Design and Engineering for Acoustics

Peter Griffiths
Ove Arup Acoustics, Consulting Engineers, Sydney

SUMMARY

Lightweight materials are now available with strength and durability enabling long life structures to be built. Besides offering a unique form of curved architecture, such structures are very sensitive to environmental change. Because of the differences in geometry, scale and materials which are inherent properties of lightweight membranes their acoustic properties have to be considered in detail.

These properties offer exciting possibilities for acoustic design. In turn, the forms which are possible with these materials can present particular acoustic issues which must be addressed to fully realise the functionality of the enclosed space.

This paper discusses the fundamental acoustic properties of sound absorption, curvature of space, and sound insulation relating to membrane structures. A range of sound absorption values of various membrane types and configurations is presented, the behaviour of sound in a predominantly curved architecture is examined, and a range of sound insulation values, again of different membranes and configurations. An acoustic design case history is also presented illustrating how the issues were addressed and the membrane properties used to good effect.

1. INTRODUCTION

Acoustics has been linked with building design and engineering for thousands of years. There has long been an awareness that the acoustic environment created by any partially or fully enclosed space is a fundamental characteristic of its architecture. It is as much a representation of the physical expression of the building as its mass, its structure, and its texture. It is not an "add on extra"; it is an inevitable consequence of every endeavor to construct. It follows from this simple realisation that internal environments can be manipulated in the design process to achieve or enhance certain desirable acoustic characteristics within a space – characteristics which allow the specified human activities to successfully occur.

The history of acoustic design is varied. Early Greek actors had small megaphones built into the masks they wore on stage to direct their voices to the audience. Nearly one thousand years ago churches were built in Sweden with cavities in their walls to reduce low freqency reverberation. However the relationship between architectural design, engineering and acoustic outcomes as we know and practice today owes it beginings to a newly designed lecture theatre in which speech was largely unintelligible.

USA 1895. The President of Harvard University approached the University's Physics Department to study the lecture theatre of the just completed Fogg Art Museum in which sounds persisted for such a time that only a jumble of confused noise rather than recognisable words reached the audience. This study was considered to be risky and was given to an Assistant Professor, Walter Sabine, whose previous work had been in optics and electricity.

Sabine eventually established a relationship between room volume, the amount of acoustic absorption in the room and the time taken for sound to fade away. This phenomenon was called reverberation time and was established as a critical factor determining speech intelligibility. From that time an important aspect of room acoustic performance could be calculated during the design process. This was the start of a continuing search for predictability in architectural acoustics. It is indicative of the relative lack of concern the scientific community placed on acoustics to remember that this most commonplace experience of sound in rooms was established at a time when physicists were making revolutionary early discoveries in atomic physics.

Acoustics is a physical science. It is concerned with the behaviour of sound (vibration) in different materials (e.g. air or structure) and the way in which sound behaves in an enclosed space. All of these aspects are physical phenomena and can be described by various laws of physics. As new materials develop and new forms and structures become part of the contemporary architectural and engineering language, so must the understanding of the acoustic properties and consequences relating to these elements be grasped by designers. Nowhere is this more important than in the use of modern lightweight structures. This area in particular offers exciting challenges for innovative acoustic solutions, provided the designer is equipped with a clear understanding of the singularity of the acoustic properties of lightweight structures and their resultant forms.

Flexible membranes are very different in geometry, scale and material composition to ”standard” building materials and forms. They offer a curved architecture with its own acoustic behaviour. This paper summarises the unique acoustic properties of flexible membranes, and how these properties affect the overall design. An illustrative design case history is discussed.

2. FIRST PRINCIPLES

There are a number of basic principles which establish the fundamental design elements which must be necessarily understood. They are:

- **Frequency.** Sound is vibration in a medium. It can be described in terms of its oscillating frequency, measured in Hertz (Hz). All sound is made up of a complex of several frequencies, from low to high. The behaviour of sound in and with any material is always frequency dependent. Acoustic design is generally concerned with eight octave bands of frequencies described in terms of the octave band centre frequencies from 63Hz to 8000Hz (or 8kHz), with each octave band centre frequency twice that of the preceeding band.
- **Wavelength.** Each frequency has its own wavelength. The wavelengths of the octave band centre frequencies with which we are generally concerned range from approximately 5.5m at 63Hz to 43mm at 8kHz. Whilst these dimensions are comparable to the scale of many building elements and room surfaces they nevertheless represent a large range when considering the way each frequency component may behave. The resulting behaviour between an acoustic wave front and a building element may be completely opposite for low and high frequencies (large and small wavelengths). At low frequencies (large wavelengths) sound

waves commonly bend round objects. But at high frequencies (small wavelengths), objects and surfaces are generally larger than the wavelength of the incident wavefront and sound behaves much like light, travelling in straight lines and forming shadow zones.

- **Absorption.** As sound travels through a medium, or when it comes in contact with a material, surface etc, some component of the acoustic energy is absorbed. There are a number of different physical ways in which this absorption can occur, depending on the medium or material. The amount of absorption provided by a material is described by its absorption coefficient, ranging from 0 to 1. Values approaching 0 indicate that the material provides low acoustic absorption while values approaching 1 indicate high levels of absorption. Absorption is always frequency dependent. No material is equally absorbent at all frequencies.
- **Reflection.** Reflected sound is the component of a wavefront which is not absorbed when the front is incident upon a surface. As with absorption, reflection is always frequency dependent.
- **Diffusion.** Acoustic diffusion is generally considered to be the ability of a surface to scatter the incident wavefront. A non–diffuse surface will create specular reflections (ie the angle of reflection equals the angle of incidence). A surface may be diffuse for one frequency and non–diffuse for another.
- **Sound Transmission Loss (or Sound Reduction).** A measure of the reduction of sound provided by a material between a source and receiving room. Sound transmission loss is always frequency dependent.

3. THE INTERACTION OF SOUND WITH MEMBRANE STRUCTURES

How can membrane structures be approached in terms of acoustic design? How do they behave and what are their acoustic properties that can be used to design the desired environment? Let us assume that the acoustic targets have been set – that the function of the space is clearly defined and the range of human activities that will occur is well understood. Of course these targets are set independently of the building structure and fabric. Whether or not we can meet these targets with our construction type (in this case a membrane structure) depends upon the performance of the components and how we detail the components.

Typically these targets can describe the control of sound entering the space (its sound insulation) and the way we require sound to behave within the space (its room acoustic). For the purposes of this paper, the following performance aspects of membrane structures are examined:

- sound absorption
- curved and concave forms
- sound transmission loss

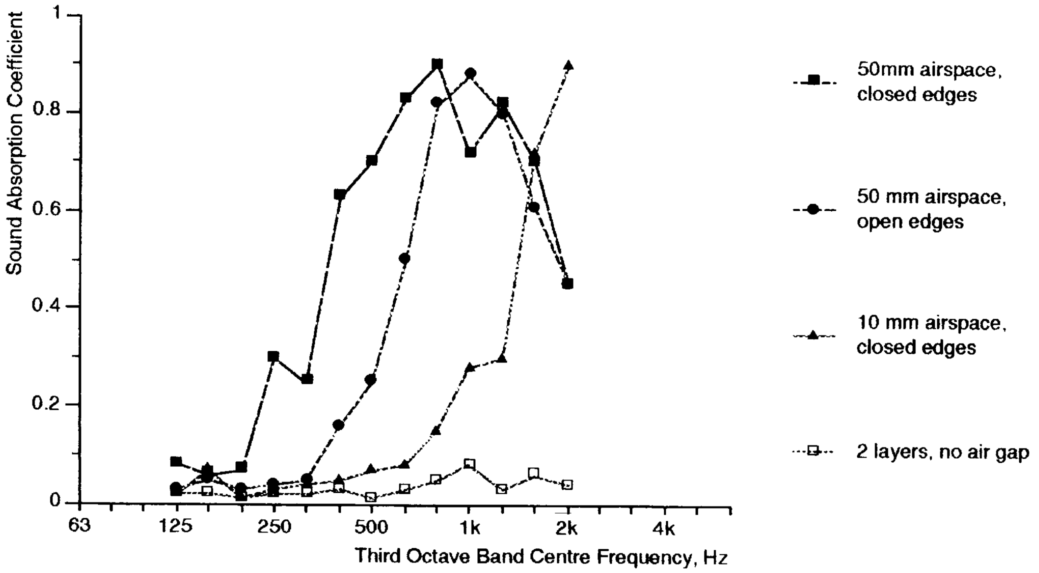
3.1. Absorption

Figure 1 shows impedance tube test data for two samples of Duraskin membranes under various conditions. The samples differ in mass (0.32kg/m2 and 0.245kg/m2 in Figure 1a and 1b respectively). The heavier membrane is also perforated.

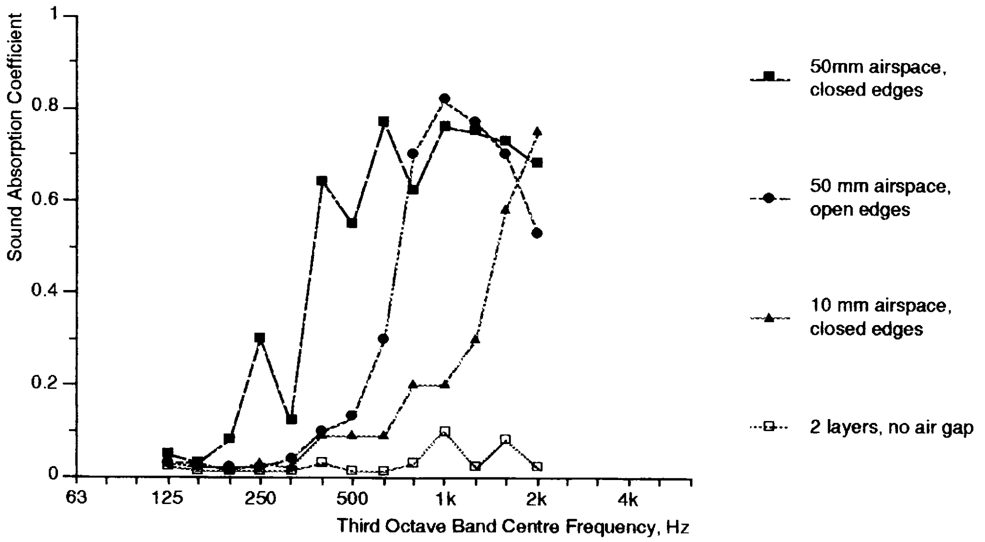
The effect of differing edge conditions is also shown, with the conditions being as follows:

- 50mm airspace behind sample, with closed edges
- 50mm airspace behind sample, with open edges
- 10mm airspace behind sample, with closed edges
- 2 layers of material with no airspace behind sample

Generally absorption decreases rapidly with frequency (why the cracking of a whip sounds so sharp in a circus tent). As the airspace behind the sample decreases, the frequencies at which maximum absorption occurs increases. With no airspace sound is reflected off the sample.



a) Perforated Duraskin Fabric (18079) - 0.32 kg/m2



b) Duraskin Fabric (18069) - 0.245 kg/m2

Figure 1 (a) and (b). Values of absorption coefficients for Duraskin fabrics measured by Hoechst Aktiengesellschaft (Frankfurt) in 1979 using impedance tube method.

Moulder and Merrill(2) have described some test results for three fibreglass fabrics (Structo. Fab 450, 375 and 120 produced by Owens Corning Fibreglass, weights of 1.53kg/m2, 1.27kg/m2 and 0.407kg/m2 respectively). The two heavier fabrics are used as outer roof membranes and are completely coated to be impermeable so that the air flow resistance is effectively infinite and little sound absorption can take place. The lighter fabric is only lightly coated and is used as an inner liner; the air flow resistance was low and a high degree of sound absorption results. Figure 2 shows the results.

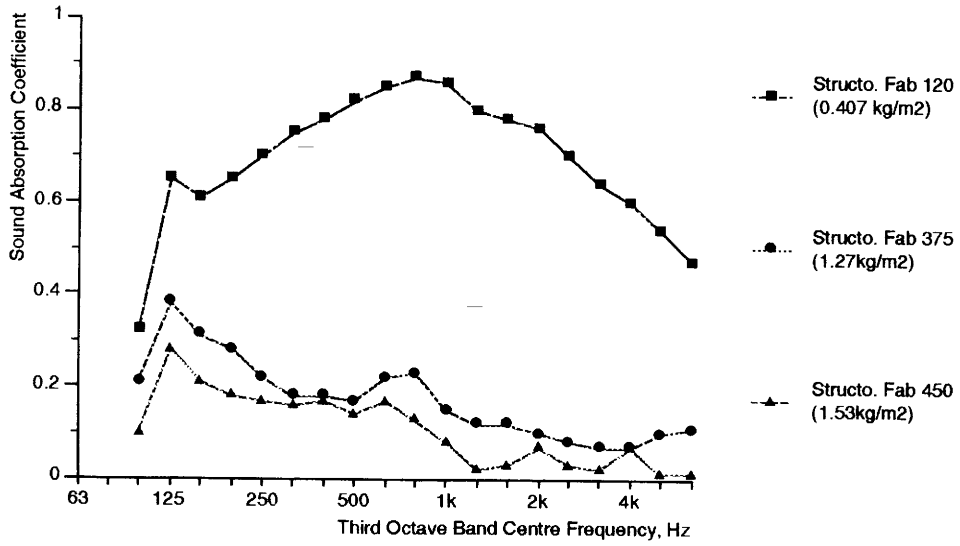


Figure 2. Measured absorption coefficients (Moulder and Merrill [2]) using the reverberation chamber method at the Owens Corning Fiberglass Technical Centre in Grantham, Ohio

The sound absorption performance is a function of the porosity of the material. Hence the use of controlled porosity membranes allows us to achieve a desired amount of sound absorption to suit the function of the space.

Sometimes lightweight membranes are insulated to limit heat loss and condensation. Figure 3 shows the results of two conditions using:

- a double membrane with an impermeable outer fabric (1.5kg/m2) plus the inner porous lining (0.407kg/m2) with an airgap of 600mm.
- the same as above but with 50mm of fibreglass insulation in the airspace.

Both solutions provide a high degree of sound absorption at low and high frequencies. The dip at 250Hz occurs because the airspace (600mm) corresponds to the half wavelength at this frequency.

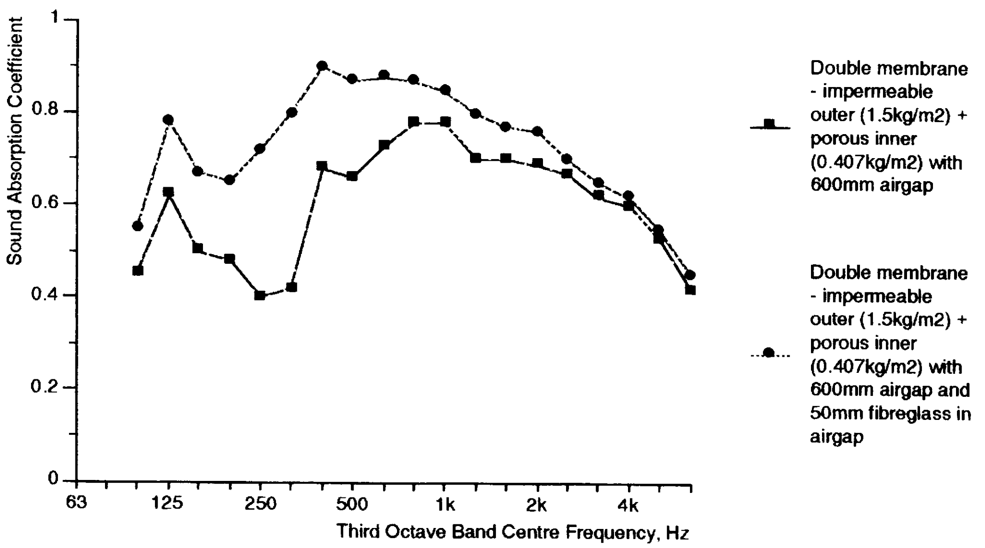


Figure 3. Effect of double membrane and cavity insulation on sound absorption (Moulder and Merrill[2]).

Lightweight membranes can have an important use as sound absorbers, comparing favourably with the low frequency performance of perforated tiles provided the densities of the impermeable membranes are low enough. By combining with different fibreglass layers, absorption throughout the high and medium frequency range can be achieved (Figure 4).

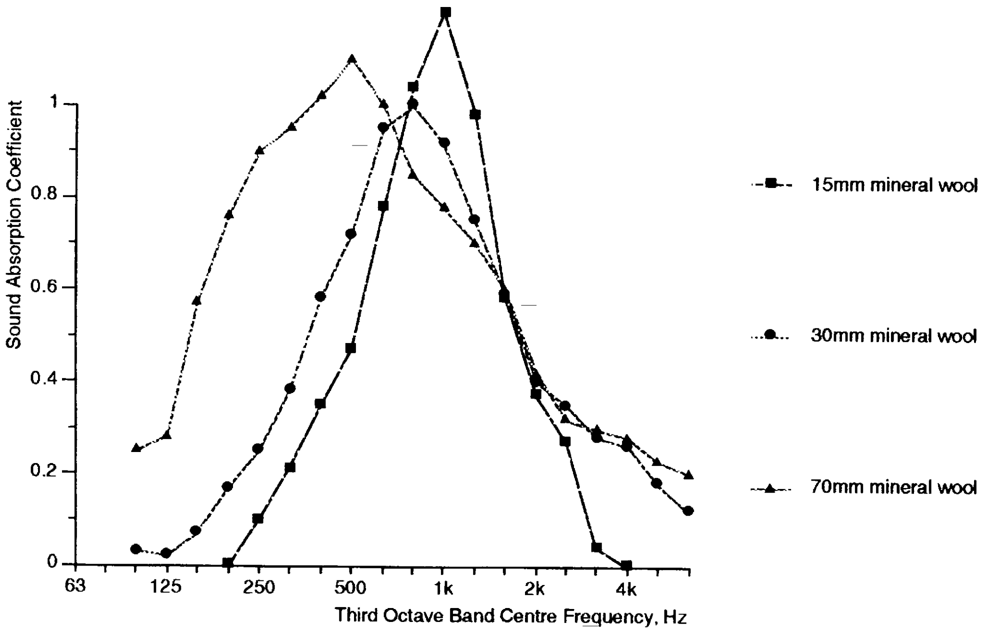


Figure 4. Absorption coefficients for fibreglass covered membranes measured in a reverberation chamber

3.2. Curved And Concave Forms

One of the basic assumption made in room acoustics is that sound energy is distributed equally throughout the space. This is not true if some of the boundary surfaces are concave, as they may be in some membrane structures, particularly pneumatic structures. Figure 5a shows the effect of curvature on sound distribution along one elevational plane in a typical pneumatic structure such as the enclosure of the North Sydney Pool. The curves at the ends focus sound which causes reflected rays to be highly concentrated in these regions.

Domes, barrel vault ceilings, and curved rear walls typically cause focusing problems. Some areas in a space bounded by these surfaces receive too much sound and others too little. When a sound source moves (actor walks across the stage, music calls for a change from violin section to horns, lecturer moves from side of demonstration table to centre) the area that received too much sound before now receives too little. The change is exaggerated and distorted by the focussing effect of the room shape on reflected sound waves. The same type of problem is also encountered in plan view. Circular and elliptical plans are the worst offenders.

Any room shape which will focus light will focus sound (or some frequency component of sound). Some time spent tracing paths from expected sound source locations to reflective surfaces and back to listener locations should reveal the problem and possible solutions.

Sometimes sound in large spaces can be enhanced at distances a long way from the sound source. This is due to reflections skipping across the surfaces (Figure 5b) and is commonly referred to as the "whispering gallery" effect. Low level speech, for example, may not be heard properly near the speaker but may be heard clearly in a focusing region even if it is a long way off.

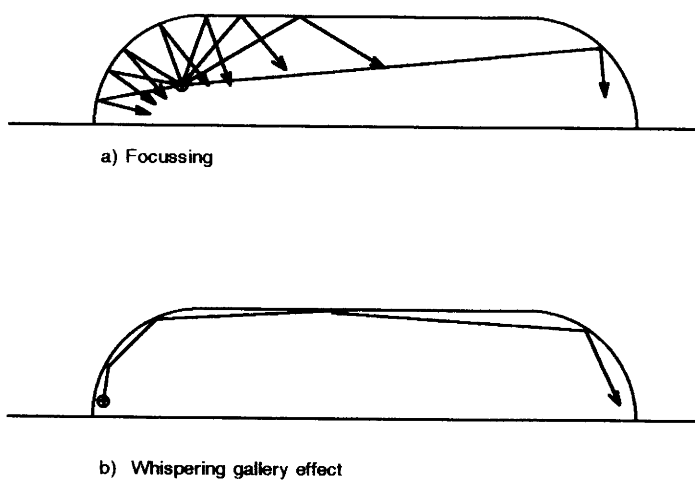
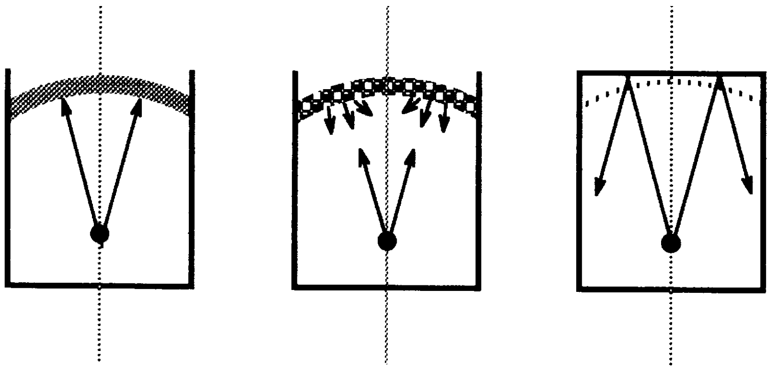


Figure 5. Effect of curved surfaces on sound distribution

Methods of avoiding focusing include the use of absorbent material, faceting the surface and by making the visual concave surface acoustically transparent (Figure 6). Increased absorption however, is not always desirable as may reduce reverberation times to less than desirable levels, especially if the space is used for musical performances.

Breaking up a concave surface into sound scattering elements provides an opportunity to develop ingenious forms. However, frequency and wavelength are again important with wavelengths ranging from about 0.1m (high frequencies) to 3m (low frequencies) and any design must embrace this wide range of dimensions.



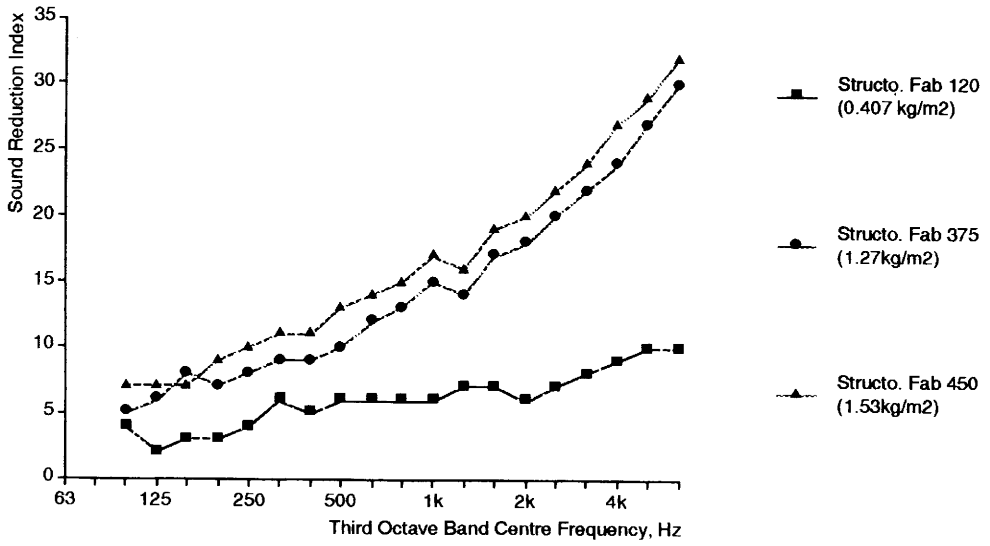
(a) (b) (c)

Figure 6. Methods for avoiding focussing by (a) absorption, (b) breaking up the curved surface, and makinng the domed surface acoustically transparent. (Cremer and Muller 3)

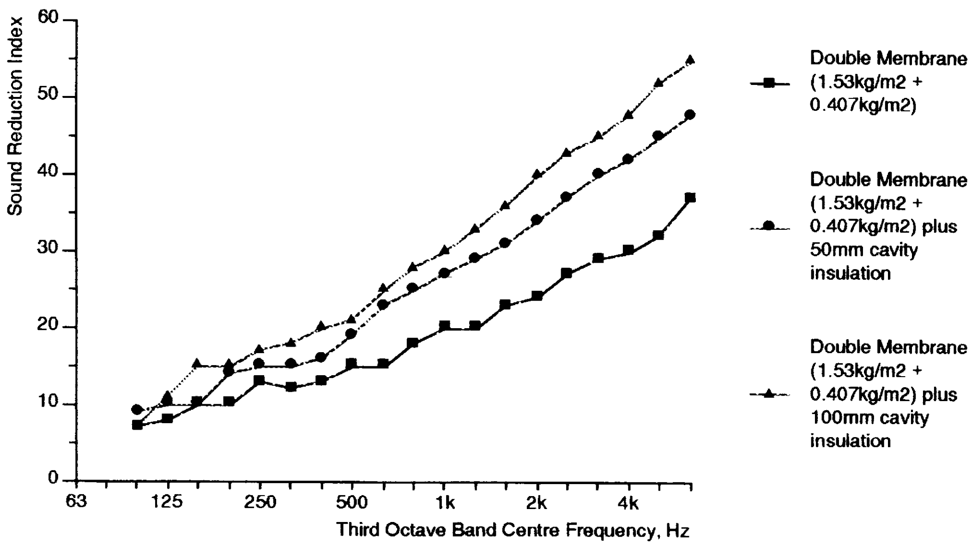
3.3. Sound Insulation

Measurements of the sound reduction index (equivalent to transmission loss) were made by Moulder and Merrill(2) for the three fibreglass materials discussed earlier. The results are shown in Figure 7a. The two heavier fabrics (1.27 and 1.53kg/m2) provide similar sound insulation values of about 10dB at lower frequencies (250Hz) to 20dB at higher ones (2kHz). The light material (0.407kg/m2) can only offer 5 – 10dB of insulation and is little better than an open window.

The effect of using a double membrane and putting 50 or 100mm of fibreglass material in the cavity is shown in Figure 7b. A double membrane construction improves the single fabric performance by 5dB, i.e. the heaviest fabric plus the light porous liner provide 14dB at 250Hz and 25dB at 2kHz. Insertion of 50mm of insulation in the cavity increases these values to 15dB (250Hz) and 34dB (2kHz). Similarly, 100mm of insulation in the cavity gives 17dB (250Hz) and 41dB (2kHz).



a) Single layer membranes



b) Double membrane plus cavity insulation

Figure 7 (a) and (b). Sound reduction index for Structo. Fab materials (Moulder And Merrill [2])

4. CASE STUDY : ALEXANDRA PALACE RENOVATION

In a major fir in the summer of 1980, a large part of the Victorian Alexandra Palace in North London was severely damaged. The Great Hall, the venue of many historic events, including recitals of considerable repute on the renowned Willis Organ, was destroyed. The massive walls for the most part remained, but the roof and interior were lost. Arup Acoustics was the acoustic consultant for the rebuilding of the Palace. This included a new arrangement for the Great Hall, developed around a brief for its primary function as an exhibition hall, but with capacity for other uses. A clear spanning roof was to replace the previous structure, which had relied on a pair of colonnades to limit the span.

4.1. The Great Hall

The Great Hall is 118m long and 56m wide. The new roof section has a height close to 30m along the central axis. The volume of the hall including the coupled volume above the lightweight ceiling is approximately 150,000m3, with capacity for 5,000 people.

Records of measurements of reverberation time in the Great Hall before the fire indicated mid–frequency values exceeding 6 seconds (unoccupied). Although highly responsive for organ recitals, this reverberation had proved very limiting for other activities needing less ”bloom” on the sound. In the new Hall, exhibition requirements suggested substantially reduced reverberation time targets. A value of 2 seconds or less would be ideal for exhibition use, but a wish remained to allow for musical events and occasional organ recitals. Two other factors influenced the choice of values, the first being the substantial cost of the extensive acoustic treatment which would be required to achieve ideal conditions for exhibitions. Secondly, there was the opportunity to develop effective public address signals within a live acoustic. The particular expertise of achieving high speech intelligibility in very reverberant spaces arose in part from recent experience of cathedral sound systems. Reverberation time at mid–frequencies was designed to fall in the range 3.5 – 4.5 seconds.

4.2. Acoustic Treatment to Roof Soffit

The interior design for the Great Hall offered little scope for acoustic treatment to walls. Limited areas of absorptive material were integrated into the formal pattern of the wall elevations but most attention needed to be at high levcel in the form of ceiling or soffit treatment. A major feature of the interior design was the use of daylight from the roof. A separate ceiling was at one stage in doubt and it was necessary to find ways of introducing absorption at the roof soffit without a significant conflict with daylighting. A series of panels was designed to fix to the framing of the glazing, hanging down to form linear baffles running at an angle with the slope of the roof. Simple aluminium framework contained mineral wool slabs faced in white weave to achieve high light reflectivity. This treatment was extremely cost effective, exposing both sides of the panels tp sound, much like the suspended baffle absorbers often used in noisy industrial workshops.

4.3. Lightweight Fabric Ceiling

The architects proposed the use of a lightweight structural fabric suspended ceiling, with substantial light transmission. Previous experience of the acoustic performance of structural fabrics indicated three possible consequences. Firstly, if it was unperforated, most high frequency sound would be reflected. Long reverberation at mid/high frequencies was undesirable and absorption of sound in the air was helpful only at very high frequencies. Elements of concave curvature in the ceiling form might also have resulted in underside sound focusing. The fabric takes up a two–way curvature, part concave, part convex, limiting the potential for focusing. Nevertheless, an unperforated construction was unwelcome.

The second possibility was an acoustically transparent arrangement with sufficient perforation to allow the sound to pass to the upper volume for absorption by the powerfully absorptive baffles, the preference from an acoustic viewpoint.

The third option was an interim condition whereby with controlled porosity, broadband absorption (approximately 50%) could be obtained. The relative benefits of the upper baffle absorption and the inner liner absorption could be reviewed if this option was followed.

The quality of light transmission was a major influence on the choice of fabric: very open fabric would give too clear a view of the various elements above the ceiling, whilst fabric strentgh and the effects of air movement were other considerations. There was also concern that variations in coating geometry might adversely affect the controlled porosity option. Small samples of fabrics (proposed as suitable for non– acoustic purposes) were subjected to normal incidence absorption tests in an impedance tube, those reasonably transparent to sound at mid–frequencies were preferred. To avoid too much vision through the fabric, some high frequency reflection (<20% above 2kHz) was accepted (see Figure 8).

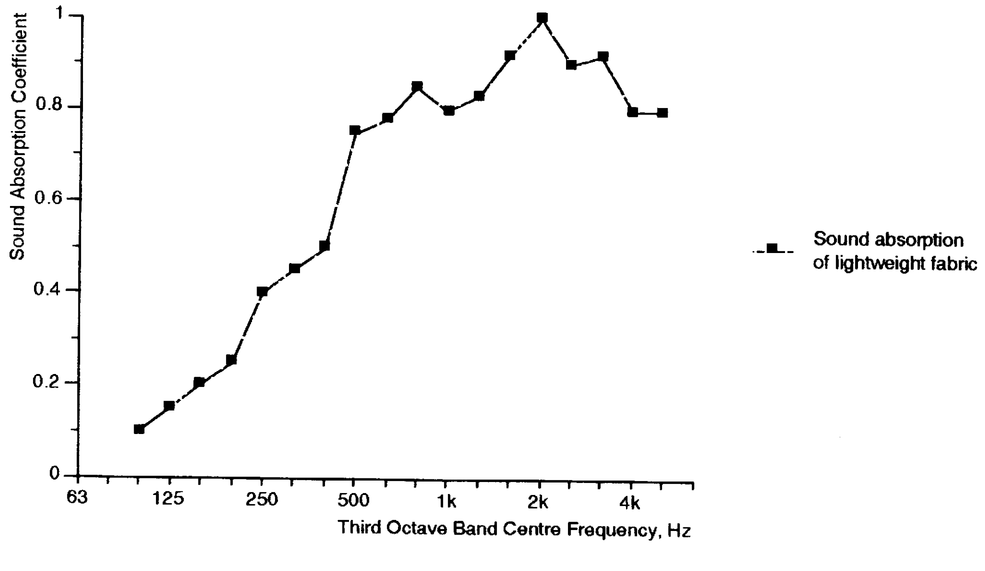


Figure 8. Sound aborption of lightweight fabric used in Alexandra Palace Great Hall
- measured using impedance tube method

On completion, measurement of reverberation time (unoccupied) demonstrated that target conditions had been achieved (see Figure 9). Fund–raising for rebuilding of the Willis Organ enabled a small (first stage) organ to be set on a new organ platform. The natural acoustic has proved to be appropriate for a wide range of uses including choral music, school examinations, exhibitions, and sporting events.

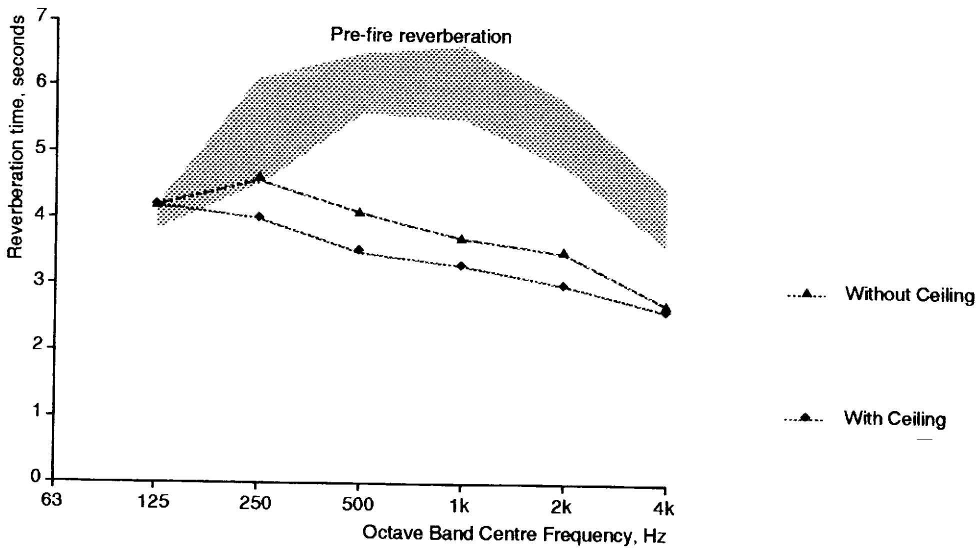


Figure 9. Measured rverberation Times in Great Hall

4.4. Public Address

The intelligibility of speech from the public address system in such a "live" acoustic depends upon:

- direction of sound onto the listening zones, with minimum unnecessary dispersion from the source to excite the reverberant response of the hall
- reflection of any sound from unoccupied hard floor surfaces towards absorptive material (in this case the ceiling), again to reduce excitation of reverberation
- careful alignment of elements of loudspeaker arrays to avoid colouration caused by phase interference
- appropriate quality of specification for the system components.

Constant directivity horns are suspended from two lighting and servicing gantries which run the length of the Hall. By careful orientation of the horns, sound projection is arranged to cover the flat floor condition and perimeter raked seating (see Figure 10). There is sufficient vertical emphasis to the distribution for floor reflections to be directed back up to absorptive treatment at high level, thereby limiting excitation of lateral reverberation. A wall mounted system or a central cluster would have enhanced reverberation and resulted in uneven coverage and substantial interference by exhibition screening.

The system provides clear intelligible speech throughout.

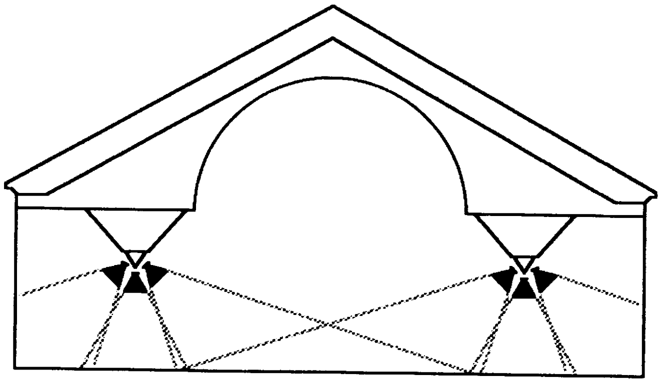


Figure 10. Loudspeaker coverage, Great Hall section

5. REFERENCES

1. Croome, D.J., (1985) Acoustic Design for Flexible Membrane Structures, Applied Acoustics 18, 399–433
2. Moulder, R. and Merrill, J., (1982) Acoustical properties of glass fiber roof fabrics, 104th Meeting of Acoustical Society of America, Orlando, Florida, USA, 11 November, 1982
3. Cremer,l. and Muller,H.A. (1982) Principles and Applications of Room Acoustics, Volume 1, Applied Science Publishers, London
4. Cowell, J.R., (1990) Alexandra Palace renovation phase 1: acoustic consultancy. The Arup Journal, Summer 1990, 14–15