist used in Type A provided a greater stiffness than that of the lattice structure of Type B, therefore offering a greater resistance to the passage of sound as a result of a more rigid structure. This result can be verified with reference to the theoretical figure discussed in Chapter 8, in which the transmission loss of a structure is plotted in relation to the three regions of control, stiffness, mass, and damping. The low frequency region, approx. 100-200Hz is controlled by the stiffness of the system and this becomes clear in practice as the system with the greatest stiffness (Type A) displays the highest standard level difference in this frequency range, as a result of its greater stiffness (30dB at 100Hz as opposed to 25dB for Type B at the same frequency). It may also be the case that the addition of floor tiles in the kitchen area of Type A would contribute to the resistance of the passage of sound as there would be an increase in the reflection occurring in the surface of the structure due to the hard nature of the tiled surfaces, and therefore more wave reflection present at the surface than Type B, with no floor tiles present. As a result of this increase in reflection, and the potential increase in the local mass of the structure, it is clear that this would result in a reduction of the sound transmitted through the tiles and into the structure itself.

The estimated mass per unit area of each of the floor and ceiling structures of Type A and B are identical. This is evident in *figures 6.1* and *6.3* in that the linear mid-frequency ranges between approximately 500Hz to 1250Hz are almost identical, located in the theoretical region (referred to in Chapter 8) in which the system is controlled by its mass. As the two masses for each Unit Type are estimated to be equal, so the results show similar linear trends throughout this frequency range.

With regard to the theoretical region controlled by the damping of the system at the higher frequency range, it is clear from Figure 6.1 and 6.3 that Unit Type B has less damping present in the structure, due to the dip occurring in the standard level difference at approximately 2000Hz (*figure 6.3*). As damping is increased, the dip decreases in depth. *Figure 6.1* shows there to be an insignificant dip in the standard level difference of Unit Type A as the curve mainly flattens out at approximately 1250Hz, before rising steadily towards the highest frequencies in the test range. This would suggest therefore, that Unit Type A has greater damping present than Unit type B. A potential reason for this may be due to the increase rigidity of the structure as a result of the box beam used in the floor joists, therefore increasing the damping within the structure, or possibly, although any difference in performance may so small that measurements may be practically impossible to record, as a result of the adhesive applied to the floor to secure the floor tiles. The depths of wave peaks and troughs in such situations are usually controlled by damping and, as in the case of Unit Type A, a 6mm thick layer of adhesive may offer some damping resistance to the overall structure.

6.6 Sound Level Annoyance Survey

As part of this research project, it was decided to carry out a series of surveys on a large selection of people resident in modularly constructed apartments in order to gain a better understanding as to which domestic noises are deemed 'annoying' by the people who may be exposed to them. It was hoped that the findings of this survey would establish whether or not the evolution of the building regulations has gone far enough to satisfactorily account for peoples' perceptions and reactions to noise nuisance. The results of this survey would highlight any potential areas where future studies could be directed in terms of the design of modular construction in order to overcome noise problems at within certain frequency ranges.

The methodological issues apparent in the analysis of people's perceptions of annoyance caused by noise are not significantly different to the issues apparent in many other areas of social science research. The potential problems arise from the fact that researchers are attempting to construct theories that will accurately represent the reality that is perceived by the respondents exposed to such sounds. The ultimate goal in this process is an attempt to understand and characterise the reality experienced by the respondents, and work that aids in the understanding of the issues in place are vital in this continuous pursuit of knowledge.

6.6.1 The Methodological Landscape

There exists a wide range of various aspects of behavioural analysis, and in the consideration of the various interests pursued in this type of research, many techniques incorporating distinct means of data collection have developed over the years. Each of these techniques can be utilised to achieve the various research objectives, with the application of these techniques being dependant on the individual aims and requirements of the researcher.

> "'*Research often falls into one of the following three categories: theoretical discourse without empirical foundation; descriptive essays which assemble a collection of impressionistic and anecdotal material; and data analyses devoid of theoretical content*" (Dann, Dennison and Pearce, 1988)

The reasons for this can be further explained in the following ways:

- There has been a tendency to conduct simple descriptive surveys
- There has been a tendency to use this wide range of different survey types in combination.

However these different techniques, while providing valuable and meaningful data, do not lend themselves well to making conclusive comparisons as they are void of in-depth information. Various authors have identified many different data collection methodologies. Upon further thought however, these varying techniques can basically be grouped into five main methodologies:

- Observation: *participant observation, non-participant observation, remote observation*
- Questionnaire Surveys: *self-completion, trained interviewers, one-point, longitudinal*
- Recalled space-time budgets: *'fresh interview', recall of 'normal' period*
- Diaries: *predetermined time locations, 'blank pages'*

- Interviews: *structured, unstructured, focus groups*

The questionnaire methodology is the most popular form of data collection used by government and private agencies, but often suffers from a lack of sensitivity and can become meaningless if the behaviour of a large group of subjects is deduced from the result found from a small population sample. It is also generally understood that questionnaire surveys are open to abuse and there has been found to be a certain amount of cross-over between academic and commercial questionnaire exercises.

In survey research, the researcher selects a sample of respondents from a population sample and administered a standardised questionnaire to them. There are a wide range of different approaches to questionnaire surveys including answers to specific questions, rating of answers on a specific scale (for example Jenkins sleep scale, 1988), judgments of similarity and specific tests. Methods of delivery can be verbal, postal, on the phone or self-completion. Sometimes respondents are required to complete questionnaires at a single point in time but they can have longitudinal time-series. An advantages of using surveys is that it has been found to be capable of collecting a large amount of data from small populations

6.6.2 Postal Surveys

One of the main advantages of postal surveys is that they are cheaper to administer than other methods of surveying, costing up to 50% less than self-administered surveys, and around 75% less than face-to-face surveys (Bourque and Fielder, 2003). Postal surveys are also significantly less expensive than group administered or drop-off surveys, removing the face-face element therefore allowing the participants to complete the questionnaire in their own time without feeling pressure from the researcher. This method also adds another benefit as there is no personal contact between the researcher and the respondent therefore substantially reducing any potential personal bias created by first impressions resulting in altered responses.

A significant drawback to the postal survey is the low response rate mainly as a result of the self-administered method. Investigations using this methodology have found that this method of surveying has a response rate of just over 20% which is substantially lower than the response rate of both telephone surveys and face-to-face surveys (Bourque and Fielder, 2003). There are other problems associated with postal surveys such as the assumptions made about the respondents physical ability, literacy level and language ability. Most surveys require participants from a random sampling, but with postal surveys, the element of control in this area is lost. Within any one group of respondents, there may be people of several different primary languages. There may also be people who are illiterate or have lower reading levels and therefore may not be able to answer the questions accurately. This issue would also be a problem when including respondents who have difficulty reading or are visually impaired.

6.6.3 Oral Surveys

The usual format that this type of survey takes is the phone interview or face-to-face questioning, both of which can be used to obtain open or closed question responses. One of the main advantages of using this method of surveying is that it gives the respondent the opportunity to question the researcher, thus clearing up any confusion which may arise from the questions posed. It has been concluded that

" *interviewing offers the flexibility to react to the respondent's situation, probe for more detail, seek more reflective replies and ask questions which are complex or personally intrusive* " (Glastonbury and Mackean, 1991)

It is well known that obtaining enough responses using any method of surveying is difficult. With oral surveys however, the researcher has more control over the response rate than in other types of survey research. Oral survey researchers can, time and money allowing, interview respondents until a satisfactory number of responses has been obtained, but with mail surveys, the researcher has to wait until the respondents have completed and returned the survey and then make a judgment as to if enough responses have been obtained.

A clear disadvantage that oral surveying has is cost. Performing face-to-face surveys on a large sample of people is very time consuming and this would in turn result in a large payroll cost, and in some cases payment for the participants. Another disadvantage is that in oral interviews, whether face-to-face or on the telephone bias from either the interviewer or the interviewee may become a determining factor. Oral surveying also has a significant effect in reducing the variation in question types that can be included on the questionnaire. For example when conducting this type of survey, it would be very difficult for the respondent to remember a series of choices of answers to a question or a scaled response without a visual reminder of the question and answer. In this situation, it is vitally important for the researcher to carefully construct the question that is to be read allowed.

6.4 Choice of Research Methodology

The objective of this study was to identify the characteristics of sounds that were present in domestic noise related problems, and determine the extent to which these sounds were perceived as being 'annoying'.

Having investigated several different methods of obtaining the data required for the research, questionnaires were chosen as the best means. Despite the body of opinion against postal surveys discussed in section 6.6.2 as the best methodology for sound perception analysis, they have a number of advantages over other methodologies:

- They can incorporate a wide range of requests for information enabling a significant database to be constructed for analysis
- They are quick to administer and have less of a discouraging factor when compared with more time-consuming methods such as diaries, thereby allowing more responses to be obtained in the given time period.

- They are cheap to administer and easier to interpret the results.
- They can allow for the inclusion of a number of different types of data collection methodologies such as straight question-responses, free-form responses and space-time budgets.

Given the limited resources available to fund a project of this type, out of the number of other methods were available - such as diaries, behavioural observation (participant or non participant), interviews (structured or unstructured) or a combination of the above - a postal survey was believed to be the most appropriate method to achieve sufficient and satisfactory results for quantitative data collection.

The survey was designed in September 2003 and consists of 7 questions separated into 4 sections. The first section, whilst providing useful information for the research also acts to create a 'warm-up' series of questions to aid in easing the respondent into the questionnaire, setting the tone and topic of the survey. Question 4 then splits the survey into 3 separate sections where the respondent is directed into answering an identical series of questions for 3 different areas of their dwelling. The questionnaire was designed in such a way that allowed for its use in as many modularly constructed buildings as possible by incorporating a standard set of questions that would achieve conformity and consistency when utilised in buildings ranging from student accommodation through to commercial privately owned residential accommodation. As a consequence of this, sound sources such as pets would not be relevant in all buildings that were to be investigated.

6.5 The Questionnaire

In order to obtain information that is of value, it was necessary to first begin with recognising the types of noises that present themselves in domestic scenarios. These sound sources were identified and the questionnaire was constructed allowing for investigations into the perceived audibility and subsequent annoyance perceived by the subject. The questionnaire opened with four 'warm-up' questions in order to help the subject in understanding the basic idea of the survey's objective and to provide information that could be useful when analysing the results obtained. The complete questionnaire can be seen in Appendix B.

The main body of the survey began at question five and was split into 3 sections, the first being a series of questions in which the subject responded with a number relating to the level of audibility and annoyance perceived from a list of pre-defined sound sources that may, or may not, be heard from above the subjects living accommodation. A scale of 1 to 5 was used with 1 representing inaudible sounds and 5 representing audible and highly annoying sounds.

The second and third sections of the survey questioned the subject as to the level of audibility/annoyance that was perceived from sound sourced that may, or may not, be heard from below the flat and adjacent to the flat. The same response scale was used in all three sections of the survey.

The building chosen to perform the survey was Senghennydd Court, a University of Cardiff hall of residence. The reason for this choice was that this particular hall of residence was identified as a modularly constructed steel framed building, using techniques similar to that used in the construction of the Unit types in Shotton. The building itself is a moderate sized 4 storey multiple occupancy residence in which each habitable room is identical throughout the building, and are stacked directly above each other, allowing the passage of sound between adjacent rooms to be almost identical in every case.

One hundred and twenty surveys were delivered to each individual room on the 1st November 2003 and the respondents were given 10 days to complete and return the questionnaires. Seven responses were returned, all of which were used in the following analysis.

6.6 Survey Results

For each section of the survey, the subjects' responses were averaged over each of the sound types to gain a more representative picture of the sound perception throughout the building.

The following graph (*figure 6.5*) shows the results obtained for section 2 of the survey – Sound annoyance levels from above the flat. It is apparent that the sound source with the highest average annoyance level for sounds sourcing from above the subjects' habitable room are footsteps, with an average annoyance response of 4. The only other sound source considered to be of an acceptably audible level is that of music. The remaining sound sources were either not audible or were only faintly audible having no annoyance factor.

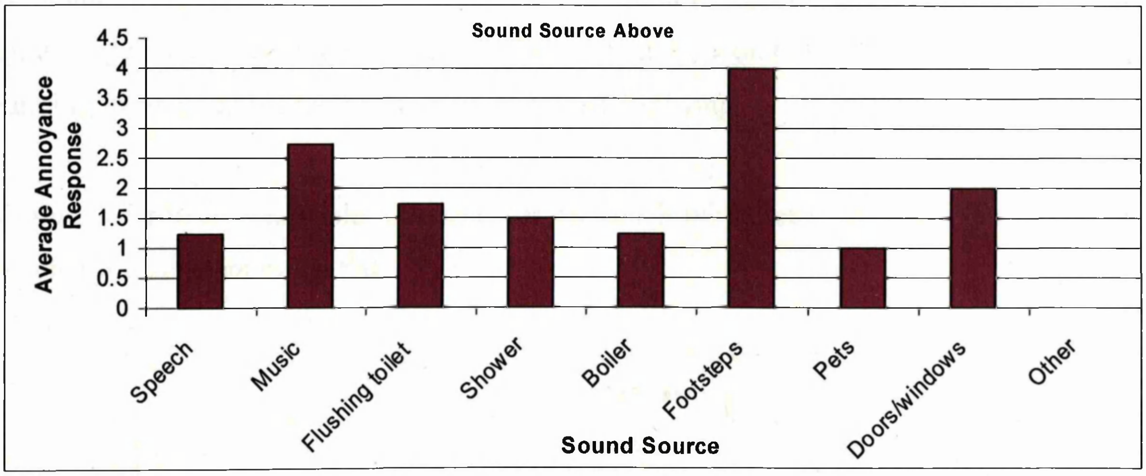


Figure 6.5 – *Graph showing the average annoyance responses for sound heard from above the flat*

Figure 6.6 shows the results obtained for section 3 of the survey – Sound annoyance levels from below the flat

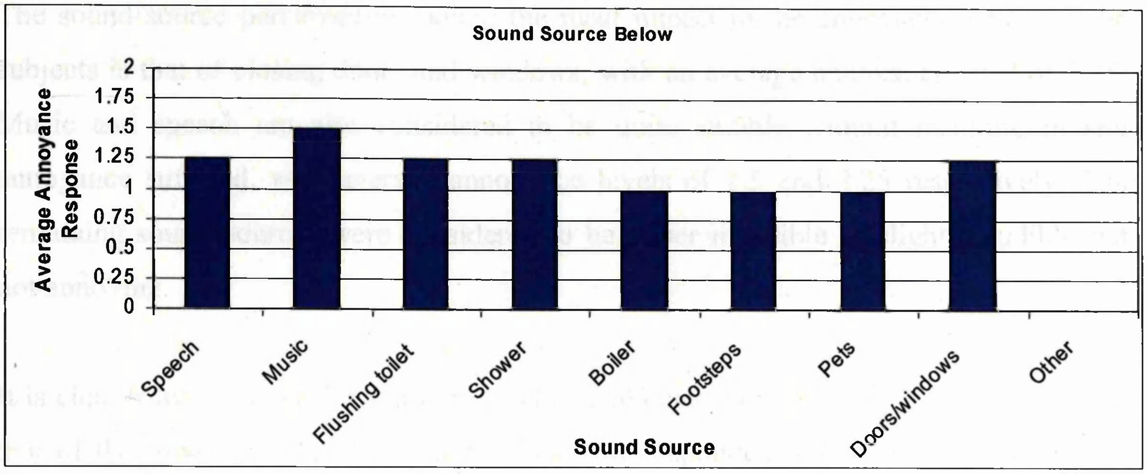


Figure 6.6 – *Graph showing the average annoyance responses for sound heard from below the flat.*

In this instance, no sounds were considered to have any adverse impact upon the respondents in terms of annoyance. Music was found to be the most audible sound with an average annoyance response of 1.5. The remaining sound sources were perceived as ranging from inaudible to faintly audible and not annoying.

Figure 6.7 shows the results obtained for section 3 of the survey – Sound annoyance levels from adjacent to the flat.

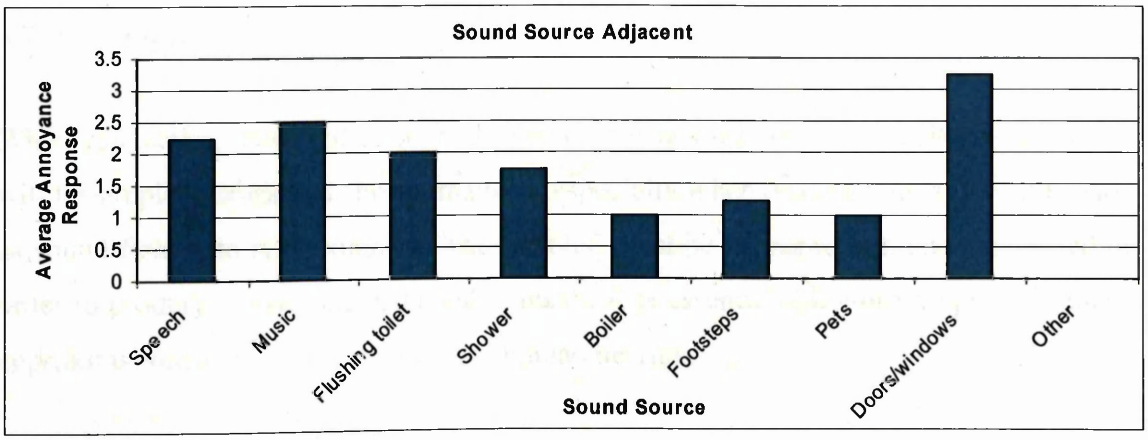


Figure 6.7 – *Graph showing the average annoyance responses for sound heard from adjacent to the flat.*

The sound source perceived as having the most impact in the annoyance levels of the subjects is that of closing doors and windows, with an average annoyance level of 3.25. Music and speech are also considered to be quite audible without resulting in any annoyance suffered, with average annoyance levels of 2.5 and 2.25 respectively. The remaining sound sources were considered to be either inaudible or slightly audible but not annoying.

It is clear from these results that the sound source considered to be the most annoying is that of the footsteps when heard from above the respondent's flats, having an average annoyance level of 4. The only other sound source being perceived as having some level of annoyance was that of doors and windows closing when heard from adjacent habitable rooms, having an average annoyance level of 3.25, which just breaks above audible and into the annoyance scale. The results therefore suggest that no other everyday sound has any adverse effect on the subjects as each of the sound sources produced inaudible or just audible responses with no sound sources being perceived as annoying. The results from this survey also fall in line with those from the survey performed by Langdon et al (1981), discussed in Chapter 4, in that the most common complaints arising from habitants of residential dwellings are due to footsteps and slamming doors/windows. In both these cases, the respondents consider these sound sources to be highly annoying.

6.7 Survey Discussion

When calculating how 'good' or 'bad' a room's acoustics are, it is inevitable that there will be simplifications and approximations, especially when dealing with subjective tests, as sound field data is so complex. The 'results' must be averaged out, and condensed in order to produce a more understandable result. It is essential therefore, to perform these approximations within the properties of human hearing.

The survey performed on the subjects in Senghennydd hall shows some correlation with similar experiments performed by other researchers (Langdon et Al, 1981), in that footsteps and doors/windows slamming cause the most annoyance to inhabitants of subjects living below and adjacent to the sound sources respectively. These sounds are described as impact sounds and are, as discussed in Chapter 5, sounds that are directly impacting upon the surfaces of the building elements and therefore are transmitted through the structure. No other sounds were found as being annoying, although several other sound sources, such as music, speech, and flushing toilets were considered audible but not enough to result in an adverse effect upon the subjects. This would suggest that the construction satisfies the requirements set out in Part E of the Building regulations as the average response for such frequencies, which can be categorised as low frequency sounds (100-300Hz) determined that these types of sound sources were not found to be annoying. This is particularly remarkable when considering the results in the light of the findings of the work previously in this chapter which found that with regards to Unit Type A and B modules, which are of a similar construction type to Senghennydd Hall, that this type of construction does not lend itself well to the resistance of low frequency airborne sound sources, such as speech and music compared to the higher frequency sound sources. This result therefore demonstrates the fact that the construction methods and design of Sengennyyd Hall does indeed fulfill its role in reducing the perceived annoyance of low frequency airborne sounds to an acceptable level. Of course, there are elements of high frequencies within these types of sound sources, but it is thought that the level of this frequency range is not high enough to present any significant issue in terms of sound transmission through the building elements, particularly as the rooms in which the survey was conducted were fully furnished with carpets, beds, curtains etc, and therefore readily absorb high frequency sounds.

The other sound sources that were incorporated in the design of the survey but were not considered to be audible were noises associated with boiler systems and domestic pets. However, the hall of residence operated on a policy of no pets and so no conclusions can be drawn in terms of the frequency content of this particular sound source and whether or not the building elements themselves are capable of resisting the passage of sound associated with domestic pets. Furthermore, it has not been possible to establish the location of the boiler systems within Senghennydd Hall as I have not been permitted to view the architect plans for this development. It would not therefore be reasonable to assume that the results obtained, in which noises associated with boilers were not audible to the subjects, are evidence enough that the building elements satisfactorily resist the passage of sound within the frequencies associated with this type of sound source.

However, the survey results highlighted two sound sources which are considered to be annoying by the subjects living adjacent to and below the sources of impact sounds, that of footsteps and doors/windows slamming. These sound sources have predominantly low frequency content (approximately 250-350Hz). As discussed previously in this chapter, modular construction similar to that of Unit Type A and B has been found to have excellent resistance to the passage of low frequency impact sounds. In this instance however, low frequency impact sound sources present a problem for the inhabitants of the building in that the average annoyance level response is around 4. Again, these types of sounds contain some high frequencies and, as discussed above, an increase in frequency of impact sounds results in a decrease of sound reduction. This may contribute towards the level of annoyance perceived by the subjects in that the majority of the sound they perceive as annoying may in fact have been the high frequency content of the impact sounds, and it is this element of the sound source that is audible between separate dwellings. It is clear then that in this instance, Senghennydd hall does not adequately resist the passage of impact sound to an acceptable level based on the response scale for this experiment. As yet, it is not known whether this particular building satisfies the requirements of Part E of the Building Regulations as I have not been able to obtain a copy of the on-site acoustic test report and so have no means of comparing the data I have obtained with the technical reports carried out by the construction company.

This type of data sampling and analysis is not without its drawbacks, and many problems were faced in the data collection. Having been denied access to any design or construction details of the building in which the survey was carried out, nor being granted access to any of the three other apartment blocks that I sought access to perform this survey, it is difficult to be able to provide a more detailed explanation as to the acoustic behaviour of the hall of residence, nor obtain a more reliable subject response as the results discussed above were based on a participation rate of approximately 5.8%. This level of participation is considered low and as such, any data obtained, whilst resembling the predicted results and that of similar works of other authors, cannot be concluded as definitive but merely a contribution to the continued understanding of this area of work to aid others in future surveys. It is encouraging to note, however, that this survey identified sound sources such as footsteps and doors and windows slamming as being the noises perceived by occupiers as the most annoying, and similar results have been found to be true by other surveys in this field of study (Langdon et al, 1981; BRE).

Chapter 7 Damping Ratio Experiments

In the early stages of this engineering doctorate, the overall goal was to perform vibration analysis experimentation on actual full scale modular frames constructed by Living Solutions using standard vibration analysis techniques, and develop these methods to achieve a tailor made, concise experiment that could be incorporated within the design team at Corus. By performing this work, it was hoped that valuable data could be provided to Corus, in which vibrational investigations into the actual design and scale of the frames used in modular construction would increase the understanding of the vibrational behaviour of light steel framed modular construction, which would in turn aid in the achievement of acoustically robust modules that could be assured to surpass the minimum requirements set out in the Approved Document E of the Building Regulations during the design stages of future product lines. Of course, by succeeding in this section of my research, the potential to decrease time spent in constructing prototypes for testing, and therefore reduce costs would be significant, speeding up the entire process of the product line by gaining vital understanding and knowledge of the details of construction at the early stages of the process.

7.1 Damping Ratio Experiment

When considering sound transmission through structures, it is important to understand the paths that sound can take and methods of minimising or preventing this transmission. It can initially be assumed that in order to reduce sound transmission though modular steel structures, damping can be applied to the steel elements themselves. There are several mechanisms of damping:

(i) Internal molecular energy dissipation

(ii) Radiation of sound – Dependant on frequency, structure and scale

(iii) Friction at joints and interfaces – which would be of paramount importance in modular construction as this is the area in which sound transmission is most likely to occur and is also the area in which there is scope to make significant gains in developing various techniques and designs to address such problems.

Each of these mechanisms has different dependence on frequency and amplitude and so research in the area of design details is critical to achieving satisfactory sound reduction levels within the building elements.

7.1.1 Objectives

So as to gain a better understanding of the basic principles at work in relation to the damping behaviour of steel, and to gain experience in the use of vibration analysis equipment, an experiment was set up to investigate the damping behaviour of a selected range of steel specimens that are used in Corus' Modular construction industry and to investigate the damping effect of steel coatings such as plastisol. Once this primary experiment was complete, it was then hoped to develop this research into more sophisticated experimental techniques using full scale testing. The initial experiment was set up to investigate the effect of coating on galvanized steel, by measuring the damping ratios of various grades of steel and to determine if the coating on a range of steel samples had any effect on the steel ability to withstand vibrations.

The two main objectives of this experiment were:

(i) To determine the logarithmic decrement and damping ratios of four grades of steel.

(ii) To investigate the effect that various types of coating has on the damping behaviour of steel.

7.2 Experimental Procedure

Using a Fast Fourier Analyser, amplifier, and an accelerometer, a simple experiment was set up, illustrated in *figure 7.1*, designed to test the above hypotheses.

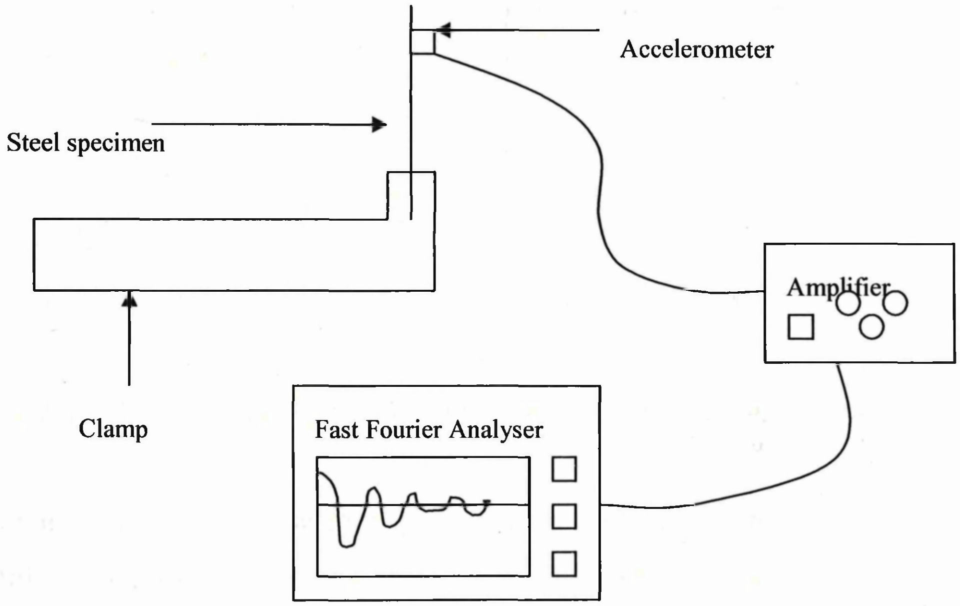


Figure 7.1 – *Diagram showing apparatus used.*

As acceleration (mV) is proportional to displacement (m), this test method was chosen as the fast Fourier analyzer is capable of displaying results in which the displacement of the cantilever system, measured as acceleration, can be easily plotted and viewed in graphical exponential damping format.

Measures were taken to ensure the structure played a minimal role in transmitting vibration after initial excitation of the samples. The steel specimen was clamped in place onto a heavy base which was then placed on a damping mat *(Figure 7.2)*.

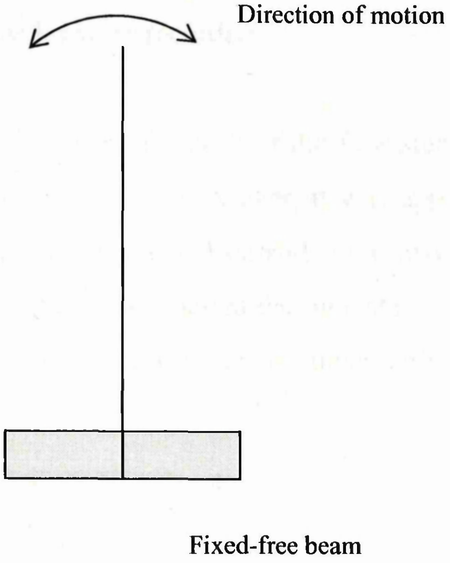


Figure 7.2 – *Drawing showing clamp system and vibration motion of specimen*

Small strips of rubber were placed between each side of the sample and the clamp in order to reduce the vibration transmission through the structure therefore isolating the steel specimen. An accelerometer was then magnetically attached to the specimen at the location as shown in *figure 7.3*. The accelerometer was connected to an amplifier, which in turn was connected to the fast Fourier transform (FFT) analyzer in order to create graphical representations of the decrease in damping.

7.3 Test Method

7.3.1 Experimental Method 1

The following steps were carried out to test each steel specimen.

- Using the finger, the steel specimen was bent from the top centre position.
- At a random displacement, approximately 20mm from the vertical, the steel sample was released and allowed to come to a natural rest.

- The first 3.2 seconds of the vibration cycles were measured, although only the first eleven cycles were recorded.

This procedure was performed five times for each of the four steel specimens (specimen A, B, C, & D) to obtain a reliable average. However, it was apparent from the ensuing results that the initial damping cycle displayed considerable levels of noise. Therefore, for each test result the first cycle peak was disregarded in order to allow the sine wave to become 'smoother' and hence increase the accuracy of the experiment

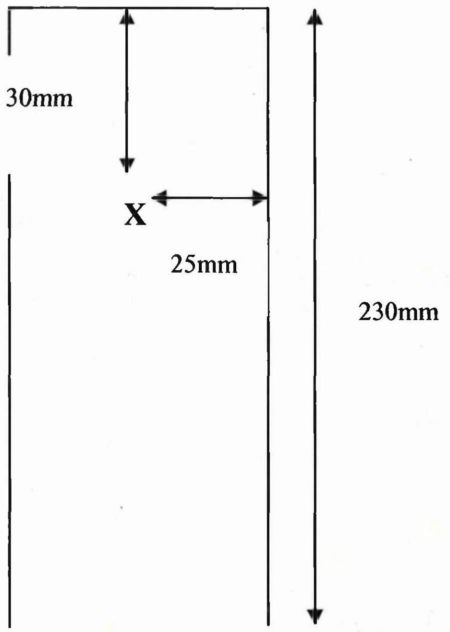


Figure 7.3 – *Diagram showing accelerometer location (* X *)*

7.3.2 Experimental Method 2

A further six identical plastisol coated steel specimens were each subjected to the experimental procedure described above and again, the 2nd to 11th cycle peak values were recorded. From this data the logarithmic decrement and damping ratios were calculated. Each of the steel specimens plastisol coating was then removed using acid and the experiments were repeated, recording the same set of data values for each of the six specimens. Using the formulae (Fahy and Walker, 1998):

$$\text{Logarithmic Decrement } (\sigma) = Ln(X_n/X_{n+1}) \qquad eq.7.1$$

$$\text{Damping Ratio } (\zeta) = (\sigma)/2\pi \qquad eq.7.2$$

the values for each steel specimen were calculated and recorded in the tables shown in the appendices. Standard deviations were found for each steel specimens' logarithmic decrement and damping ratio calculations in order to assess the accuracy of the results found. The full tables displaying each of the results can be viewed in appendices E.

7.4 Results

7.4.1 Experiment 1 Results

The tables and graphs show the corresponding peak values for the first ten cycles. Also shown in the tables are the values, for each repeated experiment, of the damping ratios between each consecutive cycle.

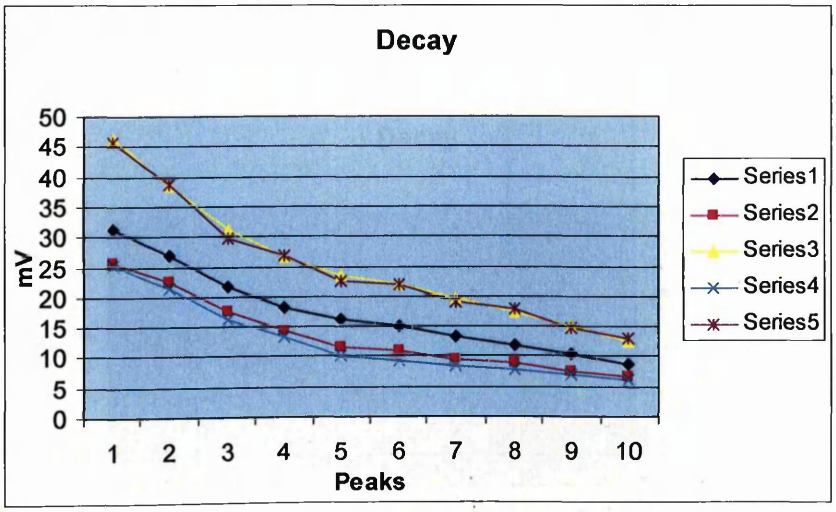


Figure 7.4 – *Peak mV values for specimen A, illustrating gradual decay of vibration. (5 tests)*

At a frequency of approximately 19.7Hz, specimen A has a logarithmic decrement of 0.15 +/- 0.06. This was taken over a period of ten cycles, and is an average score of the five experiments. It has an average damping ratio of 0.023 +/- 0.001 over the five experiments.

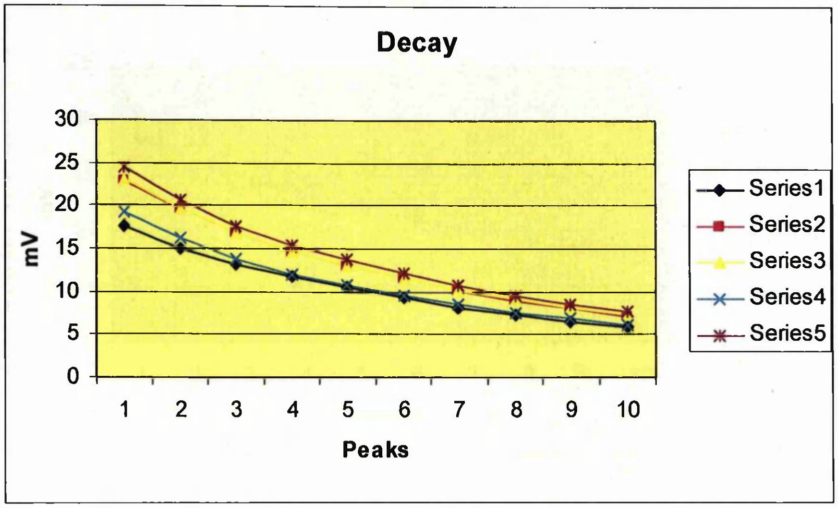


Figure 7.5 – *Peak mV values for specimen B, illustrating gradual decay of vibration. (5 tests)*

At a frequency of approximately 8.6Hz, specimen B has a logarithmic decrement of 0.13 +/- 0.02 and a damping ratio of 0.020 +/- 0.001.

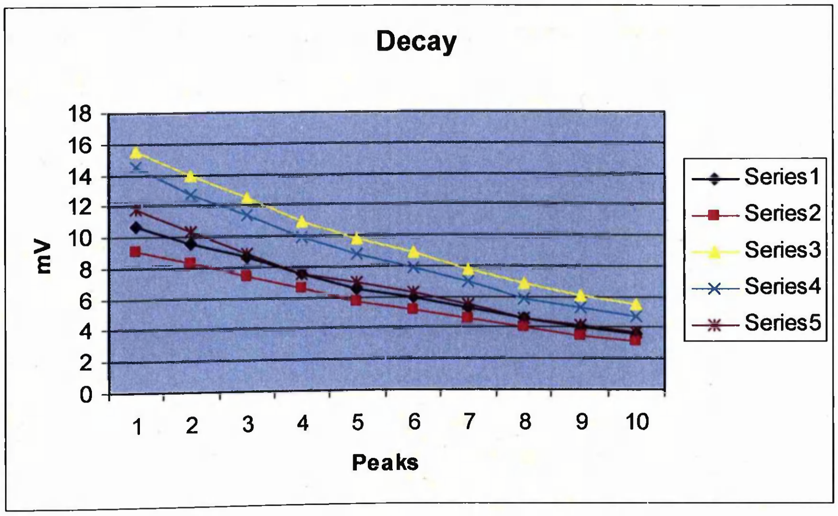


Figure 7.6 – *Peak mV values for specimen C, illustrating gradual decay of vibration. (5 tests)*

At a frequency of approximately 5.6Hz, specimen C has a logarithmic decrement of 0.12 +/- 0.02 and a damping ratio of 0.019 +/- 0.001.

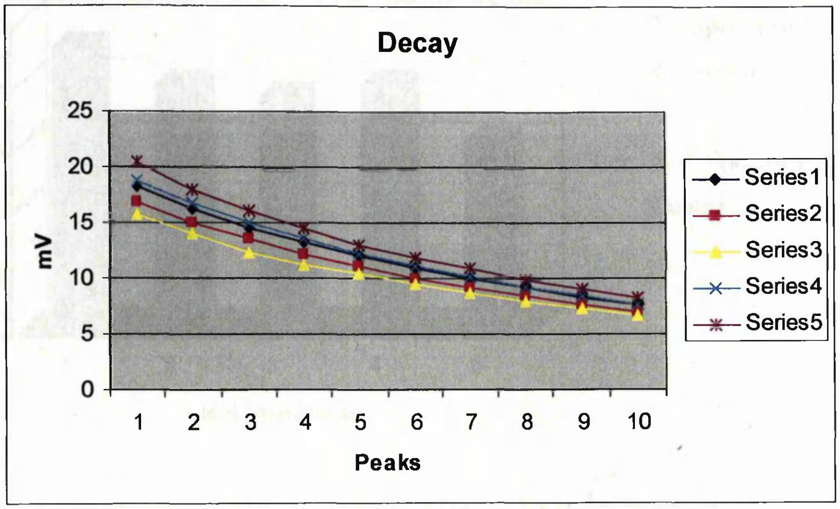
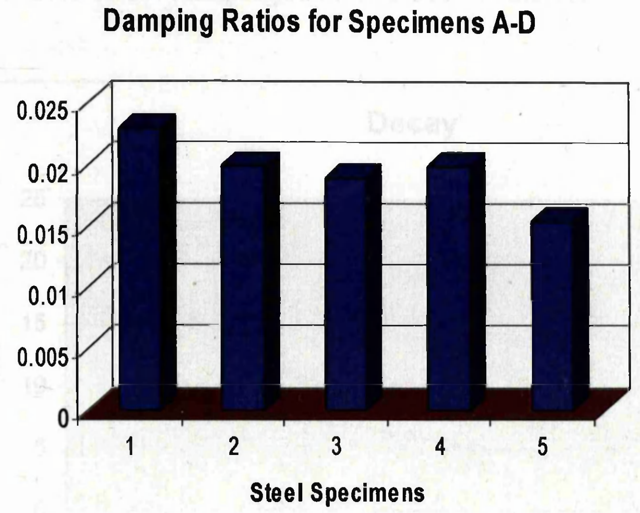


Figure 7.7 – *Peak mV values for specimen D, illustrating gradual decay of vibration. (5 tests)*

At a frequency of approximately 18.9Hz, specimen D has a logarithmic decrement of 0.098 +/- 0.012 and a damping ratio of 0.0155 +/- 0.0003.

Figure 7.8 illustrates the values of the damping ratios for each of the steel specimens. Notice the addition of a fifth steel specimen. This specimen was the plastisol coated steel after removal of the coating.



1 = Specimen A – Galvanised
2 = Specimen B – Tinplate
3 = Specimen C – Plastisol Coated
4 = Specimen C – Plastisol coating removed
5 = Specimen D – Polypropylene Coated

Figure 7.8 – *Comparison of the average damping ratios between all the steel specimens*

7.4.2 Experiment 2 Results - The damping effect of coating

In the following results of specimen C (plastisol coated steel), w represents specimen 'with coating' and wo represents 'without coating', i.e once coating has been removed.

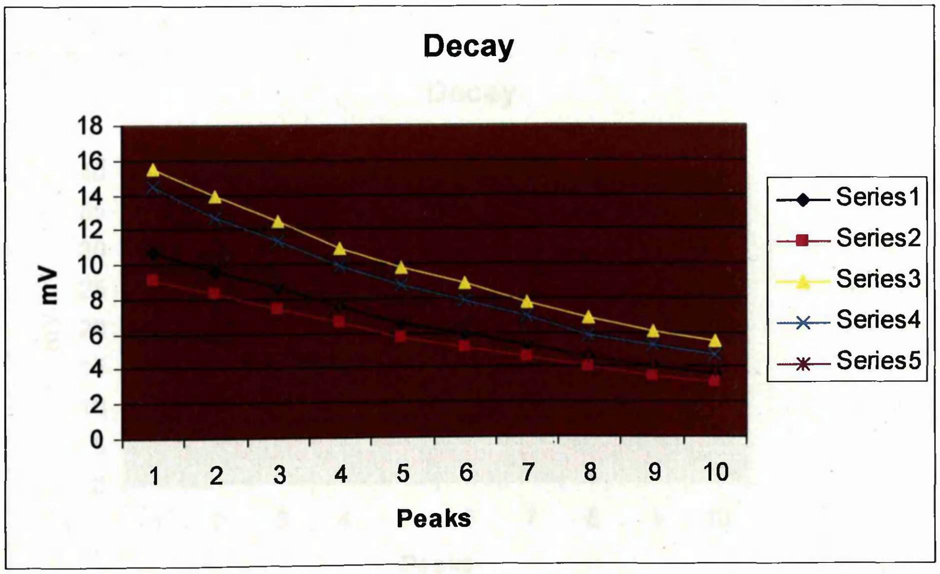


Figure 7.9 – *Peak mV values for specimen C1w, illustrating gradual decay of vibration before coating removal. (5 tests: series 1-5)*

At a frequency of approximately 5.6Hz, specimen C1w has a logarithmic decrement of

0.12 +/- 0.02 and a damping ratio of 0.019 +/- 0.001.

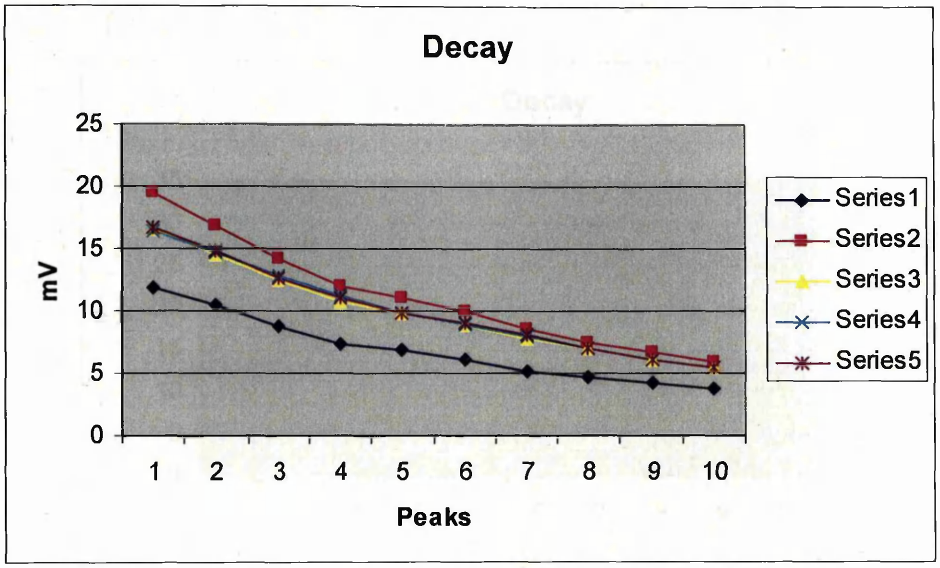


Figure 7.10 – *Peak mV values for specimen C1wo, illustrating gradual decay of vibration after coating removal. (5 tests)*

At a frequency of approximately 5.56Hz, specimen C1wo has a logarithmic decrement of 0.126 +/- 0.026 and a damping ratio of 0.020 +/- 0.001.

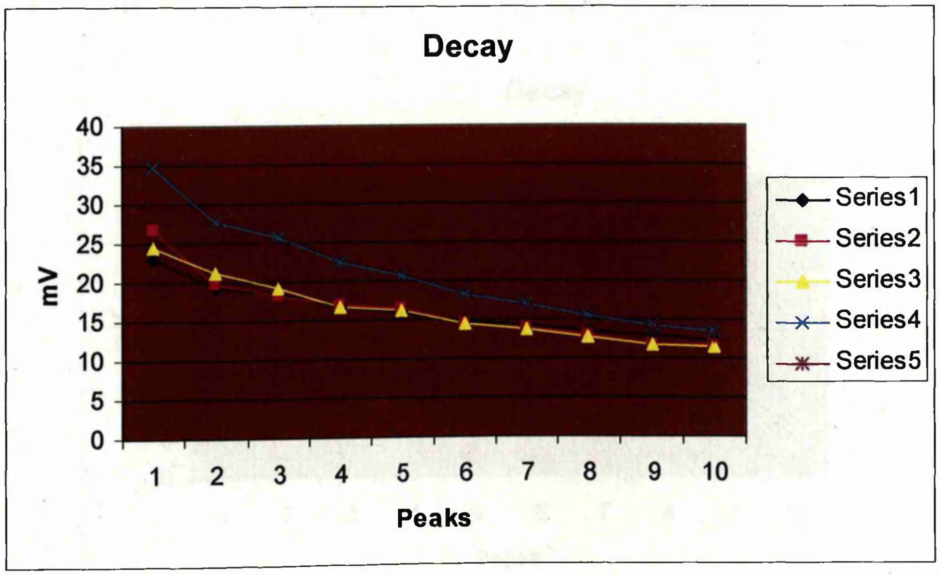


Figure 7.11 – *Peak mV values for specimen C2w, illustrating gradual decay of vibration before coating removal. (5 tests)*

At a frequency of approximately 8.2Hz, specimen C2w has a logarithmic decrement of 0.09 +/- 0.06 and a damping ratio of 0.014 +/- 0.002.

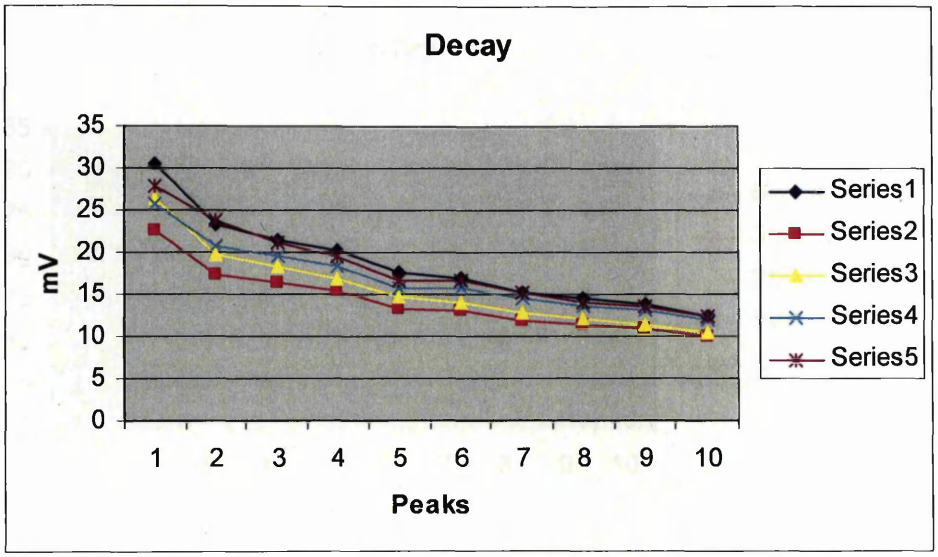


Figure 7.12 – *Peak mV values for specimen C2wo, illustrating gradual decay of vibration after coating removal. (5 tests)*

At a frequency of approximately 8.3Hz, specimen C2wo has a logarithmic decrement of 0.09 +/- 0.06 and a damping ratio of 0.015 +/- 0.001.

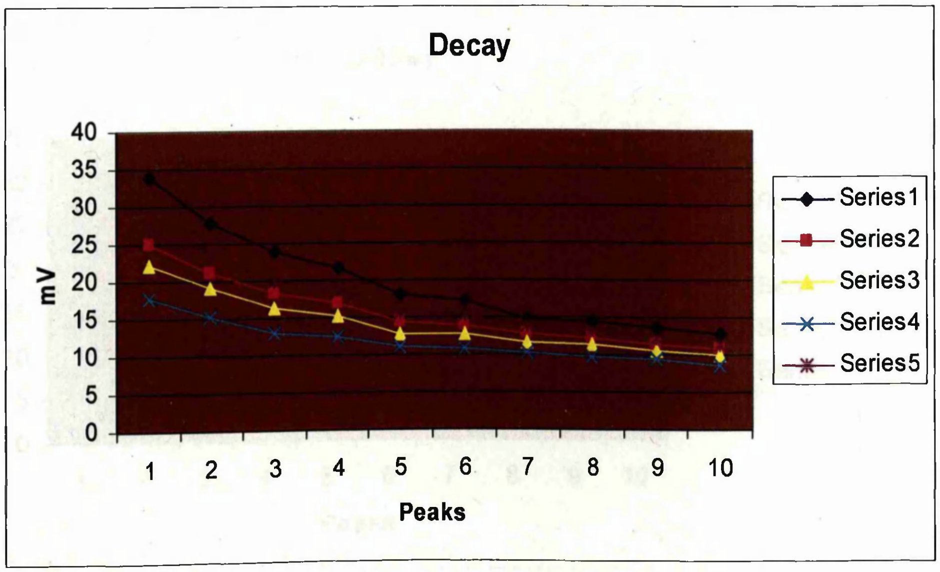


Figure 7.13 – *Peak mV values for specimen C3w, illustrating gradual decay of vibration before coating removal. (5 tests)*

At a frequency of approximately 8.2Hz, specimen C3w has a logarithmic decrement of 0.09 +/- 0.05 and a damping ratio of 0.015 +/- 0.002.

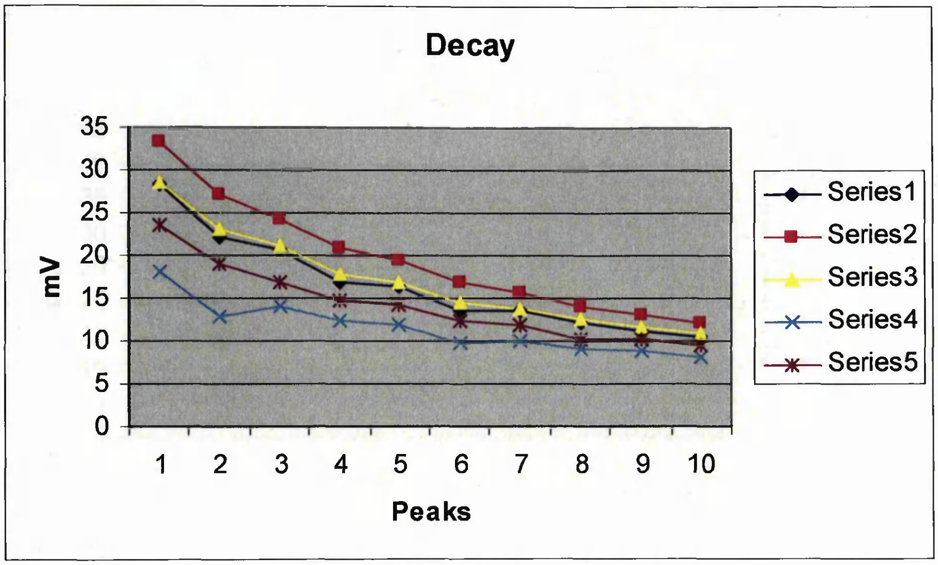


Figure 7.14 – *Peak mV values for specimen C3wo, illustrating gradual decay of vibration after coating removal. (5 tests)*

At a frequency of approximately 8.1Hz, specimen C3wo has a logarithmic decrement of 0.10 +/- 0.08 and a damping ratio of 0.016 +/- 0.001.

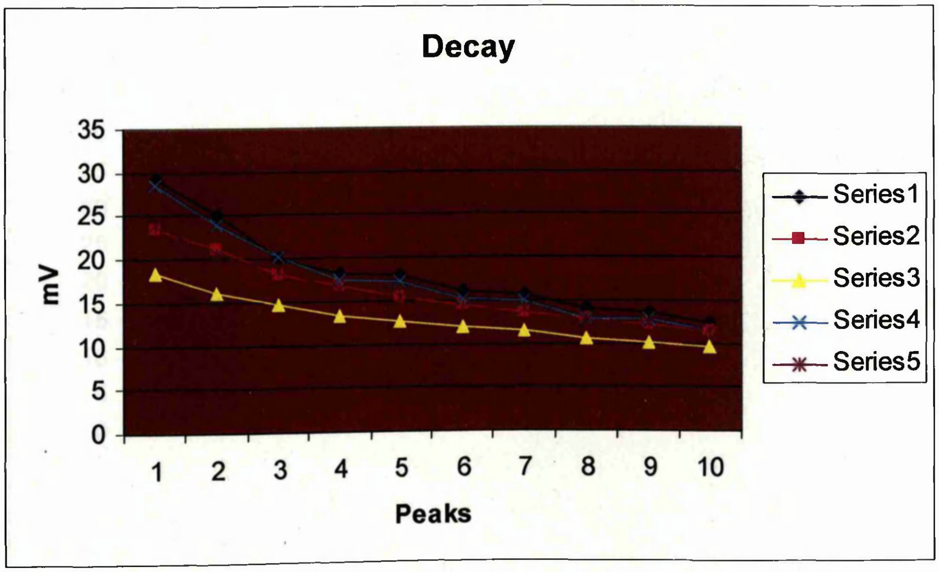


Figure 7.15 – *Peak mV values for specimen C4w, illustrating gradual decay of vibration before coating removal. (5 tests)*

At a frequency of approximately 8.3Hz, specimen C4w has a logarithmic decrement of 0.09 +/- 0.05 and a damping ratio of 0.014 +/- 0.001.

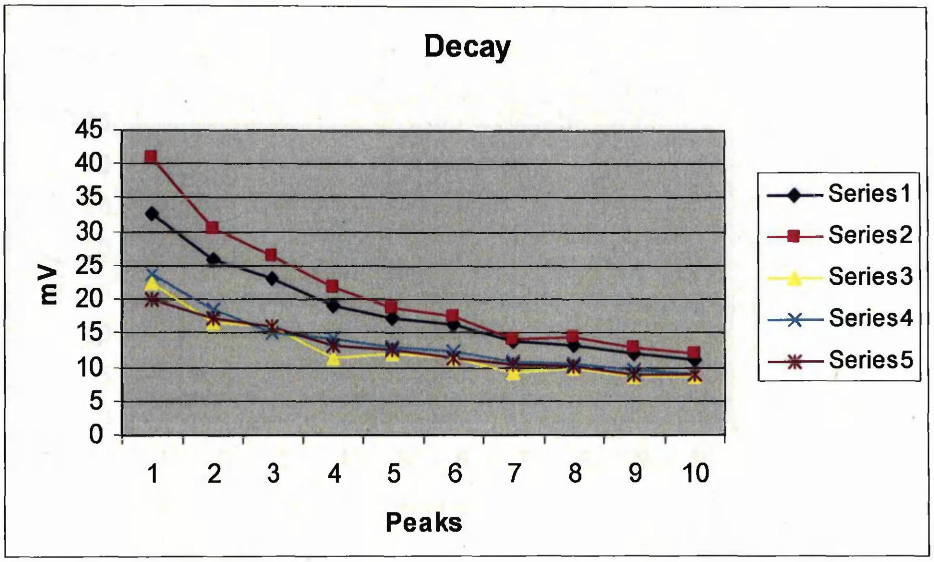


Figure 7.16 – *Peak mV values for specimen C4wo, illustrating gradual decay of vibration after coating removal. (5 tests)*

At a frequency of approximately 8.2Hz, specimen C4wo has a logarithmic decrement of 0.11 +/- 0.09 and a damping ratio of 0.018 +/- 0.002.

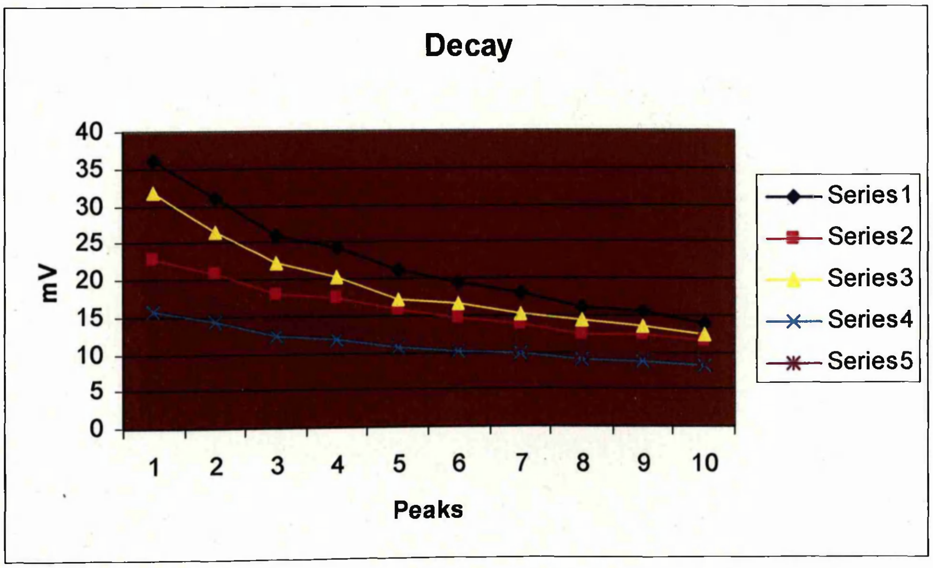


Figure 7.17 – *Peak mV values for specimen C5w, illustrating gradual decay of vibration before coating removal. (5 tests)*

At a frequency of approximately 8.1Hz, specimen C5w has a logarithmic decrement of 0.09 +/- 0.05 and a damping ratio of 0.014 +/- 0.002.

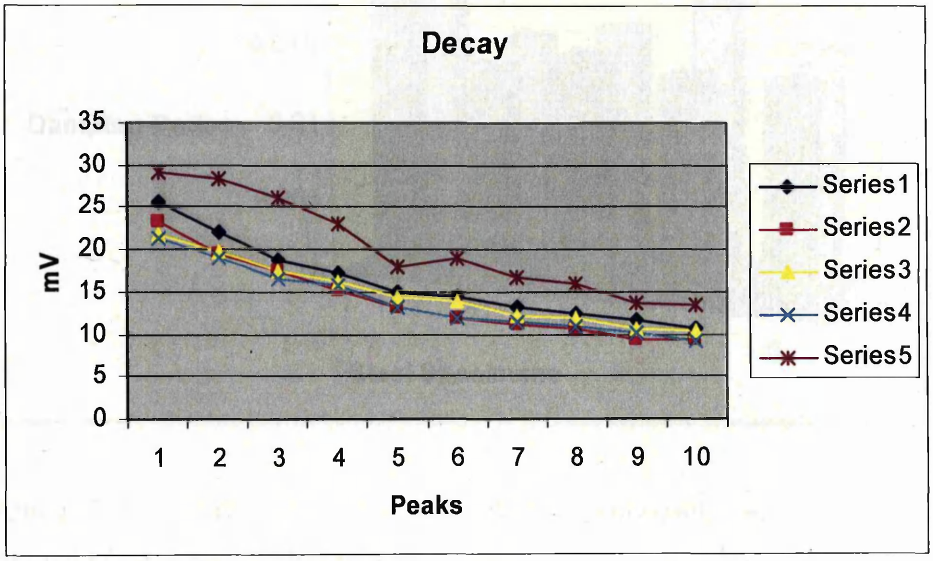


Figure 7.18 – *Peak mV value for specimen C5wo, illustrating gradual decay of vibration after coating removal. (5 tests)*

At a frequency of approximately 8.5Hz, specimen C5wo has a logarithmic decrement of 0.09 +/- 0.06 and a damping ratio of 0.015 +/- 0.001. Figure 7.19 illustrates the change in damping ratio after the coatings have been removed from each steel specimen.

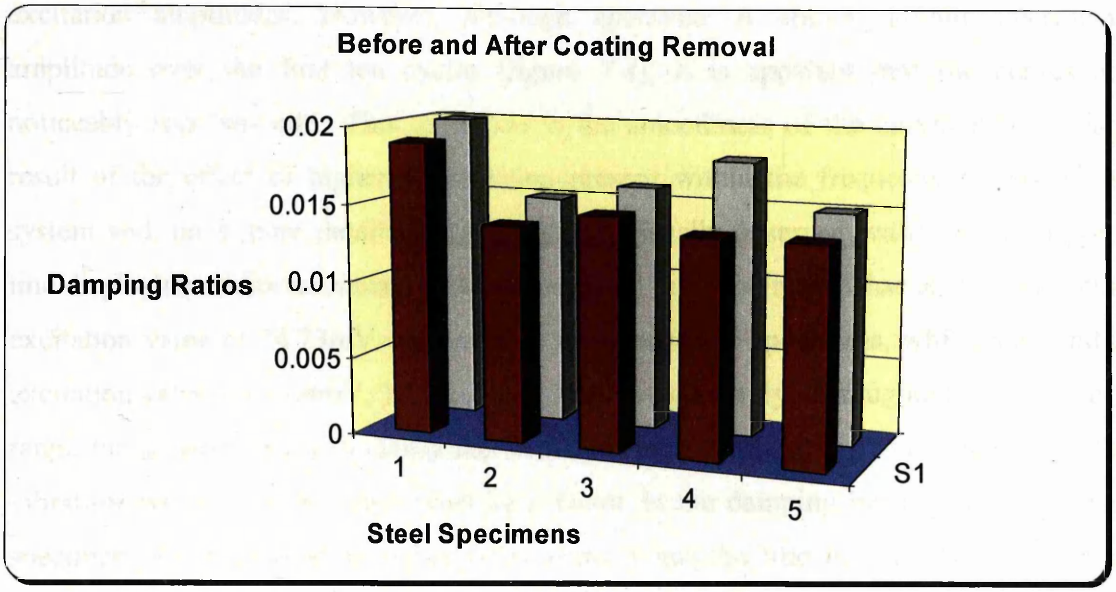


Figure 7.19 – *Damping ratios of each steel specimen before and after removal of coating. (Averaged over 5 tests)*

The average damping ratio of each of the five steel samples, before coating removal is calculated as being 0.015 +/- 0.002. The average damping ratio of each of the five steel samples, after coating removal is calculated as being 0.017 +/- 0.002. It is therefore calculated that each of the specimens displays a percentage increase in the damping ratio of between 5.3% and 7.1%. However, the one exception to this is specimen 4 (plastisol removed) which shows a much larger increase in damping ratio of 28.6%, the reasons for which are described below.

7.5 Damping Discussion

7.5.1 Experiment 1

It is apparent, as expected, that the displacement amplitude of each excited steel specimen decreases with time. Specimens B, C and D show the smoothest decrease in amplitude, as illustrated in *figures 7.5, 7.6* and *7.7* across the entire range of initial excitation amplitudes. However, although specimen A shows definite decreasing amplitude over the first ten cycles (*figure 7.4*), it is apparent that the curves are noticeably less 'smooth'. This reduction in the smoothness of the curves may be as a result of the effect of higher nodes being present within the frequency ranges of the system and, on a more detailed plot, would be visually observed with a more 'jagged' line displaying additional noise. It should be noted that specimen A has an average initial excitation value of 34.73mV compared to the other three specimens, which have initial excitation values of 21.4mV, 12.4mV, and 18mV respectively. Throughout the frequency range the structure used to clamp the steel specimen in place is an integral part of the vibration system and therefore must be a factor in the damping behaviour of the steel specimen (A). However, at higher frequencies it may be true that the clamp structure plays a more significant role in the damping behaviour of the system which may account for the difference in damping curves that are apparent in *figure* 7.4 between the five tests performed on specimen A.

As a percentage of decrease in amplitude from initial excitation to the amplitude at the tenth cycle, the results are as stated below:

Specimen A – 73.1%
Specimen B – 68.3%
Specimen C1 – 66.6%
Specimen C2 – 67.8%
Specimen D – 58.5%

Specimen A has the largest percentage amplitude decrease. This however is probably a direct result of also being the thickest and stiffest sample. Specimen D has the lowest percentage decrease, again probably resulting from being the thinnest and most flexible sample. This is not therefore a useful comparison tool for the specimens.

The aim of this experiment was to determine the damping ratio of several grades of steel, some coated, some not. It was determined that steel specimen A (galvanized steel) has a damping ratio of 0.023 +/- 0.001; specimen B (tinplate) has a damping ratio of 0.020 +/- 0.001; specimen C1 (plastisol coated) has a damping ratio of 0.019 +/- 0.001; specimen D (polypropylene coated) has a damping ratio of 0.0155 +/- 0.003. Again, these results are displayed in Appendices E. In each case, the variation in the number of repeated experiments for each specimen were all found to lie within the calculated standard deviations. It is apparent that the thickest and stiffest steel specimen (A) displays the highest damping ratio, and that the thinnest and most flexible steel specimen displays the lowest damping ratio. It can therefore be assumed that there is a direct correlation between the damping ratio of steel and the steel's damping properties, as a high damping ratio results in a large amplitude decrease from the initial displacement. These results would also suggest that the above correlation is ultimately governed by the thickness and stiffness of the steel, and would therefore require further investigations in this area.

7.5.2 Experiment 2

After removal of the plastisol coating from the steel sample, the tests appear to show that in each case, the same steel specimens have higher damping ratios than when the coating was present. This is illustrated in *figure 7.19*. By taking the average damping ratio over the five samples, it is clear that there is a very small increase in the damping ratio after the coating has been removed. This increase is 0.016. These results are the opposite of those which were expected. There may be several reasons for this: The most likely cause is thought to be that the experimental set-up may not have been sensitive enough to detect small changes in damping variation. This is discussed in further depth below; the accelerometer used may have been functioning correctly; the technique used to excite the specimens may potentially not have been reliable. However, notwithstanding the above points, it should also be noted that the measured data for each of the repeated experiments were all found to lie within the error calculated by the standard deviations in both coating and coating removed experiments. This would suggest that since the error ranges overlapped, no measurable difference could be found in the measured damping ratios of each specimen and so it can be said that removing the coating on each of the steel specimens had no effect on the specimens' ability to resist vibration.

However, from the results obtained, it is also evident that there is a larger percentage increase in damping when the initial displacement of the steel specimen is at its largest. This result is confirmed through the measured test data (displayed in Appendices E), as the experiments performed on the steel specimens in which the initial amplitude was greater, the average logarithmic decrement values over 10 cycles for each of the tests were also found to be greater. The mV readings displayed in the Appendix E are measures of acceleration, which, as discussed in section 7.2, is proportional to displacement, a measure of amplitude. It can therefore be stated that as the initial amplitude decreased over each of the repeated experiments, so the average logarithmic decrement decreased. Although there are some results which do not fall into this pattern, such as steel specimen A for example, the general trend is that there is a clear correlation between the initial displacement and the percentage increase in damping. This suggests that there may be a variance in the reliability of the findings which is dependant on the initial displacement, the reasons for which are discussed in section 7.7.

7.6 Conclusion on Damping Ratio

The damping of such specimens is influenced by amplitude and frequency. At higher frequencies, acoustic radiation occurs which would significantly interfere with the results obtained. For this reason, and because the damping levels are extremely small, it is very difficult to identify the exact effect that the coating has on the steel specimens. Although the experiments were conducted using limited levels of equipment, the following conclusions can, however, be drawn from the investigations:

- The variation in the measured damping ratios for each of the steel specimens, with the exception of the galvanized steel specimen with and without coating, were found to fall with the standard deviation errors. It can therefore be said that the experimental set up determined there was no measurable difference between the damping ratios of the steel specimens once the coating had been removed. Therefore the coating had no impact in the steel's ability to resist vibration.

- There is a direct correlation between the damping ratio of steel and the steel's damping properties, as a high damping ratio results in a large amplitude decrease from the initial displacement. This correlation may ultimately be governed by the thickness and stiffness of the steel, as the thicker steel samples provided a larger decrease in amplitude over the recorded cycle.

- The general trend over the series of tests on each of the steel specimens would suggest that the percentage increase in the levels of damping in the specimen is dependant on the initial displacement, and therefore amplitude, of the steel specimen.

7.7 Further Damping Considerations

Using the fixed-free clamp system in these experiments may not have provided sufficient precautions to minimise the damping occurring between the steel specimen and the clamp. As a result of the design of this experiment, the results obtained are not as expected. The most likely cause of these discrepancies is due to the damping effect of the clamp potentially interfering with the predominantly small levels of damping that were primarily the intended measurement. Without the provision of adequate equipment and the means to repeat the experimentation, it became impossible to carry out more rigorous investigations into the damping behaviour of steel and to redesign this experiment to a completely satisfactory quality, overcoming the damping effect of the clamp. On repeating this experiment, a more suitable experimental set up would involve suspending the steel specimens from both ends as illustrated in *Figure 7.20.*

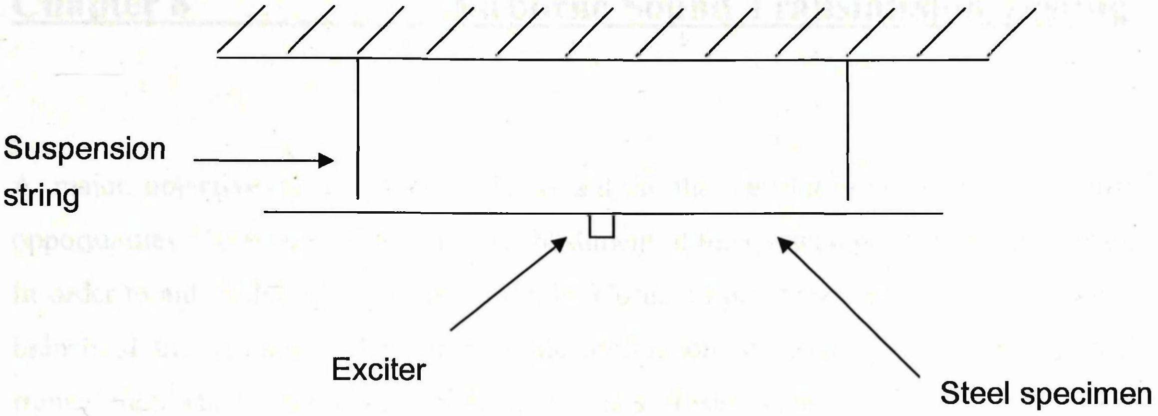


Figure 7.20 – *Illustration of improved experimental set up for damping ratio tests.*

In this experimental design, the suspension of the steel specimen from a solid structure would minimise or even eliminate any extraneous damping that would be present within the clamp method. The use of an exciter would provide a more controlled environment in which to excite the specimens over an accurate and sufficient frequency range. By using the experimental method, any unknown effects that would impact upon the steel as a result of the clamp and excitation method would be reduced or eliminated.

The next stage of this experiment would have been to analyse the results that have been obtained, and investigate the exact effect that the clamping conditions have in greater depth. This would be achieved by investigating the consequences that different initial excitation amplitudes have on the damping behaviour of the steel. A possible method to achieve this would have been to apply least-square-fit analysis to each sample tested. This would aid in the elimination of the apparent 'errors' that seem to occur during the first two or three cycles of each test, and help to establish any effect that variance had in the initial amplitude of vibration.

Chapter 8 Airborne Sound Transmission Testing

A major objective of this project is to aid in the development of new business opportunities which contribute to the establishment of the Corus long term business plan. In order to aid in the research carried out by Corus, in particular the 'Living Solutions' branch of the business, where large scale production of modularly constructed steel framed multi-storey dwellings is being undertaken, it was decided to design and perform an experiment to investigate the construction techniques used by Living Solutions in the construction of separating floors and ceilings. After detailed studies in to the various construction types used within Corus, I led a team of people in the construction of hybrid floor and ceiling panels using methods and designs taken from the P4 range of Corus Module Designs. All these designs satisfy the requirements stipulated in Part E of the Building Regulations and it was predicted that the hybrid panels would also satisfy the building regulations. In order to test the panels for building regulation compliance, the panels were transported to Southampton University and airborne sound insulation tests, were carried out to establish the transmission loss of the system and therefore the acoustic performance. By considering the details of the designs, it was anticipated that the panels' acoustic performance could be enhanced. Whilst not being directly involved in the sound testing itself, the role I played in the project management, panel construction, and contribution to the test preparation was significant in the success of this experimental work.

ISVR consulting were engaged by Corus Strip UK to undertake measurements on a combined floor and ceiling structure to establish the airborne sound insulation. Two separate floor and a ceiling elements were constructed using standard building materials enveloping a light steel frame. The Transmission Loss or Sound Reduction Index relates the Sound Power to the transmitted Sound Power through the sample. The Transmission Loss measurements were performed in the Reverberant Suite of the Rayleigh Laboratories of the ISVR, University of Southampton between 16th and 18th February 2004. The Transmission Loss test was carried out according to BS EN ISO 140-3:1995 and the British Standard BS 2750: part 3:1995, ‘Acoustics – Measurement of sound insulation in buildings and of building elements Part 3. ‘Laboratory measurements of airborne sound insulation of building elements’. BS EN ISO 717-1:1997, ‘Acoustics – Ratings of sound insulation in buildings and of building elements’ was also used.

8.1 Reverberation Chambers

The reverberation chambers used for this experiment are constructed using reinforced concrete and are separated from the foundations and neighbouring walls by rubber vibration isolators. Each chamber was designed with an inclined ceiling and non-parallel walls to ensure that a uniform distribution, in terms of frequency, of the normal acoustic modes of the room.

8.1.1 Large Reverberation chamber

The large chamber measured 9.15m in length, by 6.25m, to a height of 6.10m. The total volume was 348m^3 and had a total surface area of 302m^2. All the inside surfaces of the chamber are finished with a hard gloss paint to give a high reflection coefficient. The thickness of each wall measured 0.305m, and the ceiling measured 0.460m thick and included two removable sections (1.75m x 0.86m) which provided access for a chain hoist. The equipment used in this experiment was connected to the main computer in the control room from the chamber via the cable ports in the walls. A glazed window measuring 0.305m by 0.305m permitted visual observation from the control room. The floor area was also 0.305m thick and had a steel vibration isolated pad, measuring 2.1m by 3.6m, set into it, which prevented any vibrations resulting from the test equipment being transmitted into the test chamber. The chamber contained two sets of double doors, one connecting the chamber with the corridor, in which entry can be gained for building materials, and another opening into the adjacent smaller reverberation chamber. The latter of the two sets of doors incorporated removable panels measuring 1.07m by 1.07m to create the void to insert materials for transmission loss testing. The doors measured

2.56m by 2.26 by 0.13m were a sandwich construction of wood wool, wood and steel, and have an average transmission loss in excess of 50dB. The doors could be removed revealing the doorway itself, measuring 2.4m by 2m in order to test larger panels. In this instance, the larger void created was used to insert the ceiling and floor partitions ready for transmission loss testing. At each corner of the floor there was an air inlet vent, with four outlet vents high up on one of the walls. With all the vents open the air can be changed at a rate of 100m^3 per minute. As this facility was not required in these experiments, the vents were covered by steel plates with a diagonal stiffness to reduce the panel vibrations.

8.1.2 Small Reverberation Chamber

The small chamber measured 6.4m by 4.6m to a height of 4.3m. The total volume was 131m3 and the total surface area was 153m^2. As in the larger chamber, the walls and ceiling measured 0.305m in thickness and finished with hard gloss paint to produce a high reflection coefficient. In one wall there were four cable ports to connect the test equipment to the main computer, and a double glazed window to allow observation from the control area. There were three sets of double doors present in this chamber, one to the larger reverberation chamber, one to a large anechoic chamber, and the other to the common control area. This chamber also provided the facility for air changing, but again, steel plates were used to cover up the vents as this was not needed for these experiments.

8.2 Construction Details

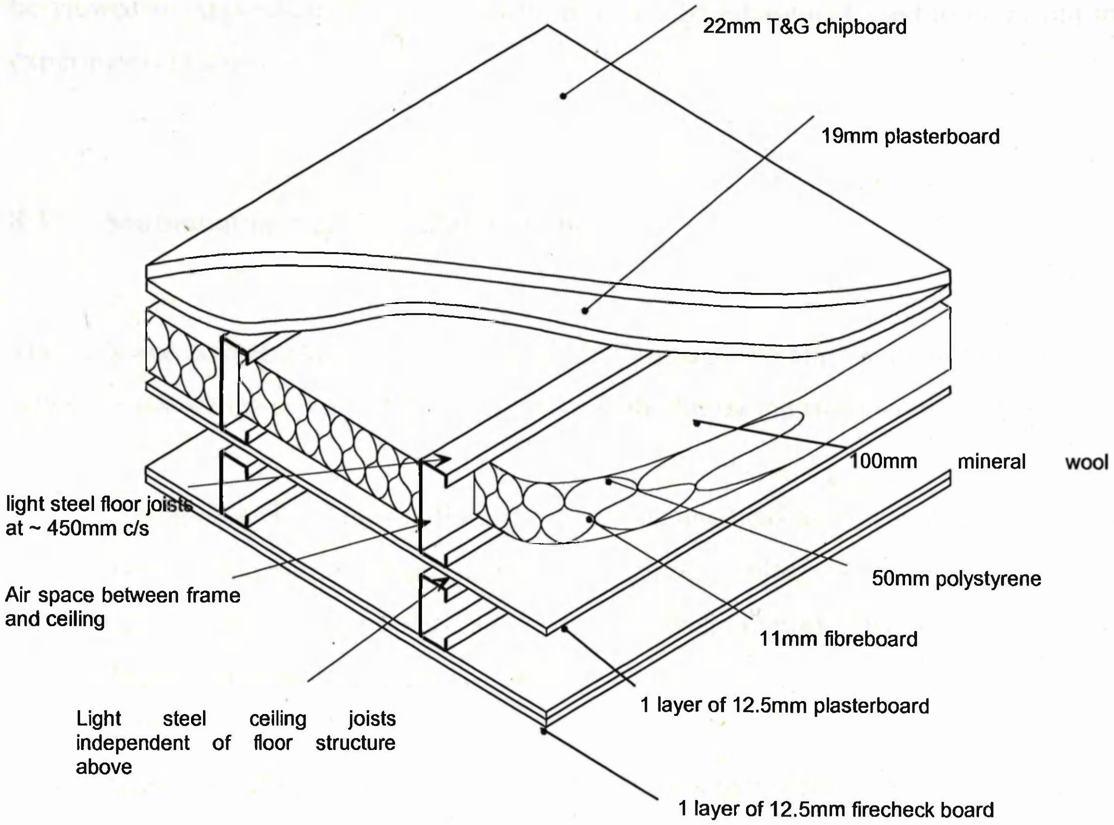


Figure 8.1 - *Diagram showing floor and ceiling panel construction*

Table 8.1 – *Floor and Ceiling Test Panel: Construction details of Corus P4 range.*

Floor	**Ceiling**
1 x 22mm T & G chipboard	1 x 11mm OSB fibreboard
1 x 19mm Lafarge plasterboard	2 x 1.5mm light steel C-sections
2 x 2mm light steel C-sections	4 x 1.5mm light steel C-sections
4 x 1.6mm light steel C-sections	100mm Crown Wool insulation
100m Crown Wool insulation	1 x 12.5mm Lafarge plasterboard
50mm Polystyrene	1 x 12.5mm Lafarge firecheck board

Both the ceiling and floor panels had a test area of 1865mm x 1820mm, Floor depth – 250mm, Ceiling depth – 156mm. Photographs detailing the construction of the panels can be viewed in Appendices C, together with a list of the equipment used to carry out the experiments (Table C1)

8.3 Southampton Experimental Method

The floor and ceiling panels were transported to Southampton University test chambers in order to measure the sound reduction indices and the following steps were taken:

- The combined ceiling and floor structure was mounted in the aperture between the two reverberant chambers, and sealed in place. A block wall was constructed in the gap below the panels and allowed to dry over a period of two days.
  The free area sample size was $3.3m^2$.

- A broad band sound field was generated in the small reverberant chamber (source room). This was sampled by making two circular microphone traverses, lasting a combined time of 128 seconds and continuously averaging one-third octave spectra.

- The transmitted sound field was sampled in the large reverberant chamber (receiver room), again for two circular paths.

- The reverberation times in one-third octave bands were determined for the receiver room.

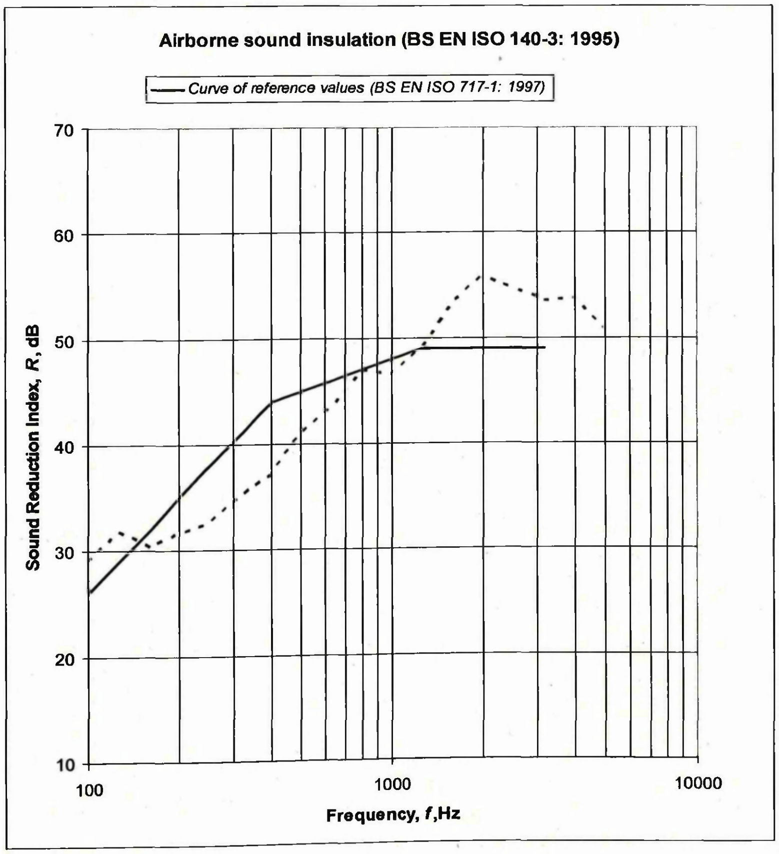
  - The sound reduction indices for each one-third octave band were calculated from the test data and the single number rating of airborne sound insulation derived using British Standard ISO 717.

8.4 Southampton Results

Freq	Source	Receiver	RT60	Diff	SRI
/Hz	/dB	/dB	/s	/dB	/dB
100	99.64	66.43	6.46	33.21	29.10319
125	98.87	63.66	7.68	35.21	31.85447
160	101.86	68.82	9.21	33.04	30.47346
200	102.39	67.63	8.11	34.76	31.64107
250	103.88	68.13	8.07	35.75	32.6096
315	104.47	65.92	7.84	38.55	35.28402
400	103.53	62.86	7.48	40.67	37.19988
500	101.66	57.1	7.39	44.56	41.03731
630	98.78	51.94	7.37	46.84	43.30554
800	98.44	47.59	6.77	50.85	46.94675
1000	99.41	48.58	6.27	50.83	46.59354
1250	98.16	44.81	6.05	53.35	48.95842
1600	98.49	40.16	5.53	58.33	53.54811
2000	99.85	38.64	4.79	61.21	55.80422
2500	98.82	38.02	4.13	60.8	54.75036
3150	95.82	35.54	3.52	60.28	53.53629
4000	92.81	31.21	2.72	61.6	53.73655
5000	90.87	31.36	2.12	59.51	50.56422

Weighted Sound Reduction Index R_w = 45 dB (BS EN ISO 717-1:1997)

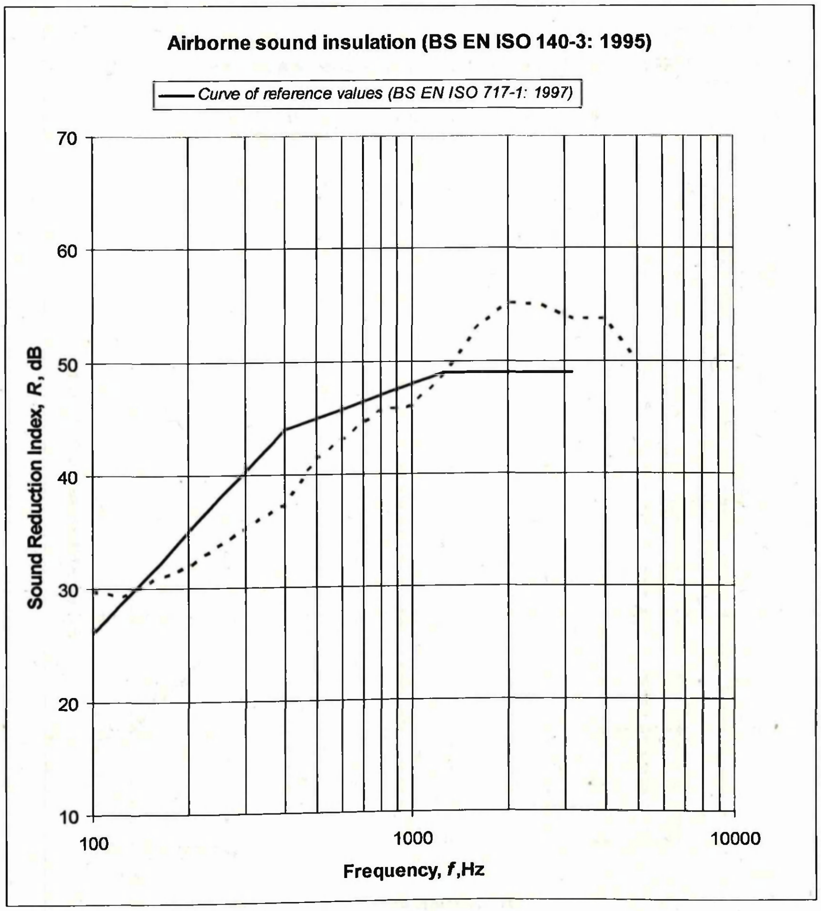
Table 8.2/Figure 8.2: *Sound Reduction Index of Floor and Ceiling with 21mm air gap.*



Freq /Hz	Source /dB	Receiver /dB	RT60 /s	Diff /dB	SRI /dB
100	103.0	69.1	6.5	33.9	29.8
125	102.3	69.5	7.7	32.8	29.4
160	100.4	66.9	9.2	33.5	30.9
200	102.5	67.5	8.1	35.0	31.8
250	102.8	65.9	8.1	36.9	33.8
315	104.1	65.1	7.8	39.0	35.7
400	103.4	62.7	7.5	40.7	37.2
500	101.6	56.7	7.4	44.9	41.4
630	99.8	52.8	7.4	47.0	43.5
800	98.3	48.7	6.8	49.6	45.7
1000	99.4	49.1	6.3	50.3	46.1
1250	97.9	44.9	6.1	53.0	48.6
1600	98.3	40.6	5.5	57.8	53.0
2000	99.9	39.3	4.8	60.6	55.2
2500	98.6	37.6	4.1	61.0	55.0
3150	95.6	35.1	3.5	60.5	53.8
4000	92.5	30.9	2.7	61.6	53.7
5000	90.6	31.8	2.1	58.9	49.9

Weighted Sound Reduction Index Rw = 45 dB (BS EN ISO 717-1:1997)

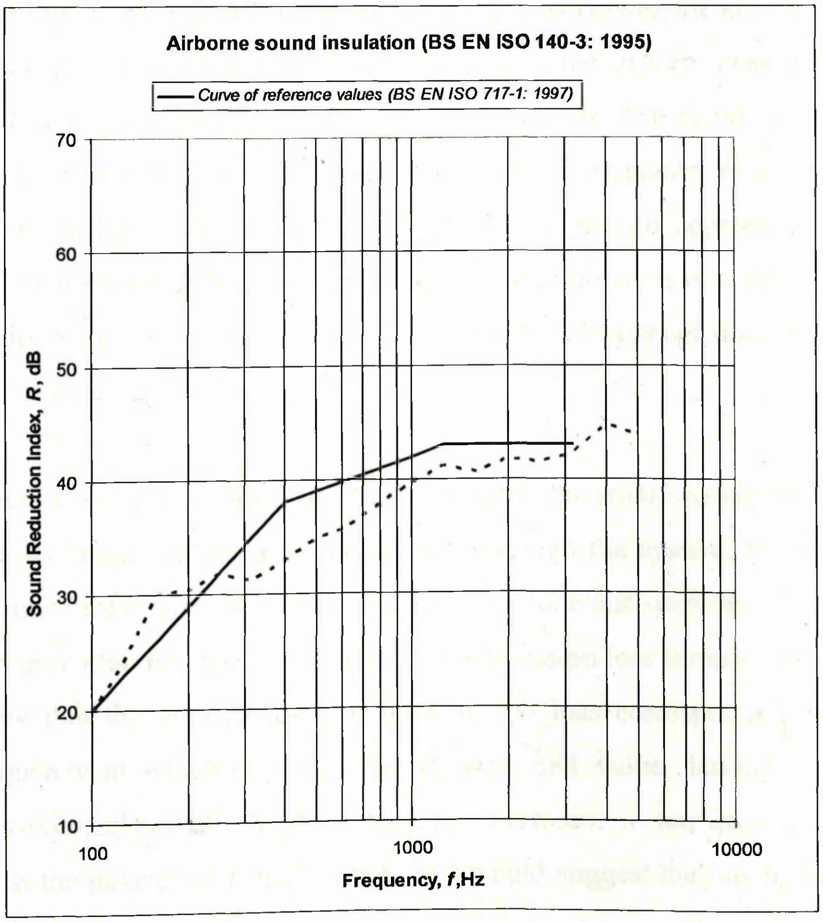
Table 8.3/Figure 8.3: *Sound Reduction Index of Floor and Ceiling with 42mm air gap*



Freq /Hz	Source /dB	Receiver /dB	RT60 /s	Diff /dB	SRI /dB
100	102.5	78.7	6.5	23.9	19.7
125	102.4	74.9	7.7	27.5	24.1
160	100.4	67.8	9.2	32.7	30.1
200	102.5	68.9	8.1	33.6	30.5
250	103.1	68.0	8.1	35.1	31.9
315	103.9	69.3	7.8	34.5	31.3
400	103.5	67.1	7.5	36.4	32.9
500	101.7	63.3	7.4	38.4	34.9
630	100.0	60.6	7.4	39.4	35.8
800	98.4	56.5	6.8	41.9	38.0
1000	99.5	55.6	6.3	43.9	39.7
1250	97.9	52.4	6.1	45.5	41.1
1600	98.3	52.9	5.5	45.4	40.6
2000	99.7	52.5	4.8	47.2	41.8
2500	98.4	50.9	4.1	47.5	41.5
3150	95.4	46.4	3.5	49.0	42.3
4000	92.1	39.5	2.7	52.6	44.8
5000	90.1	37.2	2.1	52.9	43.9

Weighted Sound Reduction Index R_w = 39 dB (BS EN ISO 717-1:1997)

Table 8.4/Figure 8.4: *Sound Reduction Index of Ceiling only*



8.5 Southampton Discussion

The results above show that the weighted sound reduction index values are 45dB for the combination floor and ceiling panels with a 42mm air gap, 45dB for the combined floor and ceiling with a 21mm air gap, and 39dB for the ceiling panel tested on its own. It is therefore apparent that, as expected, the ceiling provides less resistance to the passage of sound that the combination of floor and ceiling. This is obviously due to the significant rise in material properties such a mass and stiffness between the ceiling and floor and ceiling. However, the interesting point found in these result is that of the variation in the size of the air gap present between the floor and ceiling when tested together. It was found that simply doubling the distance between the floor and ceiling, and holding all other parameters constant had no impact upon the acoustic performance of the panels as the weighted sound reduction index remained identical. As discussed in Chapter 6, the sound reduction index (R_w) is directly proportional to the mass if the system. It would therefore be reasonable to assume that simply increasing the air gap from 21mm to 42mm would not give rise to a sufficient increase in the overall mass of the combined panels relative to the initial mass of the combined panels. The results show that the SRI of the partitions is practically identical throughout the frequency range used, having a SRI of approximately 29dB at 100Hz, increasing to a peak of approximately 55dB at 2000Hz, and then tailing of to approximately 50dB at 5000Hz. It is clear therefore that the effect of doubling the thickness of the air gap has little impact upon the performance of the partitions at any frequency.

Discussed in more depth later in this chapter, the sound reduction index of a partition is directly related to the transmission loss through the system, the reverberation time and volume of the receiving room, and the area of the test specimen. In this instance, the only variant within this test was that of the transmission loss through the partitions. The results show that the greatest level of transmission loss corresponded, as expected, with the frequency at which provided the greatest SRI value, having a transmission loss of approximately 61dB. As the frequency decreases, so too does the partition's ability to resist the passage of sound. Again, this would suggest that, as found in the Unit Type A and B test results from the Shotton on-site experiments that at higher frequencies, modularly constructed building elements have a greater ability to withstand sound, possibly due to the characteristics of the materials used in construction, i.e. porous, soft materials such as plasterboard and insulation. Of course, this result may not be unique to modular construction, as building materials such as these are utilized in a wide range of construction techniques. However, it may be reasonable to speculate that the reduced mass of lightweight construction such as steel framing would certainly result in a reduction in the stiffness controlled region of the structure, demonstrated by the reduced SRI values at the lower end of the frequency range. The higher end of the frequency range clearly results in a significant increase in the acoustic performance of each of the partitions tested, and therefore the stiffness of the overall building element is sufficient to aid in the reduction of sound at higher frequencies.

Part E of the Building Regulations state that separating floors and ceilings between dwellings must achieve an SRI value of 45dB or more when exposed to airborne sound. The floor and ceiling tested in the above experiment satisfies this requirement, although the ceiling, when tested on its own, does not meet the requirement. In reality however, a ceiling would not be the sole separating element between two habitable rooms, and so this result can be ignored. In relation to the floor and ceiling combinations

8.6 Mathematical Modelling

In order to be able to compare the acoustic performance of various building element constructions, it is important to know the sound *transmission loss* (TL) of these structures. Once this vital information is known, important factors can be determined such as the acoustic privacy between separate rooms, the likely level of disturbance from outdoor noise sources, e.g. traffic noise, and to provide information to allow for the engineering of optimum solutions for noise control problems. A major part of this research work has been developing a mathematical model to predict the *transmission loss* (TL) and thereafter, the acoustic performance of any given building element.

Laboratory measurements can be taken for many different types of panel constructions. However, it is impractical to test every possible design and combinations of design, and so there is a clear need to have reliable methods for predicting the transmission loss of any given partition construction.

Due to the limited resources available and without the means to perform economical practical experimentation during this research, a major portion of the work carried out in this engineering doctorate has been investigating the potential to develop a mathematical model that can be utilised as a tool to predict the *transmission loss* (TL) and thereafter, the acoustic performance of any given building element. There are many commercial packages readily available which predict the acoustic behaviour of separating elements within construction for example AutoSEA and EASE, the majority of these use techniques such as ray tracing, and statistical energy analysis. However by creating a mathematical model using text book equations, it was hoped that a model could be developed that would accurately simulate the acoustic behaviour of partitions of varying materials when exposed to sound at varying angles. The following sections in this chapter detail the method and reasons behind the each phase of the construction of the mathematical model.

8.6.1 Initial Theory

When sound is incident on a surface of a room, some sound will be reflected, some absorbed, and some transmitted through the element. The incident sound causes the element to vibrate. These movements are small, and are usually not visible, but result in the re-radiation of sound from the element itself, and can also result in vibrations in supporting members.

The fraction of incident energy that is transmitted is known as the *transmission coefficient* (t). By taking the inverse log of the *transmission coefficient* (t), the *transmission loss* (TL) can be calculated (Fahy and Walker, 1998).

$$TL = 10 \times \log_{10}\left(\frac{1}{t}\right) \qquad \text{eq.8.1}$$

The sound reduction, or TL, between two rooms is dependant on **all** of the elements of the structure separating them, and therefore **all** of the sound transmission paths need to be considered when assessing the total sound reduction.

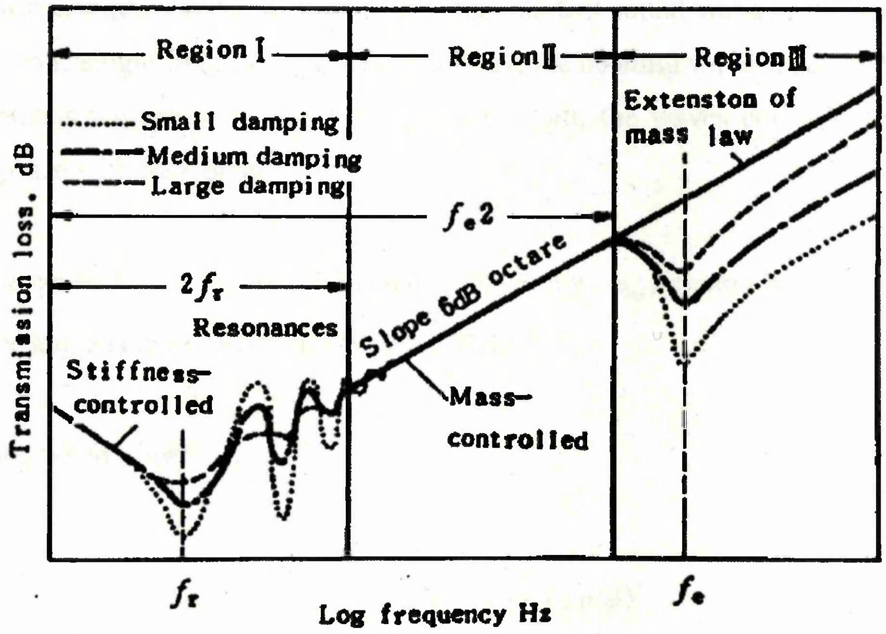


Figure 8.5: *Transmission Loss of a panel showing the three regions of control.* (Fahy and Walker, 1998)

It is apparent from *figure 8.5* that the transmission loss through a partition varies with frequency and can be divided into three different regions, each characterised by three distinct controlling parameters.

- At low frequencies, the stiffness of the material is the main controlling factor. Just above this point, resonance frequencies occur which cause major variations in the sound transmission.

- At approximately one octave above the lowest resonance, the mass of the partition becomes the controlling factor and therefore dominates the sound reduction performance. In this region, the transmission loss is dependant on the surface density of the panel, and increases by around 6dB per doubling of mass.

- High frequencies cause bending/rippling waves to occur through a partition. Unlike the compressional waves that occur in the first two regions, the velocity of bending waves increases with increasing frequency. The Bending wave's wavelength is different from that of the incident sound wave of the source except at one single frequency. At this frequency, the bending wave speed in the partition equals the speed of sound in air. As a result, the waves coincide and travel in phase with each other.

Critical frequency, ω_c (lowest coincidence frequency, ω_{co}) occurs when the sine of the incidence angle is unity (Fahy and Walker, 1998).

Therefore, when $\sin(\phi) = 1$,

$$\omega_c = c_o^{\,2}\left(\frac{m}{B}\right)^{1/2} = \omega_{co} = \omega_c / \sin(\phi)^2 \qquad \text{eq.8.2}$$

and is therefore not dependant on the angle of incidence, where m = mass per unit area of the partition, B = bending stiffness of the partition, c_o = speed of sound in air. However at any angle other than that of unity,

$$\omega_{co} = \left(\frac{m}{B}\right)^{1/2} \left(c_o \sin(\phi)\right)^2 \qquad \text{eq.8.3}$$

which is dependant on the angle of incidence.

At these frequencies, a severely negative effect on the partition's ability to reduce sound transmission can be seen and is represented by the 'dips', centred on the *coincidence frequency*, ω_{co}, in the region of the graph where coincidence is the controlling factor. The depth and width of the coincidence dips are determined by losses of sound energy in the partition material (damping) and also energy losses within the supporting structure. The greater these losses, the shallower and broader the dips, and hence the less affect there is on the transmission loss of the partition.

When two layers of material are attached firmly together, they behave like one single thicker layer which if tested would show a lowering of the coincidence frequency. If however the layers are attached more loosely, surface slippage can occur during bending motions and the coincidence dip would not shift laterally. The resulting friction between layers may increase the energy losses producing a higher transmission loss in the frequencies surrounding the coincidence frequency.

8.6.2 Software

The computer programming package chosen for the creation of a sound transmission simulation was 'Matlab'. The code uses the finite plate theory to calculate the transmission coefficients below, around and above the coincidence frequency, taken from 'Fundamentals of Noise and Vibration' (Fahy and Walker, 1998)

8.6.3 Model Development

An infinitely large partition is constructed using multiple layers of standard building materials and placed adjacent to each other, where it is assumed that there are no joins within the materials, no presence of flanking transmission, no method of attaching the materials to each other, and the effect of friction is negligible. The constructed partition is then assumed to be of finite size (1.82m x 1.86m), and placed within an aperture of a wall separating two reverberant chambers. The aperture is of dimensions 1.82m x 1.86m.

The partition is exposed to a diffuse-field sound source, created on one side of the partition, and the transmission loss across the partition is calculated. Having introduced the properties of the reverberant chambers, the data is then converted into the sound reduction index of the partition over each of the 1/3 octave bands in the frequency range 100-5000Hz.

The following section shows the series of steps taken to construct the algorithm, creating the simulation.

- Series of initial inputs: Number of layers; Density of Layers; Mass per unit area; Young's modulus; Poisson ratio; Thickness.
- A loop is created to run the code over incident angles between 1° and 89° at intervals of 1°. This step generates a diffuse sound field in the source chamber within the angle range.
- The critical frequency and coincidence frequencies are calculated, from which the simulation is constructed around.
- The code is then forced through a frequency loop where the 1/3 octave frequencies are set, and the reverberation times (RT60) of the test chambers at each of these frequencies is set.
- The infinite plate theory calculations are now inputted to determine the transmission coefficients (t) below, around, and above the critical/coincidence frequencies, for each of the 1/3 octave band frequencies. To convert t to TL, the inverse log of the coefficients is taken.

-------- below ω_{co} --------

```
TL1(i,j) = 20*log10(w*m*cos(A)/2*po*co));
```

-------- around ω_{co} --------

```
t2(i,j) = 1/(1+(n*wco*m*cos(A))/(2*po*co))^2;
TL2(i,j) = 10*log10(1/t2(i,j));
```

-------- above ω_{co} --------

```
t3(i,j) = (1/(1+B*k^4*sin(A)^4*cos(A))/(2*po*w))^2);
```

```
TL3(i,j) = 10*log10(1/t3(i,j));
--------     --------
```

- Each of the inputted partition contributions is summed and the resulting TL, over the 1/3 octave range is doubled in order to generate a diffuse sound field over 178°.
- The rms values for each TL are now calculated to obtain an accurate average over the angle range.
- The final step is to integrate the effect the reverberation chambers have on the behaviour of the partition within the aperture. This is achieved by introducing the Sabine formula, which states that:

$$\text{Sound reduction index } SRI = TL + 10\log RT60 + 10\log\left(\frac{S}{0.163\times V}\right) \qquad \text{eq.8.4}$$

where $RT60$ = reverberation time in the receiving room at each 1/3 octave band frequency,

S = area of test specimen,

V = volume of the receiving room. (Fahy and Walker, 1998).

- The SRI at each of the 18 1/3 octave band frequencies is then plotted, providing a graphical representation of the acoustic performance of the partition.

8.6.4 Model Results and Discussion

A single layer of chipboard measuring 1.82m x 1.86m was inserted within the aperture in the wall separating the two reverberant chambers, and a diffuse sound field was generated in the source room. As the chambers in this simulation have been modeled on the chambers in Southampton University, the reverberation times in 1/3 octave bands were assumed to be identical to those of the Southampton chambers. The transmission loss was measured in the receiving room over the frequency range 100Hz-5000Hz, and the sound reduction indices were determined at the 1/3 octave frequencies. In this experiment the thickness of the chipboard was varied, consequently affecting the mass per unit area, whilst all other parameters were held constant.

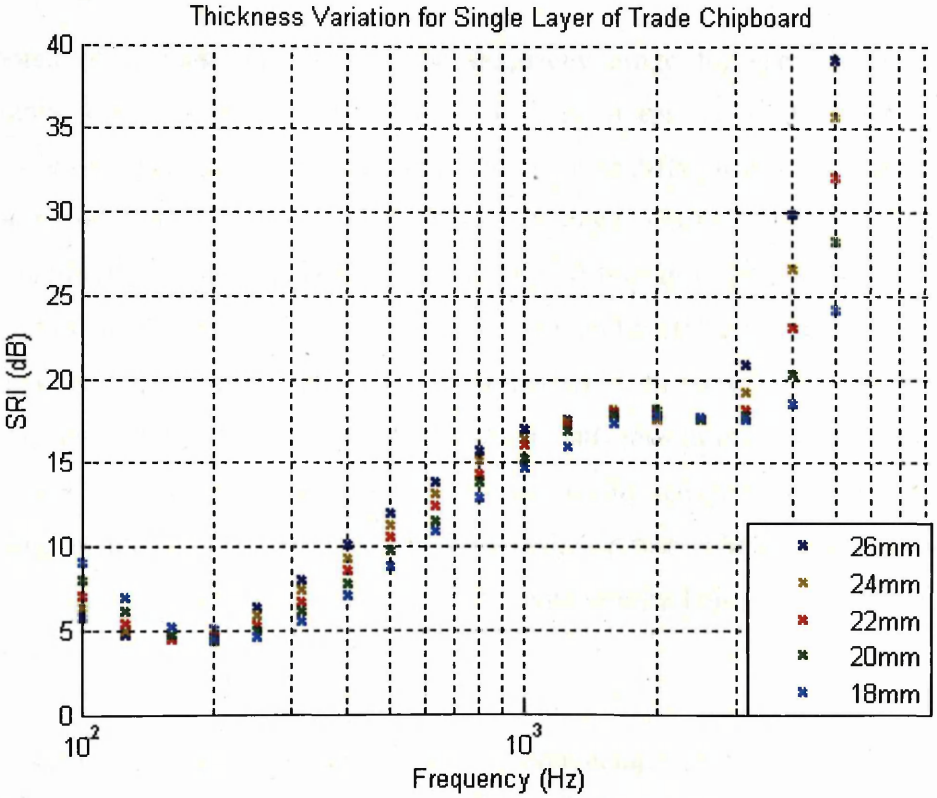


Figure 8.6 *Results of a single layer of chipboard measuring 1.82m x 1.86m, fixed within the aperture. The thickness of the partition was increase, hence increasing its mass.*

It is apparent from *figure 8.6* that for all 5 tests, an increase in thickness of a partition results in an increase in the sound reduction of that partition. *Figure 8.6* reflects the shape of the theoretical graph discussed earlier in that there are 3 regions apparent. In the low frequency region, the stiffness of the material is the main controlling factor. At around 200Hz, resonance frequencies occur which reduce the partitions ability to attenuate sound, shown by the first dip on the graph. Above 315Hz (approx one octave above the lowest resonance), the mass of the partition becomes the controlling factor and dominates the sound reduction performance (mass law). In this region, the transmission loss is dependant on the surface density of the panel, resulting in a more linear correlation. The higher frequency, stiffness controlled region of the graph contains the point at which the coincidence becomes the controlling factor and partition's ability to reduce sound transmission is severely weakened.

The amount of increase in TL over the frequency range for each partition varies considerably. 18mm thick chip board has an increase of approx. 15dB, whereas 26mm chipboard has an increase of approx. 33dB. The greatest difference in TL between each of the partitions is at the high end of the frequency range. Above 3150Hz, the difference between partitions increases rapidly. This would hold true in reality, as a material with the properties similar to chipboard have a greater ability to attenuate sound at high frequencies, and the level of attenuation would increase with increasing thickness. There is a clear difference between the SRI of each of the partitions in the mid-frequency range (315-1000Hz) with, as expected, the thickest layer having the greatest sound reduction. This is due to the fact that the heavier the panel, the less vibration would occur in response to the sound waves, resulting in less sound energy being radiated through the partition.

The coincidence dip for the 26mm chipboard layer occurs at 2000Hz and the SRI is 17.71dB. The coincidence dip for the 18mm chipboard layer occurs at 3150Hz and the SRI id 17.64dB. It is therefore apparent that a thinner material (less stiff) has its point of coincidence occurring at a higher frequency to that of a thicker material with otherwise identical properties.

Below the resonance frequency, it can be seen that the data points 'flip over'. i.e. at around 160Hz, the 18mm panel has greater transmission loss than the 26mm panel. It can also be seen that the depth of the dip reduces as the thickness of the panel increases indicating that the thicker material remains more stable when exposed to changes in frequency, due to its greater stiffness.

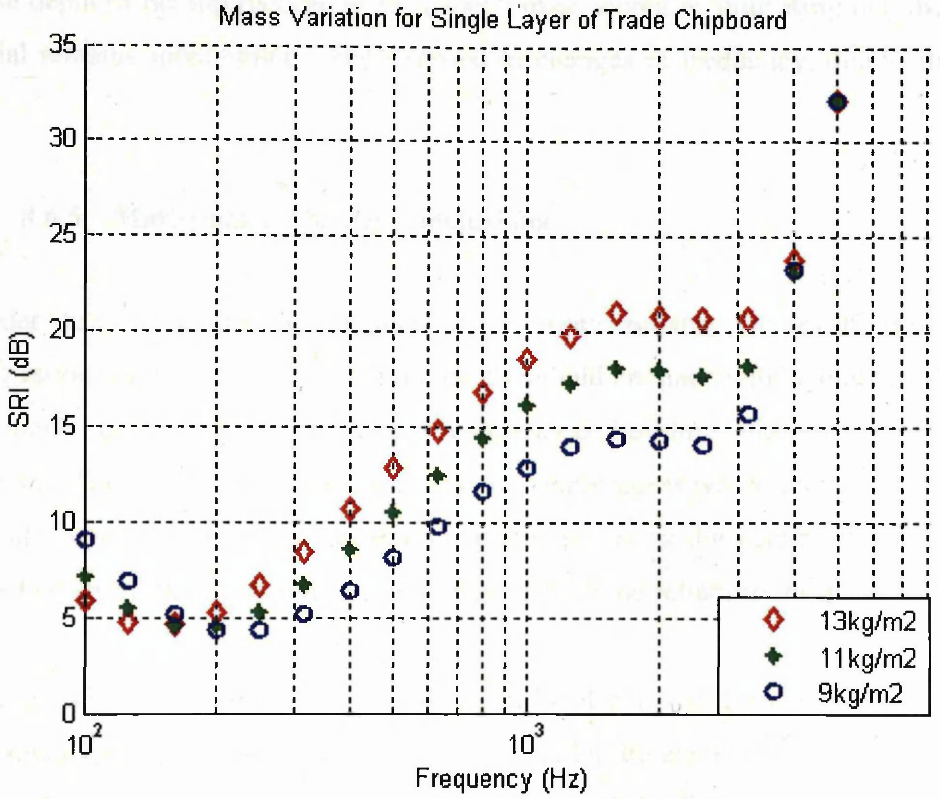


Figure 8.7: *Results of a single layer of chipboard measuring 1.82m x 1.86m, fixed within the aperture. The density of the partition was varied, hence increasing its mass.*

It is apparent from *figure 8.7* that for all 3 tests, an increase in mass of a partition results in an increase in the sound reduction of that partition. Again, this graph reflects the shape of the theoretical graph discussed earlier in that there are 3 regions of control apparent.

Figure 8.7 shows that the coincidence dips begin to occur at around 1600Hz for the 13kg/m^2 and the 11kg/m^2 partitions, whereas the dips occur at around 1250Hz for the 9kg/m^2 partition. It is also apparent in *figure 8.7* that the heavier partition (13kg/m^2) has a resonance frequency at around 160Hz, whereas the lighter partition (9kg/m^2) has its resonance frequency at around 250Hz.

Below the resonance frequency, the data points 'flip over'. i.e. at around 160Hz, the 9kg/m^2 panel has greater transmission loss than the 13kg/m^2 panel. It can also be seen that the depth of the dip reduces as the panel's mass increases indicating that the heavier material remains more stable when exposed to changes in frequency, due to its greater mass.

8.6.5 Mathematical Model Conclusions

In order to verify the mathematical code more reliably however, some future considerations may be necessary. Comparisons should be made with actual test data from experiments performed on modularly constructed building elements in laboratory conditions. The next logical step in this development process would therefore be to repeat the Southampton reverberation chamber experiments using the parameters inputted into the mathematical model, therefore further establishing the reliability of the model.

The effect of resonance and coincidence cannot be eliminated. However, it is possible to draw several conclusions from this work. In order to achieve the highest SRI, the resonant frequencies should be as low as possible, and the Critical frequency as high as possible (preferably below and above the threshold of human hearing respectively). Although there is probably not a generic solution that can be applied to all partitions, there are several steps that can be taken to aid in achieving the largest range of mass controlled region.

- Reducing the stiffness of a partition (reducing thickness, therefore stiffness) lowers its resonant frequency and raises its critical frequency, effectively expanding the region in which the partition is controlled by its mass.

- Increasing the mass (holding thickness constant, increasing density) also lowers the resonant frequency and raises the critical frequency.

- Stiff partitions are required if higher performance is required at low frequencies (except below resonance)

- Stiff partitions have a lower point of coincidence, reducing the performance in the mid-frequency range (important speech frequencies).

- The most superior partitions are heavy, high mass, limp, highly damped materials which have a large weight to stiffness ratio.

The above steps have been found to be useful in the continued understanding of the acoustic behaviour of separating elements used in construction, and it has been found in the mathematical model described in this chapter that making some minor adjustments to physical construction of the partition through the variation of properties such as mass and stiffness has an impact upon the sound transmission through the partition, and ultimately the acoustic performance of such elements. This work reiterates that of readily available theory.

8.6.6 Obtaining an Approximation for Southampton Test Data

To contribute to the information required to be able to accurately assess the acoustic performance of any building element, it is clear that significant practical experimentation is necessary. This, of course, is time consuming and expensive and so the need for accurate prediction models becomes apparent. The development of such prediction models has progressed concurrently with the accumulation of substantial empirical data. Comparisons with such data have lead to the development of theoretical models that can be specifically designed for actual structural designs. Some of these prediction techniques have been discussed previously in this chapter.

8.6.6.1 Approximation Method

To predict the sound transmission behaviour of a single leaf partition, the mass law is commonly used. This theory assumes that thin homogenous panels respond to incident sound pressure and that the panel's bending stiffness is neglected. (Heckl, 1981).

However, if this is the case, the mass law is not capable of predicting the sound transmission behaviour of the panel at frequencies near the critical frequency. This can be overcome through achieving suitable adjustments to the approximation through the incorporation of coincidence effect at frequencies below the critical frequency (Sewell 1970).

Using the measured data from the Southampton test result for the ceiling panel in the reverberation chambers, it was intended to establish an approximation for the standard ISO 717 airborne sound insulation tests.

A model was created simulating the exact characteristics of the reverberation chambers in Southampton using Microsoft Excel in which the sound levels in the source and receiving rooms were inputted at each of the 18 one-third octave bands. The RT60 values were also inputted into the model. The sound reduction index of the partition (R) was then calculated using equation 8.4, corresponding to that of the test data itself.

By characterising the ceiling panel in the aperture between the two chambers using simple calculations, the necessary partition parameters were established in order to input in to the following approximations:

The first approximation used to compare with the measured value of R was an equation which calculates the transmission loss of sound that is normally incident on the partition, and is represented by the following expression (Fahy and Walker, 1998):

$$R(0) = 20\log[fm]-42 \qquad \text{eq.8.5}$$

in which (0) indicated normal incidence. In this instance, R(0) is determined as the product of mass per unit area and frequency (Hz). It can therefore be said that R(0) increases by 6dB per doubling of mass or indeed frequency. Figure 8.8 shows the comparison made between the measured sound reduction index and the approximation that sound is normally incident on the partition.

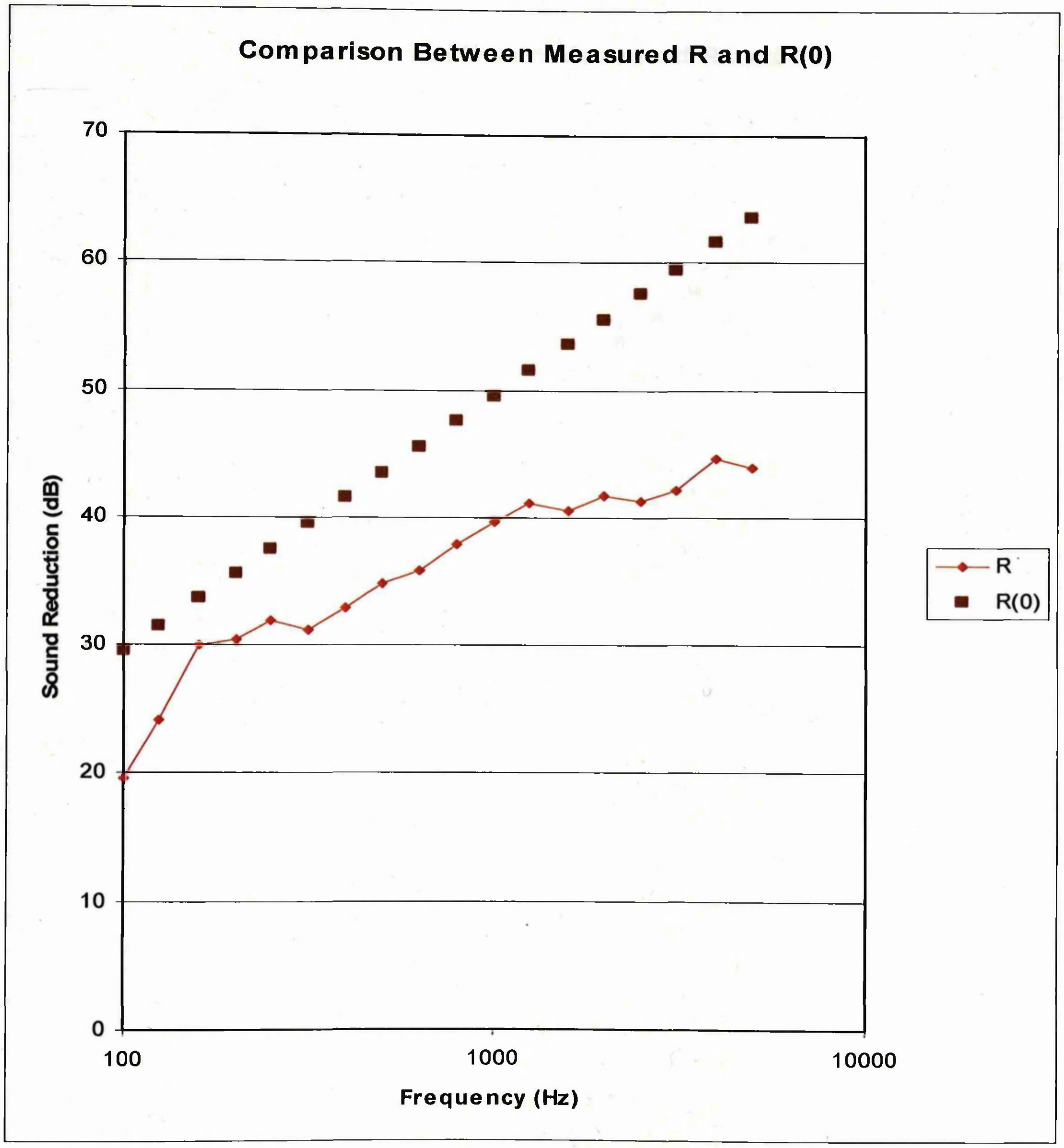


Figure 8.8 – *Graph showing comparison between measured R and approximation using normally incident sound R(0), (eq.8.5)*

The second approximation that was used is represented by equation 8.1 and shows that the transmission loss of a partition can be calculated as the log of the transmission coefficient of that structure, and is again controlled by the product of the mass per unit area and frequency. *Figure 8.9* shows the comparison made between the measured R value and the transmission loss approximation.

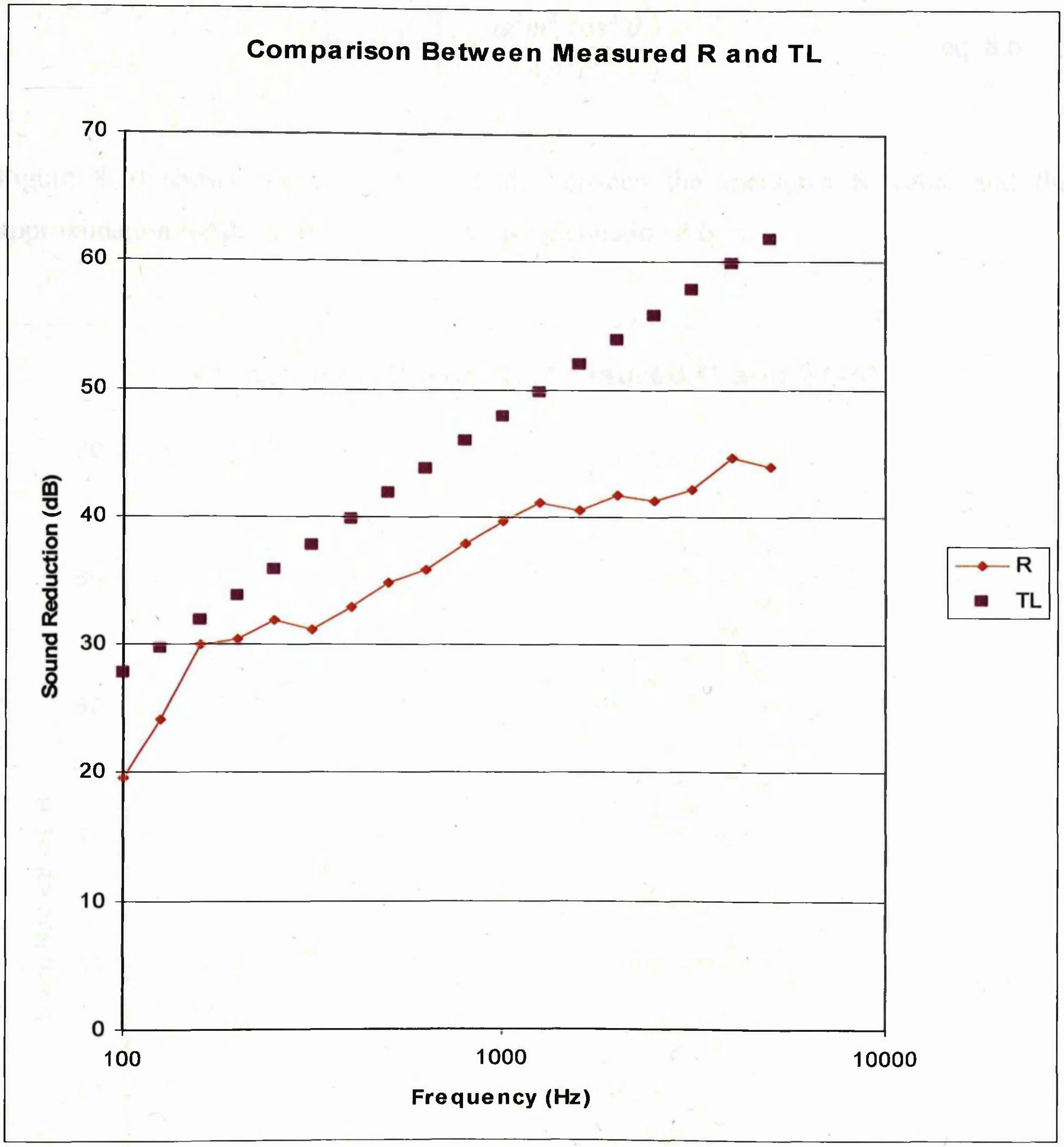


Figure 8.9 – *Graph showing comparison between measured R and approximation using TL calculation (eq.8.1)*

The third approximation is based on the assumption that sound incident on a partition can be simply approximated as inputting $\cos\theta = 0.5$, represented by equation 8.6 to achieve an approximation for a diffuse sound field. This claim was originally made by Cremer, Heckl and Ungar (1973) and it was hoped that this approximation would provide the closest resemblance to the measured R values for each of the Southampton reverberation tests.

$$R = 10\log\left(1 + \frac{\omega^2 m^2 \cos^2\theta}{4\rho^2 c^2}\right) \qquad \text{eq. 8.6}$$

Figure 8.10 shows the comparison made between the measures R value and the approximation for the diffuse sound field using equation 8.6.

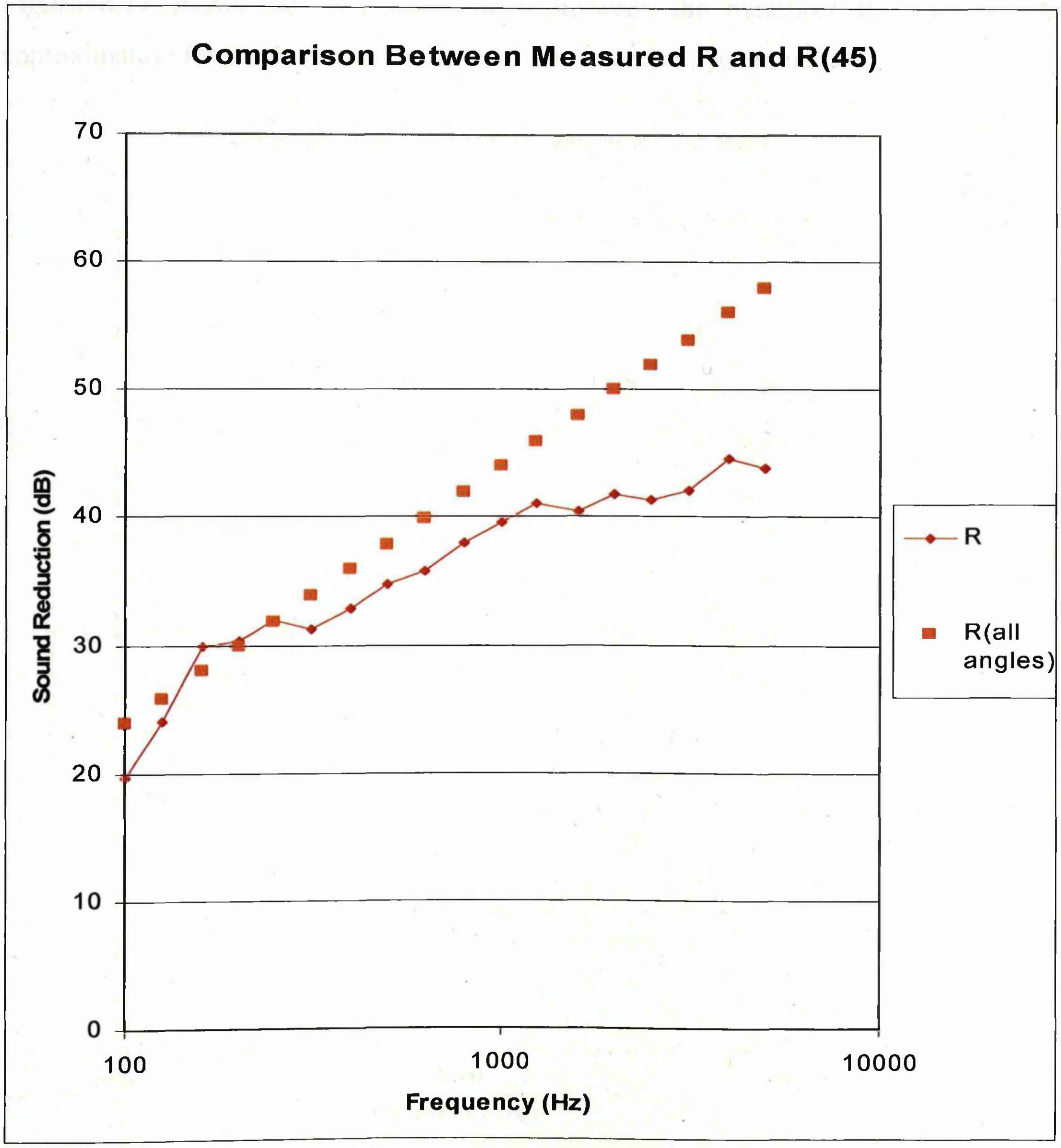


Figure 8.10 – *Graph showing comparison between measured R and approximation using approximation of* $\cos\theta = 0.5$ *(eq.8.6).*

The final approximation is represented by equation 8.7, and is termed the diffuse sound field incidence. In this instance plane waves are assumed to propagate with equal probability from all directions (Fahy and Walker, 1998).

$$R(d) = R(0) - 10\log_{10}[0.23R(0)] \qquad \text{eq. 8.7}$$

Figure 8.11 shows the comparison made between the measures R value and the approximation for the diffuse sound field using the above approximation.

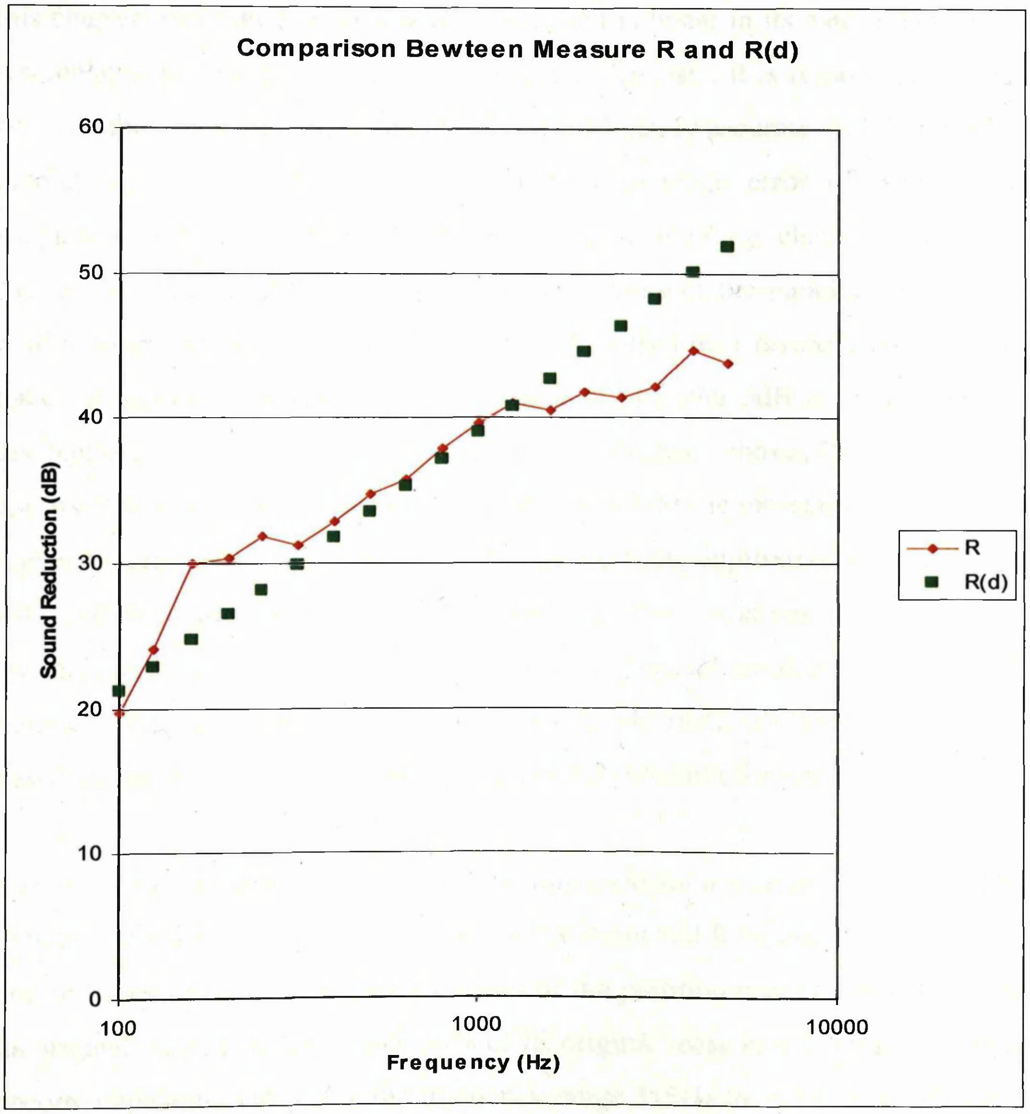


Figure 8.11 – *Graph showing comparison between measured R and for the diffuse sound field incidence. (eq.8.7)*

8.6.7 Approximation Discussion

It is evident from the above series of graphs that the approximation which most closely resembles the actual measured sound reduction index of the ceiling partition is that of R(d), in which the sound transmission through the partition can be represented by equation 8.7. It can be seen from figure 8.11 that between 315Hz to 1250Hz, the approximation follows the linear fashion of the measured R value to an error of a maximum of 1.36dB at 315Hz. This section of the graph is, as discussed previously in this chapter, controlled by the panel's mass, and is linear in its nature. Due to this close resemblance of this approximation to the actual test data, it is reasonable to assume that between these frequencies, equation 8.7 is a sufficiently accurate tool that can be used to predict, to within a satisfactorily small error (average error of 0.83dB across the frequency range), the acoustic performance of a building element. However, below 315Hz the approximation does not accurately represent the panel's sound transmission ability, in that the approximation yields significantly lower results than the measure test data. The greatest difference in values stands at just over 5dB at 160Hz. This apparent discrepancy is also evident at higher frequencies, above1250Hz, in which the approximation values continue to rise linearly, whereas the measured data tails off. At the higher frequencies, the greatest difference between the approximation and the measured data stands at approximately 8dB at 5000Hz. This variation is as expected as the approximation does not incorporate the realities of actual constructions such as flanking noises, surface penetrations, inconsistencies in the materials and construction, and is based on the mass law which cannot be applied throughout the whole frequency range.

Figure 8.12 illustrates in further depth, the approximation's behaviour when exposed to a variation in mass of the panel in relation to the measured R values at each of the one third octave bands. It this experiment, the mass of the partition was varied as a percentage of its original mass, plus and minus 30% of its original mass in increments of 10%. It now becomes apparent that within the frequency range 315Hz to 1250Hz an increase in mass of the partition by 10% would result in the approximation having an average error of 0.2dB at each 1/3 octave band, whereas the original approximation has an average error of 0.99dB at each 1/3 third octave band. It is also apparent that at lower frequencies, below 315Hz, an increase in mass within the approximation would result in the increase in the sound reduction of the partition, getting closer to that of the measured R values. However, at higher frequencies, above 1250Hz, the measured R values tail off with increasing frequency and so a reduction in the mass within the approximation in this region is required, to follow more closely with the measured R values.

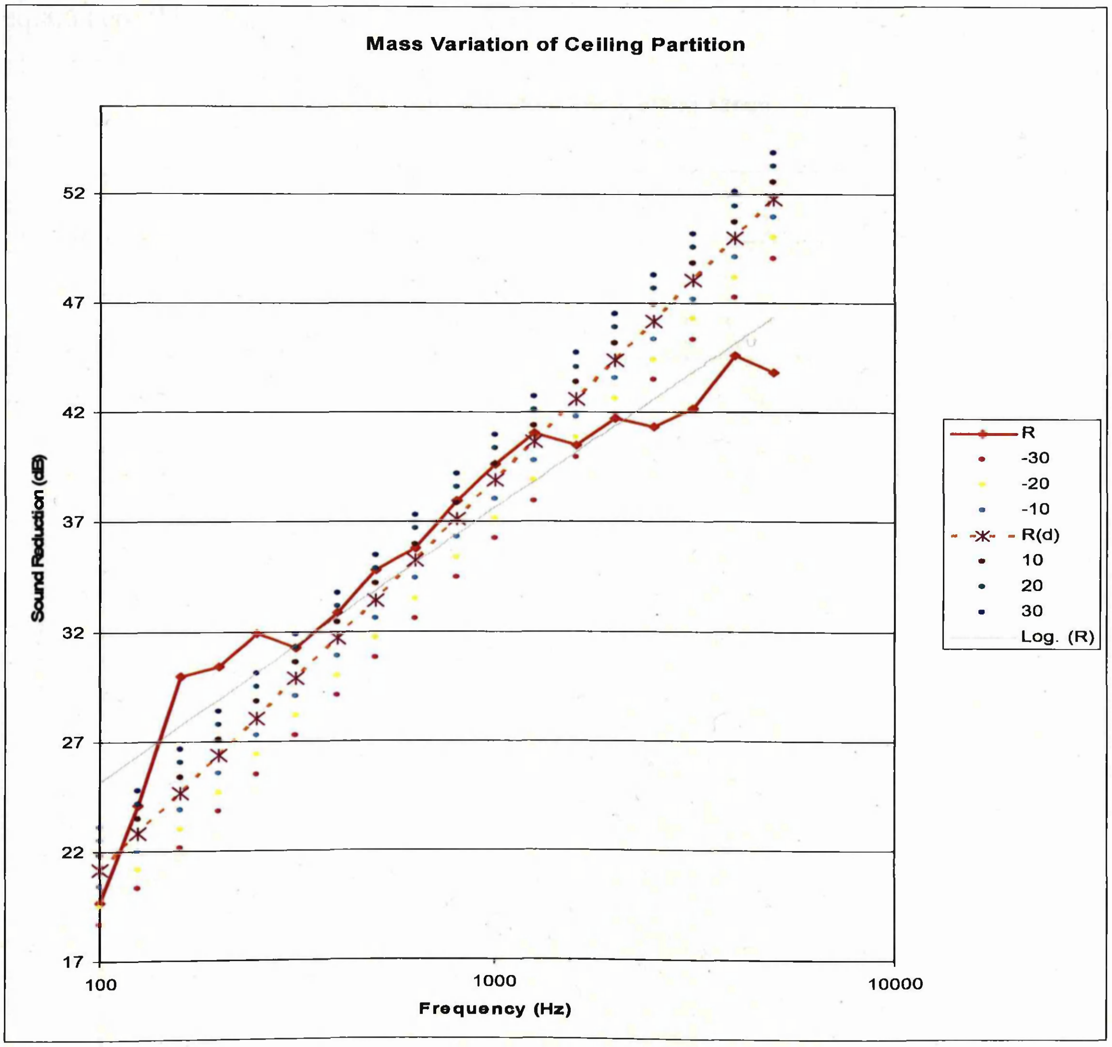


Figure 8.12 – *Graph showing comparison between measured R values and approximation when mass was varied as a % of its original mass using equation 8.7.*

The above method was repeated to obtain approximations for comparison with the measured R values of the ceiling and floor panel with a 42mm gap between the two, and a 21mm gap between the two. In these cases, it was found that the approximation most closely resembled that of the measured data at the lower end of the frequency range, between 125Hz and 500Hz, the most linear section of the graph. However, the approximation which followed most closely the experimental data of the 42mm air gap partition was that of equation 8.6, where the diffuse sound field was calculated using eq.8.6 ($\cos\theta = 0.5$).

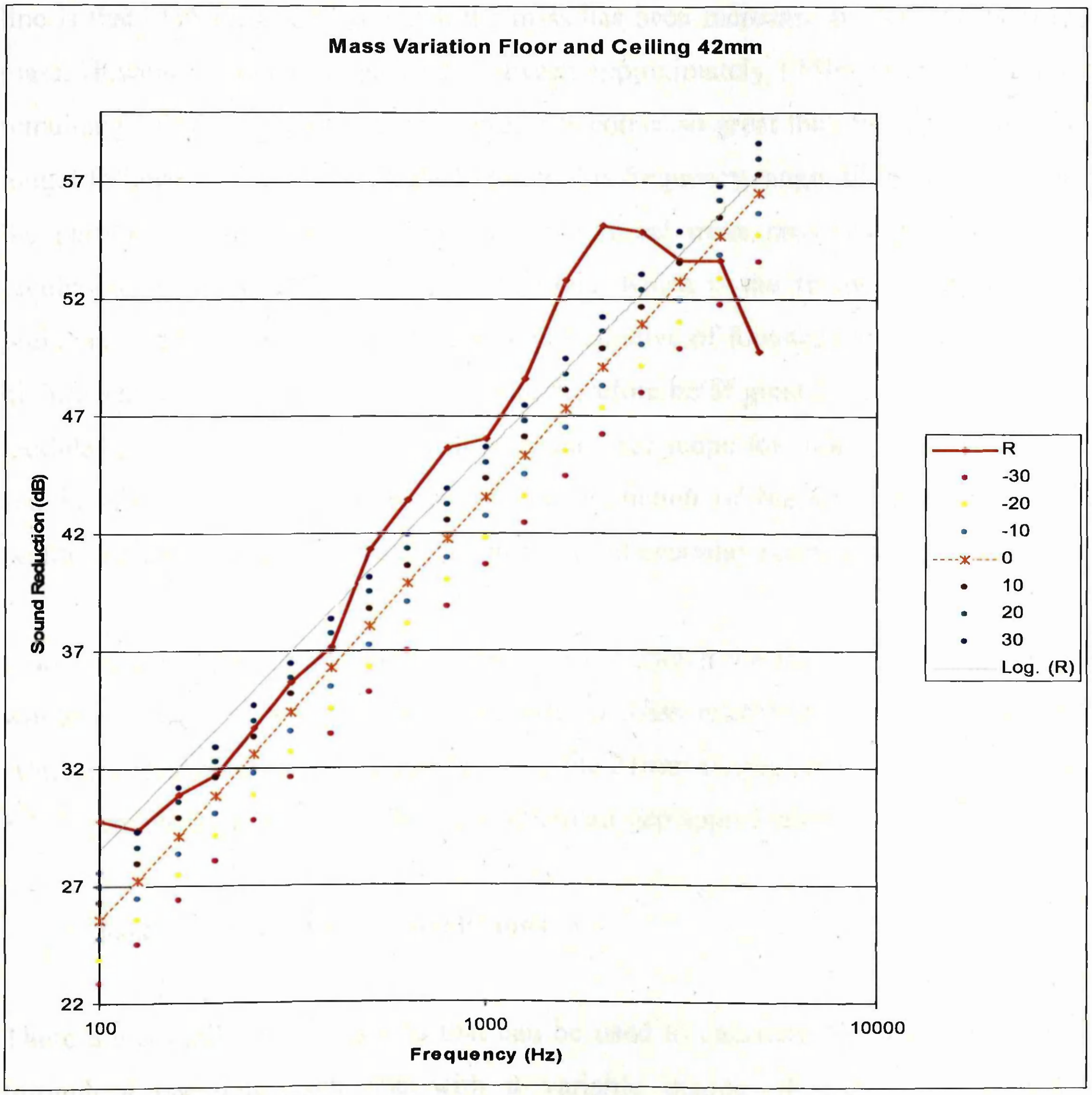


Figure 8.13 – *Graph showing comparison between measured R values and approximation when mass was varied as a % of its original mass using equation 8.6.*

The general trend in *figure 8.13* is that as the frequency increases the accuracy of the approximation diminishes, with the exception of frequencies above approximately 2000Hz. Again the approximations, by definition, do not take into consideration any variations in the materials' properties, and effects of the cavity and flanking sounds etc, and therefore produce linear results. This would explain the reverse in the relationship between the approximation and the actual measured results at the higher frequencies. *Figure 8.13* also illustrates a trend line (shown in grey) taken from the measured results. It is apparent from the figure that the approximation that most closely follows the trend line is that of the partition in which the mass has been increased by 30% of its original mass. However at lower frequencies, between approximately 125Hz to 400Hz, although remaining below the trend line, the increase becomes so great that the approximation no longer follows the measured results. Between this frequency range, an increase in mass of the partition by approximately 20% of its original mass provides the most reliable prediction of the panel's acoustic performance, which is the frequency range that has previously been identified as that being representative of footsteps and doors slamming, highlighted in Chapter 6. This result would therefore be of great beneficial use to Corus' modular construction business as it provides a huge scope for further investigations and can be utilised as a significant aid in the prediction of building elements' acoustic performance particularly in this 'problem range' of everyday sound sources.

It was assumed that simply halving the air gap between the floor and ceiling partitions would not result in any significant increase in mass relative to the total mass of the structure. Therefore, the results produced for the 21mm air gap approximation test (figure 8.13) were identical to those seen in the 42mm air gap approximation.

8.6.8 Approximation conclusions

There are several approximations that can be used to calculate the sound transmission through a partition, each one with a variable degree of accuracy. As with all approximations there are many assumptions and postulations that contribute to the success or failure of the results and this experiment has achieved its aim of determining to what extent various approximations most accurately resemble the results of actual measured data. It was found that:

- Equation 8.7, the approximation used to represent a diffuse sound field R(d) most closely resembled the measure sound transmission data in the Southampton Reverberation Experiments.

- Between the frequencies 315Hz to 1250Hz, the mid-frequency range, the approximation followed the linear fashion of the measured R value to an error of a maximum of 1.36dB at 315Hz.

- Between these frequencies it is reasonable to assume that this approximation is sufficiently accurate to be able to predict the acoustic performance of a building element.

- Within this frequency range, increasing the mass of the partition by up to 10%, increases the accuracy of the approximation.

- When combining the floor and ceiling panel with 21mm and 42mm air gaps, it was found that the increase in mass resulted in the linear section of the graph shifting to a lower frequency range (125Hz-500Hz). The approximation using eq.8.6 ($\cos\theta = 0.5$) most closely resembled this change. An increase in mass of the partition by up to 20% further increases the accuracy of the approximation.

Chapter 9 Conclusions

Following investigations into the environmental issues prevalent in multi-storey residential dwellings, the demand for new housing, and the governments desire to re-vitalise the city centres of UK urban centres, this research has attempted to contribute to the knowledge and expertise required to develop the necessary technologies to achieve cost effective solutions to the ever increasing demand for higher standards of living. Several areas of research have been investigated to achieve the objectives of this project, set out in Chapter 1, and are summarised below.

Sound transmission is influenced by many different physical parameters, and varies throughout a frequency range. The acoustic behaviour of building elements such as a separating wall has three regions of control, stiffness, mass, and damping, each of which displays varying characteristics. An experimental procedure was therefore set up to investigate the damping effect of coating on various grades of steel used in the construction of modular buildings. The damping ratios of such steel specimens firstly with coating, and then with the coating removed, were measured and found to be, as expected, extremely small. Before removal of the coatings the thicker, stiffer steel specimens displayed the highest damping ratios, and as the thickness of the steel specimens decreased, so did the damping ratios. This was as expected, and reasons have been discussed. However, the surprising result was that once the coatings had been removed from the specimens, and the experiments repeated, the damping ratios increased. These results are the opposite of those expected and possible reasons have been proposed. In each case, the errors calculated fall within the standard deviations and so it can be concluded that simply removing the coating from the steel specimens had no measurable effect on the specimens' ability to resist vibration. Further thought highlighted the inadequacies in the experimental design in that the method used was not capable of being able to reliably measure the damping effect of the coating due to the extremely small levels of damping present in the system, the difference in damping between the coated and non-coated specimens being even smaller. The limitations of this approach, and possibly methods of overcoming these issues have been discussed. This work has highlighted opportunities that may exist in the investigation of the damping effect of coated steel and the role it has to play in establishing acoustically superior modular designs using coated steel.

Perceived sound annoyance and objective noise measurements are separate entities but are intrinsically united. A sound annoyance survey was therefore performed on a population sample resident in modularly constructed residential dwellings in Cardiff. Through establishing the type of noises that present annoyance issues in this type of dwelling, and identifying the frequency ranges of such noises, areas of success and failure are highlighted. The chosen survey method was performed and the results illustrated and discussed. From the choice of sound sources presented to the subjects, only two were identified as being both audible and annoying; Footsteps and doors slamming. These sound sources, whilst being of wide frequency content, are predominantly low frequency sounds, and this result re-enforces the concerns highlighted previously in this research regarding low frequency sound attenuation associated with this method of construction. These results are discussed in detail and are found to correlate well to that of other work in this field.

Using first principle standard equations, a computer modelling technique has also been developed to simulate a laboratory environment in which to test and predict the acoustic performance of single layer partitions. The model is constructed using the third octave frequency range (100Hz-3150Hz), incorporating the three distinct controlling parameters of stiffness, mass, and damping, establishing the transmission loss of partitions below, around, and above their critical frequencies. Simulations have been run, where a partition inserted into the aperture having in the first instance its thickness varied, whilst all other parameters remaining constant, and secondly its density varied, yields results that were to be expected. Throughout the period of this research, the suitability of the mathematical model has been cross examined and where necessary altered and improved to achieve the original objectives. Successful validation of this model has been achieved through comparisons made with the theoretical data available.

The experimental data obtained in reverberation tests has been utilised and vigorously examined, with the experiment re-created using software in order to establish approximations that accurately resemble that of the measured data. It was found that over the frequency range 315Hz to 1250Hz, an approximation method could be achieved that satisfactorily represented the measured data values. However, this frequency range fails to fully incorporate the frequencies highlighted as being problematic (250-350Hz) in the sound annoyance survey. Nevertheless, the approximation appears to provide sufficient evidence to suggest that within the mass controlled region of a partition's transmission loss, an approximation can in fact be identified as being capable of predicting the acoustic performance of a building element. Below and above this region, the possible reasons and limitations that exist within the approximation have been discussed.

The exploitation of laboratory measurements shouldn't be underestimated as the results obtained in this research along with the development of the mathematical model used to predict the performance of separating elements in this environment have been proven to be accurate and reliable, relating well to that of the results obtained in the Shotton on site testing. It is therefore apparent that the use of laboratory test environments and both mathematical prediction modeling and the successful development of approximation methods hold significant potential for use within Corus. The practical works in this thesis have successfully highlighted areas of achievement and areas that require further investigation with regards to the acoustics performance of modularly constructed building elements. The theoretical efforts detailed in this research have clearly indicated the potential that exists within this field, with the mathematical model reliably predicting the acoustic performance of modular construction elements, thereby assisting in the design of new modules and speeding up the processes that exists between initial idea generation to finished product. An attempt has been made to contribute to the continued understanding of the relationship between quality design and acoustic performance, essential to creating faster turn-around times and therefore early returns on investment, providing a path that may ultimately lead to eliminating the costly and time-consuming necessity for proto-type construction and testing.

Appendices

(A) Shotton Experiment

The following table identifies the equipment used in the Shotton full scale experimentation, May 2003.

Table A1 - *Schedule of Equipment for Shotton Experiments*

USE	TYPE	SERIEL No.
Noise Source	Norsonic 211A Tapping Machine	25175
Measuring System	Norsonic 840 Real Time Analyser	16009
	B&K 4165 ½" Condenser Microphone	1253564
	B&K 4165 Condenser Microphone	1867520
	B&K 2639 Microphone Pre-amplifier	1202653
	B&K 2639 Microphone Pre-Amplifier	1286051
	B&K 3923 Rotating Microphone Boom	1113618
	B&K 3923 Rotating Microphone Boom	1213966
Calibration	B&K 4231 Sound Level Calibrator	1795485

Shotton Unit Types A & B

Figure A1 – Cross section of Unit Type Construction

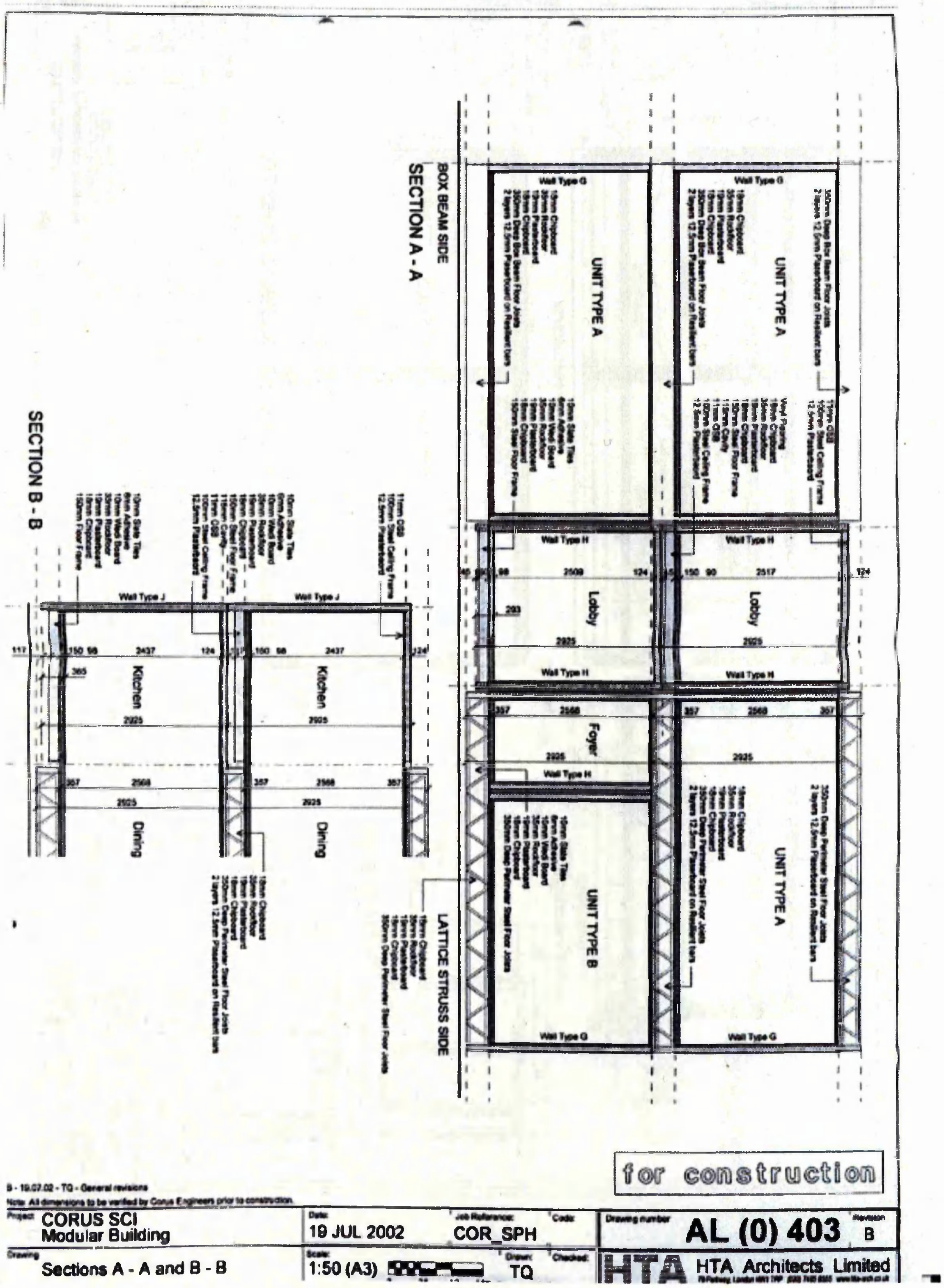
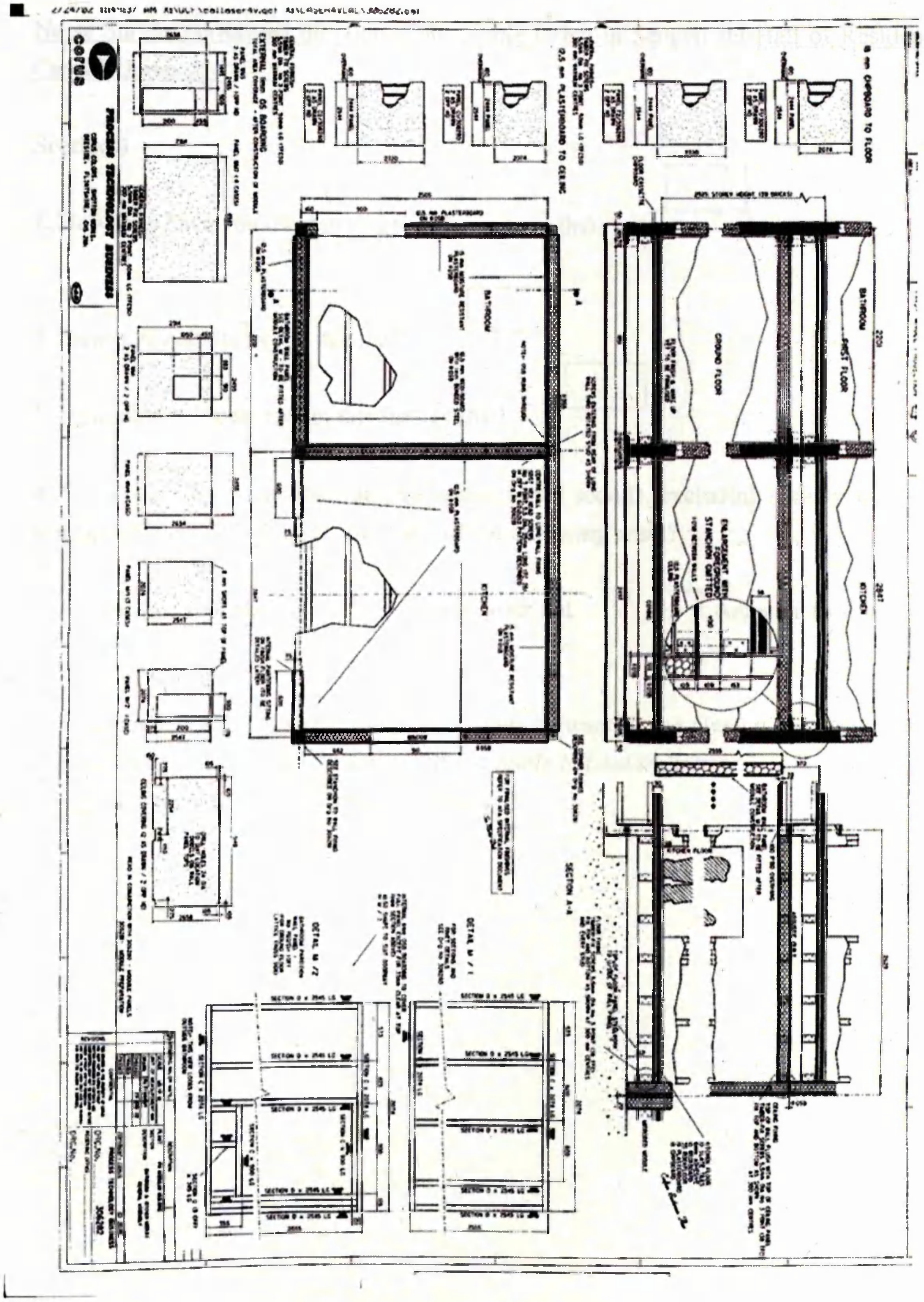


Figure A2 – Construction Materials and Details



(B) Noise Survey

Noise Survey performed on population sample living in Sengenydd Hall of Residence, Cardiff University

Section 1

1. How long have you lived in this flat? (years/months) ☐

2. How many adults live in this flat? ☐

3. How many children live in this flat? (<16) ? ☐

4. From anywhere in this flat, do you hear external sounds, excluding sounds that come from outside the flat complex, from any of the following areas?

☐ Above your flat ☐ Below your flat ☐ Adjacent to your flat

For section 5, 6, and 7, use the following ratings to describe the given noise disturbances:
1 = inaudible *2= Faintly audible* *3= Audible but not irritating*
4 = Quite irritating *5 = Extremely irritating*

5. Section 2 – Above your flat

Noise type	Response
Speech	
Music	
Flushing toilet	
Shower	
Boiler	
Footsteps	
Pets	
Doors/windows closing	
Other Please specify	

6. Section 3 – Below your flat

Noise type	Response
Speech	
Music	
Flushing toilet	
Shower	
Boiler	
Footsteps	
Pets	
Doors/windows closing	
Other Please specify	

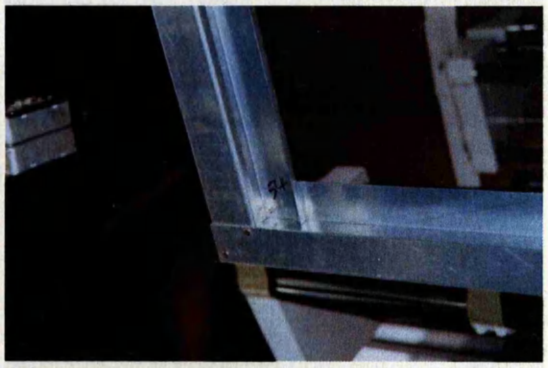
7. Section 4- Adjacent to your flat

Noise type	Response
Speech	
Music	
Flushing toilet	
Shower	
Boiler	
Footsteps	
Pets	
Doors/windows closing	
Other Please specify	

(C) Southampton Panel Construction

Below is a series of photographs showing the individual stages of construction of the floor and ceiling panels.

C-Sections



Rivets

Framework

Fireboard and plasterboard

Insulation

OSB-Board

Fibreboard + Floor frame

Polystyrene

Plasterboard + Chipboard

Floor and ceiling with 21mm gap

Equipment used to perform Southampton Reverberation Chamber Experiments

Table C1 – *Equipment list for Reverberation Tests*

Noise generator	Brüel and Kjær	Type 1405
Power Amplifier	Third Generation	Type HP400
Loudspeaker	Vitavox	Double Thunderbolt
Precision Microphones	Brüel and Kjær	Type 4134
Preamplifiers	Brüel and Kjær	Type 2619
Digital Frequency Analyzer	Brüel and Kjær	Type 2133
Pistonphone Calibrator	Brüel and Kjær	Type 4220

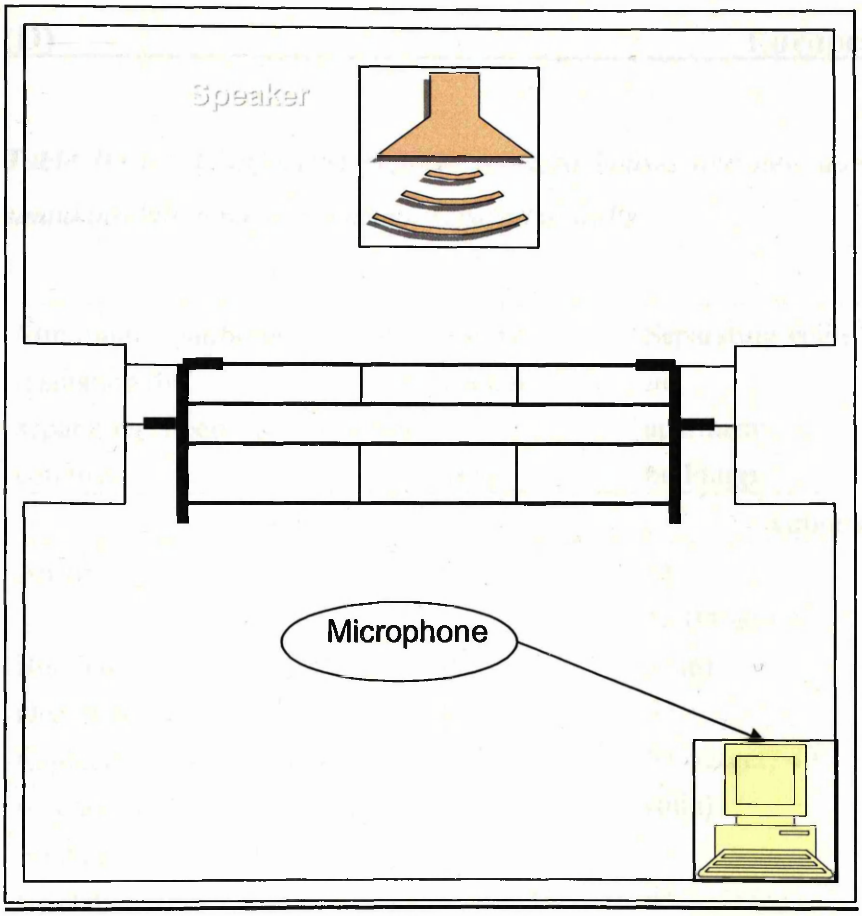


Figure C1 – Schematic illustration of reverberation chamber test setup

Table D3.1 – *Comparison between terraced houses and new apartments of airborne sound insulation requirements for separating walls.*

Minimum airborne sound insulation for separating floors in European countries	Rating system used	Separating walls in apartment buildings	Separating walls in terraced housing
		Airborne sound (dB)	
Austria	R'_w	55	60
Belgium	R'_w	52 (target) 47 (min)	52 (target) 47 (min)
Denmark	R'_w	52	52
England (current regulations)	D_{nTw}	53 (target) 49 (min)	53 (mean) 49 (min)
England (proposed regulations)	$D_{nTw} + C_{tr}$	45	45
England (Optional enhanced standard)	$D_{nTw} + C_{tr}$	50	50
Finland	R'_w	55	55
France	$D_{nTw} + C_{tr}$	53	53
Germany	R'_w	53-55	57
Ireland	D_{nTw}	49	49
Netherlands	D_{nTw}	53	53
Norway	R'_w	55	55
Poland	R'_w or D_{nTw}	52	53
Sweden (Class C-minimum requirement)	$R'_w + C_{50-3150}$	52	52
Sweden (Class A-optional quality standard)	$R'_w + C_{50-3150}$	60	50

***Table D3.2** – Comparison of the airborne sound insulation requirements for separating floors.*

Minimum airborne sound insulation for separating floors in European countries	Rating system used	Separating Floor airborne sound insulation (dB)
Austria	R'_w	55
Belgium	R'_w	52 (target) 47 (min)
Denmark	R'_w	53
England (current regulations)	D_{nTw}	52 (mean) 48(min)
England (proposed regulations)	$D_{nTw} + C_{tr}$	45
England (Optional enhanced standard)	$D_{nTw} + C_{tr}$	50
Finland	R'_w	55
France	$D_{nTw} + C_{tr}$	53
Germany	R'_w	54
Ireland	D_{nTw}	48
Netherlands	D_{nTw}	53
Norway	R'_w	55
Poland	R'_w or D_{nTw}	53
Sweden (Class C-minimum requirement)	$R'_w + C_{50-3150}$	52
Sweden (Class A-optional quality standard)	$R'_w + C_{50-3150}$	60

Table D3.3 – Comparison of impact sound transmission requirements for separating floors.

Maximum impact sound transmission for separating floors in European countries (dB)	Rating system used	Separating floor impact sound transmission (dB)
Austria	L'_{nTw}	48
Belgium	L'_{nTw}	56
Denmark	L'_{nTw}	58
England (current regulations)	L'_{nTw}	61 (mean) 65 (max)
England (proposed regulations)	$L'_{nTw} + C_I$	63
England (Optional enhanced standard)	$L'_{nTw} + C_I$	57
Finland	L'_{nw}	53
France	L'_{nw}	58
Germany	L'_{nw}	53
Ireland	L'_{nTw}	65
Netherlands	L'_{nTa}	59
Norway	L'_{nw}	53
Poland	L'_{nw}	58
Sweden (Class C-minimum requirement)	$L'_{nTw} + C_{I,50-2500}$	58
Sweden (Class A-optional quality standard)	$L'_{nTw} + C_{I, 50-2500}$	<50

__Table D3.4__ – Comparison of acoustic requirements for floors within dwellings

Acoustic requirements for floors within dwellings in european countries (dB)	Rating system used	Minimum airborne sound insulation	Maximum impact sound transmission
		(dB)	(dB)
Austria	R'_w	55	48
	L'_{nTw}		
England (proposed regulations)	R_w	40	
Finland	R'_w	39	
	L'_{nw}		63
France	$D_{nTw} + C$	41	
	L'_{nTw}		65
Sweden	$R'_w + C_{50\text{-}3150}$	40	
(Class C-minimum requirement)	$L'_{nTw} + C_{I,50\text{-}2500}$		68
Sweden	$R'_w + C_{50\text{-}3150}$	44	
(Class A-optional quality standard)	$L'_{nTw} + C_{I,50\text{-}2500}$		64

(E) Damping Experiments

Standard deviation analysis of damping experiments, with and without coating.

For each specimen test, mV readings are displayed over the 10 cycles. This measurement of acceleration is proportional to displacement and therefore amplitude. Logarithmic decrements and damping ratios have been calculated.

Specimen A

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	31.3	26.759	21.68	18.213	16.065	15.04	13.379	11.963	10.303	8.594
logdec		0.156747	0.210481	0.174255	0.125493	0.0659297	0.117027	0.111868	0.149383	0.181371
2nd	25.587	22.657	17.54	14.405	11.573	11.084	9.619	9.082	7.471	6.738
logdec		0.121616	0.255985	0.196909	0.218901	0.0431722	0.141762	0.057446	0.195266	0.103266
3rd	46.144	38.331	31.252	26.466	23.389	21.876	19.532	17.432	15.04	12.452
logdec		0.185508	0.204176	0.166222	0.123595	0.0668757	0.113336	0.113747	0.147594	0.188832
4th	25.01	21.339	16.163	13.184	10.059	9.375	8.399	7.91	6.934	6.104
logdec		0.158739	0.277812	0.203721	0.270536	0.0704212	0.109934	0.059985	0.131691	0.127493
5th	45.607	38.624	29.907	26.759	22.657	21.973	19.19	17.823	14.844	12.891
logdec		0.166187	0.255781	0.111222	0.166402	0.0306544	0.135425	0.0739	0.182894	0.141066

Damping	**1st**	0.024947	0.033499	0.027733	0.019973	0.010493	0.018625	0.017804	0.023775	0.028866
Ratio	**2nd**	0.019356	0.040741	0.031339	0.034839	0.0068711	0.022562	0.009143	0.031077	0.016435
bewteen	**3rd**	0.029525	0.032496	0.026455	0.019671	0.0106436	0.018038	0.018103	0.02349	0.030054
consecuctive	**4th**	0.025264	0.044215	0.032423	0.043057	0.0112079	0.017497	0.009547	0.020959	0.020291
peaks	**5th**	0.02645	0.040709	0.017701	0.026484	0.0048788	0.021554	0.011761	0.029108	0.022451

Attempt	**ave logdec**	**std**
1	0.14361709	0.043473
2	0.148257918	0.073517
3	0.145542854	0.044804
4	0.156703495	0.079298
5	0.140392424	0.065003
	ave	**total std**
	0.146902756	0.060284
		ave std
		0.061219

Logarithmic Decrement over 10 cycles (δ)	
1st	0.1292554
2nd	0.1334321
3rd	0.1309886
4th	0.1410331
5th	0.1263532
Average	***0.132212***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.0228574
2nd	0.023596
3rd	0.0231639
4th	0.0249401
5th	0.0223441
Average	***0.02338***
std	0.0009841

Frequency = approx. 19.7Hz

Specimen B

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	17.579	14.991	13.135	11.719	10.45	9.229	8.155	7.324	6.543	5.908
logdec		0.159255	0.13217	0.114069	0.114609	0.124251	0.123719	0.107475	0.112761	0.102088
2nd	22.999	19.63	16.797	14.502	13.038	11.573	10.205	8.985	8.057	7.178
logdec		0.158392	0.155859	0.146914	0.106418	0.119193	0.125797	0.127321	0.109015	0.11552
3rd	23.096	19.63	16.749	14.502	12.989	11.524	10.205	9.033	8.106	7.276
logdec		0.1626	0.15872	0.144052	0.110184	0.119671	0.121554	0.121993	0.10828	0.108023
4th	19.239	16.26	13.77	12.012	10.791	9.619	8.448	7.471	6.836	6.055
logdec		0.168231	0.166216	0.136586	0.107194	0.114972	0.129811	0.122901	0.088826	0.121318
5th	24.464	20.704	17.676	15.332	13.721	12.11	10.694	9.473	8.496	7.617
logdec		0.166876	0.158119	0.142266	0.111015	0.124896	0.124349	0.121237	0.10885	0.109213

Damping	**1st**	0.025346	0.021035	0.018155	0.018241	0.019775	0.019691	0.017105	0.017946	0.016248
Ratio	**2nd**	0.025209	0.024806	0.023382	0.016937	0.01897	0.020021	0.020264	0.01735	0.018386
bewteen	**3rd**	0.025879	0.025261	0.022927	0.017536	0.019046	0.019346	0.019416	0.017233	0.017192
consecuct	**4th**	0.026775	0.026454	0.021738	0.01706	0.018298	0.02066	0.01956	0.014137	0.019308
peaks	**5th**	0.026559	0.025165	0.022642	0.017669	0.019878	0.019791	0.019295	0.017324	0.017382

Attempt	**ave logdec**	**std**
1	0.12115529	0.016968
2	0.1293811	0.019701
3	0.12834202	0.02136
4	0.12845057	0.025889
5	0.12964667	0.021431
	ave	**total std**
	0.12739513	0.02053
		ave std
		0.02107

Logarithmic Decrement over 10 cycles (δ)	
1st	0.10904
2nd	0.116443
3rd	0.115508
4th	0.115606
5th	0.116682
Average	***0.114656***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.019282
2nd	0.020592
3rd	0.020426
4th	0.020444
5th	0.020634
Average	***0.020276***
std	0.000562

Frequency = approx. 8.6Hz

Specimen C1w

	Peak									
Attempt	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	10.743	9.571	8.643	7.52	6.543	5.957	5.322	4.639	4.053	3.613
		0.115517	0.101988	0.139184	0.13917	0.093829	0.112718	0.13735	0.135041	0.114919
2nd	9.131	8.301	7.471	6.592	5.713	5.127	4.639	4.102	3.516	3.125
		0.095299	0.105347	0.125172	0.143113	0.108224	0.100022	0.123024	0.154151	0.11789
3rd	15.528	13.965	12.452	10.938	9.766	8.838	7.813	6.885	6.104	5.518
		0.106091	0.114673	0.129638	0.113336	0.099846	0.123272	0.126444	0.120401	0.100929
4th	14.551	12.745	11.328	9.864	8.741	7.91	6.983	5.811	5.322	4.736
		0.132521	0.117862	0.138386	0.120867	0.099897	0.124649	0.183726	0.087904	0.116656
5th	11.866	10.303	8.936	7.52	6.934	6.25	5.567	4.639	4.199	3.662
		0.141242	0.142347	0.172522	0.081129	0.103855	0.115725	0.182357	0.099652	0.136837

attempt	ave logdec	std
1	0.121079548	0.017178
2	0.119137882	0.019675
3	0.114958819	0.010913
4	0.124718536	0.02699
5	0.130629747	0.033668
	ave	**total std**
	0.122104906	0.022648
		ave std
		0.021685

Damping	**1st**	0.018385	0.016232	0.022152	0.02215	0.014933	0.01794	0.02186	0.021493	0.01829
Ratio	**2nd**	0.015167	0.016767	0.019922	0.022777	0.017224	0.015919	0.01958	0.024534	0.018763
bewteen	**3rd**	0.016885	0.018251	0.020633	0.018038	0.015891	0.019619	0.020124	0.019162	0.016063
consecucti	**4th**	0.021091	0.018758	0.022025	0.019237	0.015899	0.019839	0.029241	0.01399	0.018566
peaks	**5th**	0.022479	0.022655	0.027458	0.012912	0.016529	0.018418	0.029023	0.01586	0.021778

Logarithmic Decrement over 10 cycles (δ)	
1st	0.108972
2nd	0.107224
3rd	0.103463
4th	0.112247
5th	0.117567
Average	*0.109894*

Damping Ratio (over 1 cycle) (ζ)	
1st	0.01927
2nd	0.018961
3rd	0.018296
4th	0.01985
5th	0.02079
Average	*0.019434*
std	0.000943

Frequency = approx. 5.6Hz

Specimen C1wo

	Peak									
Attempt	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	11.914	10.401	8.789	7.324	6.934	6.055	5.225	4.736	4.199	3.76
		0.135812	0.168401	0.182344	0.0547198	0.135552	0.14743	0.098262	0.120346	0.110427
2nd	19.532	16.797	14.161	12.012	11.084	10.01	8.643	7.422	6.738	5.908
		0.150854	0.170709	0.164586	0.0804035	0.101918	0.146835	0.152301	0.096685	0.131456
3rd	16.602	14.551	12.452	10.84	9.815	8.838	7.862	6.983	6.055	5.42
		0.131863	0.155778	0.138638	0.0993312	0.104851	0.11702	0.118562	0.142594	0.110789
4th	16.456	14.698	12.842	11.28	9.864	8.936	8.008	7.08	6.104	5.469
		0.112979	0.13499	0.12969	0.1341395	0.098804	0.109647	0.123167	0.14833	0.109849
5th	16.749	14.795	12.696	11.133	9.864	9.033	8.106	7.031	6.104	5.518
		0.124049	0.153002	0.131373	0.1210219	0.088007	0.10828	0.142276	0.141385	0.100929

attempt	ave logdec	std
1	0.128144	0.038247
2	0.132861	0.032318
3	0.124381	0.018903
4	0.122399	0.015764
5	0.123369	0.021248
	ave	**total std**
	0.126231	0.025753
		ave std
		0.025296

Damping	**1st**	0.021615	0.026802	0.029021	0.0087089	0.021574	0.023464	0.015639	0.019154	0.017575
Ratio	**2nd**	0.024009	0.027169	0.026195	0.0127966	0.016221	0.023369	0.024239	0.015388	0.020922
bewteen	**3rd**	0.020987	0.024793	0.022065	0.015809	0.016688	0.018624	0.01887	0.022695	0.017633
consecuctiv	**4th**	0.017981	0.021484	0.020641	0.021349	0.015725	0.017451	0.019603	0.023607	0.017483
peaks	**5th**	0.019743	0.024351	0.020909	0.0192612	0.014007	0.017233	0.022644	0.022502	0.016063

Logarithmic Decrement over 10 cycles (δ)	
1st	0.1153295
2nd	0.1195747
3rd	0.1119427
4th	0.1101594
5th	0.1110323
Average	*0.113608*

Damping Ratio (over 1 cycle) (ζ)	
1st	0.020395
2nd	0.021145
3rd	0.019796
4th	0.01948
5th	0.019635
Average	*0.02009*
std	0.000684

Frequency = approx. 5.56Hz

Specimen D

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st	18.311	16.26	14.6	13.233	11.983	10.987	10.01	9.18	8.35	7.666
		0.118794	0.107687	0.098308	0.099225	0.086776	0.093128	0.086557	0.094766	0.085467
2nd	16.895	14.991	13.526	12.207	11.084	10.059	9.18	8.448	7.715	6.983
		0.119568	0.102836	0.102604	0.096507	0.097035	0.091441	0.083097	0.090763	0.099688
3rd	15.723	14.063	12.354	11.328	10.401	9.473	8.692	7.91	7.324	6.69
		0.111577	0.129567	0.086702	0.085376	0.093456	0.086043	0.094275	0.076971	0.090543
4th	18.751	16.7	14.991	13.574	12.207	11.133	10.157	9.229	8.399	7.715
		0.115838	0.107959	0.099294	0.106147	0.092096	0.091751	0.095812	0.094238	0.084946
5th	20.46	17.92	16.016	14.502	13.038	11.914	10.938	9.912	9.082	8.35
		0.132554	0.112329	0.099302	0.106418	0.090154	0.085471	0.098497	0.087452	0.084033

Damping	1st	0.018907	0.017139	0.015646	0.015792	0.013811	0.014822	0.013776	0.015082	0.013602
Ratio	2nd	0.01903	0.016367	0.01633	0.01536	0.015444	0.014553	0.013225	0.014445	0.015866
bewteen	3rd	0.017758	0.020621	0.013799	0.013588	0.014874	0.013694	0.015004	0.01225	0.01441
consecucl	4th	0.018436	0.017182	0.015803	0.016894	0.014658	0.014603	0.015249	0.014998	0.01352
peaks	5th	0.021097	0.017878	0.015804	0.016937	0.014348	0.013603	0.015676	0.013918	0.013374

ave logdec	std
0.096745223	0.010965
0.098171011	0.010204
0.094945637	0.016044
0.098675622	0.009647
0.099578914	0.015711
ave	total std
0.097623281	0.012332
	ave std
	0.012514

Logarithmic Decrement over 10 cycles (δ)	
1st	0.087071
2nd	0.088354
3rd	0.085451
4th	0.088808
5th	0.089621
Average	*0.087861*

Damping Ratio (over 1 cycle) (ζ)	
1st	0.015397
2nd	0.015624
3rd	0.015111
4th	0.015705
5th	0.015848
Average	*0.015537*
std	0.000289

Frequency = approx. 18.9Hz

Specimen C2w

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	
1st	22.901	19.288	18.458	16.749	15.967	14.649	14.161	13.428	12.891	12.354	attempt
		0.171697	0.043985	0.097159	0.047814	0.086152	0.03388	0.05315	0.040813	0.042549	
2nd	26.856	19.63	18.311	17.09	16.407	14.405	13.965	13.086	11.719	11.719	
		0.31343	0.069557	0.069008	0.040785	0.130133	0.031021	0.065011	0.110332	0	
3rd	24.415	21.29	19.239	16.797	16.211	14.502	13.672	12.745	11.817	11.426	
		0.13696	0.101298	0.135739	0.03551	0.111403	0.058937	0.070211	0.0756	0.033648	
4th	34.718	27.686	25.831	22.413	20.85	18.262	17.042	15.625	14.161	13.379	
		0.226331	0.069352	0.141934	0.072287	0.132532	0.069142	0.086809	0.09838	0.056805	
5th	30.763	26.759	24.464	18.604	19.385	17.139	16.211	14.6	13.428	12.696	
		0.139442	0.089668	0.273826	-0.041123	0.123143	0.055667	0.104668	0.083679	0.056055	

Damping	1st	0.027326	0.007	0.015463	0.00761	0.013712	0.005392	0.008459	0.006496	0.006772
Ratio	2nd	0.049884	0.01107	0.010983	0.006491	0.020711	0.004937	0.010347	0.01756	0
bewteen	3rd	0.021798	0.016122	0.021604	0.005652	0.01773	0.00938	0.011174	0.012032	0.005355
consecucl	4th	0.036022	0.011038	0.02259	0.011505	0.021093	0.011004	0.013816	0.015658	0.009041
peaks	5th	0.022193	0.014271	0.043581	-0.006545	0.019599	0.00886	0.016659	0.013318	0.008921

	ave logdec	std
1	0.068577853	0.04428
2	0.092141978	0.091779
3	0.08436736	0.039221
4	0.105952441	0.053805
5	0.098336187	0.084031
	ave	total std
	0.089875164	0.064385
		ave std
		0.062623

Logarithmic Decrement over 10 cycles (δ)	
1st	0.06172
2nd	0.082928
3rd	0.075931
4th	0.095357
5th	0.088503
Average	*0.080888*

Damping Ratio (over 1 cycle) (ζ)	
1st	0.010915
2nd	0.014665
3rd	0.013427
4th	0.016863
5th	0.015651
Average	*0.014304*
std	0.002278

Frequency approx. = 8.2Hz

Specimen C2wo

Attempt	*Peak* 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st	30.372	23.341	21.387	20.215	17.579	16.895	15.332	14.454	13.77	12.5
		0.26331	0.087428	0.056358	0.13972	0.039687	0.097076	0.058971	0.048479	0.096764
2nd	22.559	17.383	16.407	15.528	13.379	13.086	12.012	11.426	10.84	10.059
		0.260641	0.057785	0.055063	0.148959	0.022143	0.085637	0.050015	0.052648	0.074775
3rd	26.386	19.825	18.262	16.895	14.689	13.985	12.891	12.11	11.524	10.45
		0.28589	0.082121	0.077805	0.139919	0.049114	0.081456	0.062498	0.0496	0.09783
4th	25.782	20.801	19.532	18.262	15.821	15.625	14.454	13.575	12.989	11.817
		0.214676	0.062947	0.067232	0.143484	0.012466	0.077901	0.062741	0.044127	0.094564
5th	27.833	23.731	21.094	19.63	16.7	16.7	15.235	14.161	13.575	12.305
		0.15944	0.117794	0.07193	0.16165	0	0.091813	0.073104	0.042262	0.098224

attempt	**ave logdec**	**std**
1	0.09864361	0.069181
2	0.089740705	0.07306
3	0.102914621	0.073967
4	0.086681933	0.059772
5	0.090690743	0.052184
	ave	**total std**
	0.093734322	0.063385
		ave std
		0.065633

Damping	**1st**	0.041907	0.013915	0.00897	0.022237	0.006316	0.01545	0.009386	0.007716	0.0154
Ratio	**2nd**	0.041482	0.009197	0.008764	0.023707	0.003524	0.01363	0.00796	0.008379	0.011901
bewteen	**3rd**	0.045501	0.01307	0.012383	0.022269	0.007817	0.012964	0.009947	0.007894	0.01557
consecuct	**4th**	0.034167	0.010018	0.0107	0.022836	0.001984	0.012398	0.009986	0.007023	0.01505
peaks	**5th**	0.025376	0.018747	0.011448	0.025727	0	0.014613	0.011635	0.006726	0.015633

Logarithmic Decrement over 10 cycles (δ)	
1st	0.088779
2nd	0.080767
3rd	0.092623
4th	0.078014
5th	0.081622
Average	***0.084361***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.0157
2nd	0.014283
3rd	0.016379
4th	0.013796
5th	0.014434
Average	***0.014918***

std 0.001077

Frequency = approx. 8.3Hz

Specimen C3w

Attempt	*Peak* 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	33.937	27.784	23.878	21.583	18.165	17.335	14.698	14.551	13.575	12.793
		0.200046	0.151503	0.101052	0.172409	0.046769	0.165016	0.010052	0.06943	0.059332
2nd	25.001	21.143	18.213	16.944	14.454	13.819	12.793	12.207	11.475	10.84
		0.167607	0.149173	0.072222	0.158943	0.044927	0.077146	0.046889	0.061839	0.056928
3rd	22.315	19.288	16.309	15.284	12.891	12.696	11.573	11.28	10.596	10.01
		0.145776	0.167766	0.064911	0.170277	0.015242	0.092612	0.025644	0.062555	0.056892
4th	17.774	15.186	13.135	12.452	11.035	10.84	10.157	9.619	9.326	8.643
		0.157363	0.145094	0.053399	0.120809	0.017829	0.06508	0.054423	0.030934	0.076056
5th	27.345	23.585	19.971	18.604	15.625	15.381	13.868	13.233	12.256	11.524
		0.147923	0.16633	0.070905	0.174504	0.015739	0.103549	0.04687	0.076698	0.061584

Attempt	**ave logdec**	**std**
1	0.108400858	0.066154
2	0.092852536	0.050575
3	0.089074945	0.058961
4	0.080109663	0.049699
5	0.09601132	0.055795
	ave	**total std**
	0.093289864	0.05473
		ave std
		0.056237

Damping	**1st**	0.031838	0.024112	0.016083	0.02744	0.007444	0.026263	0.0016	0.01105	0.009443
Ratio	**2nd**	0.026675	0.023742	0.011494	0.025296	0.00715	0.012278	0.007463	0.009842	0.00906
bewteen	**3rd**	0.023201	0.026701	0.010331	0.0271	0.002426	0.01474	0.004081	0.009956	0.009055
consecuct	**4th**	0.025045	0.023092	0.008499	0.019227	0.002838	0.010358	0.008662	0.004923	0.012105
peaks	**5th**	0.023543	0.026472	0.011285	0.027773	0.002505	0.01648	0.00746	0.012207	0.009801

Logarithmic Decrement over 10 cycles (δ)	
1st	0.097561
2nd	0.083567
3rd	0.080167
4th	0.072099
5th	0.08641
Average	***0.083961***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.017253
2nd	0.014778
3rd	0.014177
4th	0.01275
5th	0.015281
Average	***0.014848***

std 0.001645

Frequency = approx. 8.2Hz

Specimen 3wo

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	28.224	22.169	20.801	16.993	16.504	13.477	13.477	12.11	11.231	10.547
		0.241478	0.063694	0.2022	0.029199	0.202618	0	0.106953	0.075354	0.062836
2nd	33.302	27.052	24.317	20.899	19.532	16.993	15.723	14.161	12.989	12.207
		0.207857	0.106585	0.151474	0.067647	0.139253	0.077677	0.104633	0.086389	0.062093
3rd	28.614	23.048	21.192	17.872	16.895	14.551	13.868	12.598	11.719	10.84
		0.216317	0.083955	0.170389	0.056218	0.149358	0.048076	0.096046	0.072327	0.077968
4th	18.067	12.891	14.161	12.403	11.817	9.668	10.059	9.082	8.692	8.106
		0.337558	-0.093962	0.132553	0.048399	0.200718	-0.039646	0.102173	0.043891	0.069799
5th	23.536	19.044	16.895	14.649	14.258	12.5	11.914	10.157	10.254	9.571
		0.211779	0.119734	0.142646	0.027054	0.13159	0.048014	0.159551	-0.009505	0.06893

Attempt	ave logdec	std
1	0.109370136	0.085563
2	0.111511989	0.047253
3	0.107850346	0.057558
4	0.089053616	0.127676
5	0.099977052	0.070911
ave		**total std**
0.103552628		0.079289
		ave std
		0.077792

Damping	**1st**	0.038432	0.010137	0.032181	0.004647	0.032248	0	0.017022	0.011993	0.010001
Ratio	**2nd**	0.033081	0.016964	0.024108	0.010766	0.022163	0.012363	0.016653	0.013749	0.009882
bewteen	**3rd**	0.034428	0.013362	0.027118	0.008947	0.023771	0.007651	0.015286	0.011511	0.012409
consecuct	**4th**	0.053724	-0.014955	0.021097	0.007703	0.031945	-0.00631	0.016261	0.006986	0.011109
peaks	**5th**	0.033706	0.019056	0.022703	0.004306	0.020943	0.007642	0.025393	-0.001513	0.010971

Logarithmic Decrement over 10 cycles (δ)	
1st	0.098433
2nd	0.100361
3rd	0.097065
4th	0.080148
5th	0.089979
Average	***0.093197***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.017407
2nd	0.017748
3rd	0.017165
4th	0.014173
5th	0.015912
Average	***0.016481***

std 0.001464

Frequency = approx.8.1Hz

Specimen 4w

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	29.347	25.05	19.922	18.116	17.92	16.114	15.577	14.063	13.672	12.452
		0.158316	0.229049	0.095029	0.010878	0.106229	0.033893	0.102248	0.028197	0.093469
2nd	23.487	21.143	18.165	16.846	15.332	14.6	13.623	12.94	12.11	11.621
		0.105138	0.151812	0.075383	0.094171	0.048921	0.069262	0.051436	0.066292	0.041218
3rd	18.311	16.163	14.698	13.379	12.696	11.914	11.426	10.645	10.205	9.619
		0.124777	0.095013	0.094025	0.052399	0.063573	0.041823	0.070801	0.042213	0.059137
4th	28.468	23.878	20.313	17.488	17.335	15.235	14.942	12.989	12.989	11.573
		0.175823	0.161696	0.149746	0.008787	0.129132	0.019419	0.140073	0	0.115428
5th	23.878	20.606	18.604	16.26	15.528	13.965	13.965	12.696	12.354	11.426
		0.147375	0.102206	0.134669	0.046063	0.106091	0	0.095267	0.027307	0.078088

Attempt	ave logdec	std
1	0.095256564	0.068403
2	0.078181474	0.034588
3	0.071529074	0.02788
4	0.100011761	0.070299
5	0.08189623	0.049034
ave		**total std**
0.085375021		0.051588
		ave std
		0.050041

Damping	**1st**	0.025197	0.036454	0.015124	0.001731	0.016907	0.005394	0.016273	0.004488	0.014876
Ratio	**2nd**	0.016733	0.024162	0.011998	0.014988	0.007786	0.011023	0.008186	0.010551	0.00656
bewteen	**3rd**	0.019859	0.015122	0.014965	0.00834	0.010118	0.006656	0.011268	0.006718	0.009412
consecucl	**4th**	0.027983	0.025735	0.023833	0.001399	0.020552	0.003091	0.022293	0	0.018371
peaks	**5th**	0.023455	0.016267	0.021433	0.007331	0.016885	0	0.015162	0.004346	0.012428

Logarithmic Decrement over 10 cycles (δ)	
1st	0.085731
2nd	0.070363
3rd	0.064376
4th	0.090011
5th	0.073707
Average	***0.076838***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.015161
2nd	0.012443
3rd	0.011384
4th	0.015917
5th	0.013034
Average	***0.013588***

std 0.001896

Frequency = approx. 8.3Hz

Specimen 4wo

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	32.521	25.88	23.048	19.239	17.286	16.407	13.868	13.379	11.914	11.035
		0.228416	0.115891	0.18064	0.107043	0.052189	0.168124	0.035898	0.115972	0.076642
2nd	40.919	30.372	26.386	21.778	18.848	17.676	14.063	14.551	12.793	12.012
		0.298073	0.140688	0.191933	0.144493	0.064199	0.228661	-0.034112	0.128762	0.062992
3rd	22.364	16.7	15.918	11.426	11.914	11.328	9.278	9.864	8.692	8.496
		0.292044	0.047958	0.331559	-0.041823	0.050437	0.199632	-0.061246	0.126489	0.022808
4th	23.634	18.36	15.137	14.063	12.891	12.403	10.84	10.547	9.473	8.887
		0.252512	0.193032	0.073595	0.087018	0.038591	0.134695	0.027402	0.107396	0.063856
5th	20.118	17.286	15.918	13.379	12.696	11.328	10.547	10.157	9.082	8.887
		0.151718	0.082446	0.173764	0.052399	0.114009	0.071436	0.037678	0.111869	0.021705

Damping	**1st**	0.036353	0.018445	0.02875	0.017036	0.008306	0.026758	0.005713	0.018458	0.012198
Ratio	**2nd**	0.04744	0.022391	0.030547	0.022997	0.010218	0.036392	-0.005429	0.020493	0.010025
bewteen	**3rd**	0.04648	0.007633	0.052769	-0.006656	0.008027	0.031772	-0.009748	0.020131	0.00363
consecuct	**4th**	0.040189	0.030722	0.011713	0.013849	0.006142	0.021437	0.004361	0.017093	0.010163
peaks	**5th**	0.024147	0.013122	0.027655	0.00834	0.018145	0.011369	0.005997	0.017804	0.003454

Attempt	ave logdec	std
1	0.120090444	0.062749
2	0.136187595	0.098458
3	0.107539673	0.14047
4	0.108677424	0.073917
5	0.0907806	0.051347
	ave	**total std**
	0.112655147	0.088147
		ave std
		0.085388

Logarithmic Decrement over 10 cycles (δ)	
1st	0.108081
2nd	0.122569
3rd	0.096786
4th	0.09781
5th	0.081703
Average	***0.10139***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.019113
2nd	0.021675
3rd	0.017115
4th	0.017297
5th	0.014448
Average	***0.01793***

std 0.002674

Frequency = approx. 8.2Hz

Specimen 5w

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	35.939	30.958	25.831	24.219	21.094	19.483	18.116	16.114	15.625	13.672
		0.149192	0.181056	0.064438	0.138149	0.079446	0.072747	0.117107	0.030816	0.133522
2nd	22.901	20.801	18.018	17.335	15.674	14.698	13.916	12.5	12.354	11.426
		0.09618	0.14363	0.038644	0.100724	0.064292	0.054672	0.107311	0.011749	0.078088
3rd	31.739	26.466	22.315	20.313	17.09	16.651	15.137	14.307	13.623	12.256
		0.181685	0.170602	0.093998	0.172768	0.026023	0.095328	0.056393	0.048989	0.105744
4th	15.772	14.356	12.305	11.963	10.743	10.254	9.815	8.933	8.838	8.155
		0.094068	0.154162	0.028187	0.107564	0.046587	0.043756	0.09416	0.010692	0.080429
5th	19.19	16.944	14.161	13.428	11.866	11.28	10.84	9.815	9.864	8.985
		0.124476	0.179422	0.05315	0.123665	0.050646	0.039788	0.099331	-0.00498	0.093335

Damping	**1st**	0.023745	0.028816	0.010256	0.021987	0.012644	0.011578	0.018638	0.004905	0.021251
Ratio	**2nd**	0.015307	0.022859	0.00615	0.016031	0.010232	0.008701	0.017079	0.00187	0.012428
bewteen	**3rd**	0.028916	0.027152	0.01496	0.027497	0.004142	0.015172	0.008975	0.007797	0.01683
consecuct	**4th**	0.014971	0.024536	0.004486	0.017119	0.007414	0.006964	0.014986	0.001702	0.012801
peaks	**5th**	0.019811	0.028556	0.008459	0.019682	0.008061	0.006332	0.015809	-0.000793	0.014855

Attempt	ave logdec	std
1	0.107385901	0.048201
2	0.077254346	0.03981
3	0.105725622	0.057797
4	0.073289442	0.04496
5	0.084314754	0.055424
	ave	**total std**
	0.089594013	0.04953
		ave std
		0.049239

Logarithmic Decrement over 10 cycles (δ)	
1st	0.096647
2nd	0.069529
3rd	0.095153
4th	0.06596
5th	0.075883
Average	***0.080635***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.017091
2nd	0.012295
3rd	0.016827
4th	0.011664
5th	0.013419
Average	***0.014259***

std 0.002545

Frequency = approx. 8.1Hz

Specimen 5wo

Attempt	Peak 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1st (mV)	25.587	22.169	18.751	17.286	15.04	14.454	13.184	12.5	11.621	10.743
		0.143389	0.167448	0.08135	0.139184	0.039742	0.091967	0.053275	0.072915	0.078559
2nd	23.438	19.434	17.383	15.332	13.086	12.012	11.132	10.645	9.473	9.375
		0.187335	0.111531	0.125551	0.158399	0.085637	0.076082	0.044734	0.116645	0.010399
3rd	21.876	19.727	17.383	16.114	14.454	13.868	12.11	11.914	10.547	10.45
		0.103402	0.126496	0.075804	0.108717	0.041387	0.135552	0.016317	0.121873	0.009239
4th	21.29	19.141	16.603	15.723	13.282	12.012	11.328	10.938	10.157	9.082
		0.106405	0.142249	0.054459	0.168715	0.100504	0.058629	0.035035	0.07408	0.111869
5th	29.2	28.419	26.075	23.048	17.969	19.044	16.7	15.918	13.575	13.477
		0.027111	0.086081	0.123398	0.248931	-0.058104	0.131343	0.047958	0.159221	0.007245
Damping	**1st**	0.022821	0.02665	0.012947	0.022152	0.006325	0.014637	0.008479	0.011605	0.012503
Ratio	**2nd**	0.029815	0.017751	0.019982	0.02521	0.01363	0.012109	0.00712	0.018565	0.001655
bewteen	**3rd**	0.016457	0.020132	0.012065	0.017303	0.006587	0.021574	0.002597	0.019397	0.001471
consecucl	**4th**	0.016935	0.02264	0.008667	0.026852	0.015996	0.009331	0.005576	0.01179	0.017804
peaks	**5th**	0.004315	0.0137	0.019639	0.039619	-0.009248	0.020904	0.007633	0.025341	0.001153

Attempt	**ave logdec**	**std**
1	0.096425559	0.043692
2	0.101812452	0.054695
3	0.082087574	0.048613
4	0.094660338	0.04346
5	0.085909353	0.091683
	ave	**total std**
	0.092179055	0.056967
		ave std
		0.056428

Logarithmic Decrement over 10 cycles (δ)	
1st	0.086783
2nd	0.091631
3rd	0.073879
4th	0.085194
5th	0.077318
Average	***0.082961***

Damping Ratio (over 1 cycle) (ζ)	
1st	0.015347
2nd	0.016204
3rd	0.013065
4th	0.015066
5th	0.013673
Average	***0.014671***
std	0.001279

Frequency = approx 8.5Hz

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