INDUSTRIAL CLADDINGS: SOUND ABSORPTION AND TRANSMISSION

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1. INTRODUCTION

When EEC legislation for limiting exposure to noise at the workplace is introduced in 1990, it shall be the responsibility of the employer to ensure that the design and construction of factories is such that the risks resulting from exposure to noise are reduced to the lowest level reasonably practicable. This will result in greater importance being attached to the prediction of noise levels inside and around industrial buildings at any stage of their design or construction. Theoretical models are being developed to predict these noise levels but their accuracy relies on the provision of accurate values of absorption coefficient and sound reduction index of the construction materials, in particular the lightweight claddings favoured by today's industrial architects.

The sound reduction index and absorption coefficient of many cladding samples have been measured in the main sound transmission suite at the Department of Applied Acoustics, University of Salford. This paper presents the results of a selection of these measurements, chosen to represent the range of types of cladding available to the industrial architect. In addition, it presents the theory of an infinite orthotropic plate as a means towards predicting the acoustic behaviour of singleskin claddings.

2. CLADDINGS

There are many types of claddings available from which industrial building can be constructed. The original stalwart of industrial claddings is the corrugated (profiled) singleskin cladding. They are produced in a wide range of profiles, in either galvanised steel or aluminium. Corrugating the cladding sheets imparts stiffness and hence strength to the length of the relatively thin gauge and otherwise flexible sheets. The corrugation profile, originally sinusoidal, has been developed into the now familiar trapezoidal profile with a sophisticated design compromise of both maximum strength with maximum cover width. Singleskin claddings form weatherproof constructions, but have little thermal and acoustic insulation.

In order to provide better insulation, the singleskin sheets are used as part of more complex cladding systems. Doubleskin claddings consist of inner liner and outer profiled cladding sheets, with looselaid insulation in between. The liner systems range from profiled sheets to structural liner trays. Roofdeck systems are a modification of double claddings. They have a weathering membrane of bitumen and felt or asphalt instead of the outer profiled cladding. Both these systems are site-assembled combinations.

The latest development in claddings are factory-manufactured composite sandwich panels. The material is produced by combining inner and outer profiled (sometimes flat) sheets and filling the gap in between with an insulating foam which adheres to both inner surfaces, giving stiffness and strength to the lightweight cladding.

2.1 Cladding Samples

Measurements of the following samples of industrial steel cladding shall be presented:

1) Corrugated singleskin cladding.
   Nominal thickness = 0.55 mm
   Moment of area of corrugation profile = 10.05 cm^4
   Surface density = 6.2 kgm^{-2}
2) Corrugated doubleskin cladding with mineral wool insulation.
   Nominal thickness of outer skin = 0.65 mm
   Nominal thickness of inner skin = 0.50 mm
   Moment of area of corrugation profile of outer skin = 8.78
   Moment of area of corrugation profile of inner skin = 6.25
   Total surface density = 13.0 kgm^{-2}
3) Sandwich panel.
   Nominal thickness (both skins) = 0.55 mm
   Moment of area of panel = 62.5 cm^4
   Total surface density = 13.7 kgm^{-2}
4) Built-up roofdeck system.
   Nominal thickness of bitumen & felt = 3.0 mm
   Nominal thickness of urethane insulation = 30.0 mm
   Nominal thickness of profiled decking = 0.7 mm
   Total Surface density = 32.6 kgm^{-2}

An illustrative description of each sample is given in figure 1. The size of the test samples is determined by the maximum size of the test aperture, that is 3600mm wide by 2390mm high. Each test sample consisted of four or more sheets of the cladding riveted together along the side overlaps.

3. MEASUREMENTS ON CLADDINGS

3.1 Mounting of Samples

Each sample was mounted in the aperture, between the two rooms of the test suite using the same structural support and fixings as typifies an industrial construction. This nominally consisted of the sample being fixed to two Zeta purlins (type 15018), mounted horizontally in the aperture, 2m apart, with self-drilling or self-tapping screws. For each measurement, the perimeter of the sample was sealed into the aperture using Arbocaulk emulsion acrylic sealant, to prevent sound leakage at the edges.

3.2 Measurement Procedure

Measurement of Sound Reduction Index of each cladding sample was undertaken in accordance with the British Standard method of laboratory measurements of airborne sound insulation of building elements (BS2750:part3:1980).

The method for measuring the acoustic abosprtion coefficient of the cladding samples was a modification of the British Standard method for the measurement of sound absorption coefficient (ISO) in a reverberation room. The modification was required due to the fact that measurement of the absorption of the cladding with a free field backing was desired. The method adopted differed from the BS method in that the sample was mounted in the wall of the reverberation room, as opposed to being placed within it and that the adjoining source room, which is normally also reverberant, was made absorbent in order to provide the free field backing. Consequently, the reference reverberation time of the empty room, required to calculate the absorption coefficient, had to be measured on a separate occasion, when the aperture was bricked up with a double wall.

3.3 Discussion of Measurement Results

The resultant sound reduction indices and absorption coefficients for the cladding samples are presented graphically in figures 2a and 2b. Each curve represents the typical trend in the sound reduction index and absorption coefficient exhibited by the cladding type. A comparison of the SRI and absorption plots yields an apparent inverse relationship between the two measures for each sample at low and mid-frequencies.

The weighted SRI values were found to be:

1) Singleskin = 22dB
2) Doubleskin = 38dB
3) Sandwich panel = 26dB
4) Roofdeck system = 30dB

The sound transmission loss of all the cladding samples exhibits a general increase with frequency. The increase is greatest for the doubleskin sample. Doubleskin claddings are generally the best acoustic insulators. It is not surprising to find that the singleskin sample is the poorest insulator. However, it should be noted that the sandwich panel, which is typical of the most recent designs in lightweight claddings, only performed about 5dB better.

With the exception of the roofdeck sample, which is heavily damped, distinct dips occur in each of the SRI curves. At low frequencies these dips are due to structural and skin or panel resonances. However, for all the samples the most prominent drop in SRI occurs in the mid-frequency range. It occurs around 1000Hz for the singleskin sample and around 1250Hz for the doubleskin sample. There is a less prominent second dip in the singleskin sample occurring approximately an octave higher at around 2000Hz. The reason for these dips at mid-frequencies is not yet fully understood, but they are obviously detrimental to the sound insulation of the cladding. Corrugated plates have two markedly different bending stiffnesses, which act in their main orthogonal directions, i.e. perpendicular and parallel to the corrugations. As a result of this, they are said to be orthotropic and have two coincidence frequencies. It is possible that these dips in SRI are related to the orthotropic bending properties of the corrugated skins. The occurrence of dips between 1000Hz and 2000Hz in the SRI of corrugated sheets has been observed by other workers, for example Cederfeldt [2]. In the case of the sandwich panel, which is not corrugated and has a homogeneous core, the dip in the SRI curve corresponds to a single coincidence around 2000Hz.

In contrast, the absorption curves exhibit strong peaks, particularly at low frequencies. These are due to the dissipation of energy by vibration of the claddings and mass-air-mass resonanaces. These peaks do not always occur around the same frequency for all the cladding types and so are probably dependent upon the physical properties of the cladding.

4. THEORETICAL INVESTIGATION

As claddings are produced in a wide range of configurations, the development of a reasonably accurate method for predicting the acoustic properties of different types of claddings, without the need for expensive testing, would be of valuable use to the manufacturer, designer and architect.

The platelike components of many industrial cladding structures are often not essentially isotropic in construction. As explained earlier, thin metal sheet claddings are either corrugated or made into sandwich constructions in order to increase their static stiffness. Plates that are corrugated do not have the same moment of inertia about their x and y axes and hence are said to be orthotropic. They exhibit two greatly different bending stiffnesses in their x and y directions (perpendicular and parallel to the corrugations) and plane wave motion in them is not governed by the simple flat plate bending-wave theory.

In exploring theoretical explanations for the acoustic behaviour of industrial claddings, measured values are being compared with theoretical results obtained using the theory of an infinite orthotropic plate.

4.1 Transmission of sound through an infinite orthotropic plate

The equation which describes the transverse motion of an orthotropic plate, as shown in figure 3a, subject to incident, reflected and transmitted plane waves of frequency ω is:

$$P_I = \frac{\mu}{2}\frac{\partial^2 w}{\partial t^2} + \frac{\omega\rho}{k\cos\theta}\frac{\partial w}{\partial t} + (1 + j\eta)\left[B_x \frac{\partial^4 w}{\partial x^4} + 2B_{xy}\frac{\partial^4 w}{\partial x^2 \partial y^2} + B_y \frac{\partial^4 w}{\partial y^4}\right] \quad (1)$$

where μ is the surface density, B_x and B_y are the maximum and minimum bending stiffnesses of the plate ($B_{xy} = \sqrt{B_x B_y}$), and η is the loss factor (the friction of energy dissipated per radian).

Solving this equation yields the following expression for the sound transmission coefficient:

$$\tau(\varphi,\theta) = \frac{1}{1 + \eta\left[\frac{\mu k\cos\theta}{2\rho} + Q(\varphi,\theta)\right]^2 + Q^2(\varphi,\theta)} \quad (2a)$$

where

$$Q(\varphi,\theta) = \frac{\mu k\cos\theta}{2\rho}\left[\frac{\omega^2}{\omega_c^2(\varphi)}\sin^4\theta - 1\right] \quad (2b)$$

and

$$\omega_c(\varphi) = \frac{\omega_x\omega_y}{(\omega_y\cos^2\varphi + \omega_x\sin^2\varphi)} \quad (2c)$$

An orthotropic plate does not have a single critical frequency. The critical frequency $f_c(\varphi)$ is dependent upon the azimuth angle and is a function of the minimum and maximum critical frequencies, f_1 and f_2, which are obtained from the maximum and minimum bending stiffnesses respectively:

$$f_1 = \frac{c^2}{2\pi}\sqrt{\frac{\mu}{B_x}}, \qquad f_2 = \frac{c^2}{2\pi}\sqrt{\frac{\mu}{B_y}} \quad (3)$$

The minimum bending stiffness of a corrugated plate is perpendicular to the corrugations and is a modification of that for an isotropic plate:

$$B_y = \frac{c}{s}\,\frac{Eh^3}{12(1-\sigma^2)} \quad (4)$$

where c is the cross-section of the profile and s is the distance over profile. E is Young's modulus, σ is Poisson's ratio and h is the plate thickness.

The maximum bending stiffness is parallel to the corrugations and is determined by:

$$B_x = E\,I_{xx} \qquad (5a)$$

where I_{xx} is the second moment of area of the profile of the plate. It is calculated with reference to figure 3b. as follows:

$$I_{xx} = \frac{1}{c} \sum_n n_a \left[b^2 + \frac{h^2 + a_n^2}{24} + \frac{h^2 - a_n^2}{24} \cos 2\theta_n\right] \qquad (5b)$$

However, if the plate is finite, supported at each end of its span L, the static bending stiffness is determined from:

$$B_x = \frac{384\,EI_{xx}}{5L^3} \qquad (6)$$

In general, corrugating the plate spreads the effect of coincidence on transmission over a wider frequency range, thereby lowering the average SRI.

The random incidence transmission coefficient of an infinite orthotropic plate is calculated by performing a double integration of the above expression for $\tau(\varphi,\theta)$ over φ and θ:

$$\tau = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} \int_0^{\frac{\pi}{2}} \tau(\varphi,\theta) \sin 2\theta \; d\theta d\varphi \qquad (7)$$

Heckl [3] produces the following expressions for the diffuse field transmission coefficient of an orthotropic plate by neglecting damping and approximating the double integral:

$$\tau = \begin{cases} \dfrac{\rho c}{\pi\omega\mu} \dfrac{f_1}{f} \left[\ln \left(\dfrac{4f}{f_1}\right)\right]^2, & f_1<f<f_2 \qquad (8a) \\[2ex] \dfrac{\pi\rho c}{\omega\mu} \dfrac{(f_1 f_2)^{1/2}}{f}, & f<f_2 \qquad (8b) \end{cases}$$

Expression (7) has been computed using numerical integration to give values of SRI for comparison with measured values. The SRI has also been calculated using Heckl's approximation. The predicted and measured values are shown in figure 4. The infinite orthotropic plate theory offers a reasonable prediction of SRI for the single skin cladding sample especially above 1250Hz. As frequency decreases, a finite plate effectively becomes more stiff than an infinite plate, which could be why the measured SRI of the finite plate is greater than the theoretical SRI of the infinite plate at lower frequencies. Heckl's approximation for the integral does not allow SRI to be predicted below the minimum critical frequency. However the theory of an infinite orthotropic plate does not account for the most prominent dips in SRI, especially at the mid-frequencies. These dips could be associated with the resonant frequencies of the finite orthotropic plate with supported edges. Expressions for such frequencies have been derived [4]. The mass law has also been plotted in figure 4 to show the effect orthotropicity has in lowering the overall SRI.

4.2 Absorption of sound by an orthotropic plate

By solving the equation of motion of a bending wave in an orthotropic plate (1), the impedance of the plate, which is the complex ratio of pressure to normal velocity at its surface, can be written as:

$$z(\varphi,\theta) = \eta A + j\left[\frac{\rho c}{\cos\theta} - A\right]$$

where

$$A = \frac{\omega^3 \sin^4\theta}{c^4}\left(B_x{}^{1/2}\cos^2\theta + B_y{}^{1/2}\sin^2\varphi\right)^2$$

The reflection coefficient can be derived from the surface impedance and in turn yields the plate wave absorption coefficient of the orthotropic plate, $\alpha(\varphi,\theta)$. For comparison with laboratory measured values of absorption coefficient, the random incidence absorption coefficient is obtained by integrating over φ and θ, as shown for τ in expression (7).

The predicted and measured values of absorption for a single skin cladding are shown in figure 5. The prediction gives good agreement with the general trend in the measured value of absorption coefficient, within the measurement error.

4.3 Further Theoretical Investigations

The theory described can be extended to double plate models [5] by the use of an 'impedance transfer' technique. Some sandwich panel claddings, such as the sample presented in this paper, do not exhibit greatly different bending stiffnesses in their x and y directions. In which case, the above 'orthotropic' theory approaches that for an isotropic panel, where the panel will have a single coincidence dip with a 6dB/oct slope below it and an 18dB/oct slope above it. So far the theory has only dealt with infinite plates. Finite element analysis can be used to analyse sound incident on a finite plate. In addition, FEA could be used to predict the resonant modes of the claddings [5]. It has already been used to find the lower resonant frequencies in single skin claddings [6].

5. CONCLUSIONS

All the measured values of sound reduction index and absorption coefficient of the industrial claddings have been stored in a data base and will be valuable for use with computer models which predict noise levels inside and around factory buildings.

In measuring the sound reduction index and the absorption coefficient of a selection of samples of industrial claddings, the following observations were made:

1) A consistent characteristic of the SRI of corrugated claddings, which are not heavily damped, is the marked attenuation which occurs at mid-frequencies.
2) The weighted SRI of the presently popular sandwich panel claddings is more than 10dB less than that of the older style doubleskin claddings.
3) An increase in the absorption of industrial claddings occurs at low frequencies, which is due to the dissipation of energy by vibration and mass-air-mass resonances.

An estimation of the SRI of orthotropic plates can be obtained with Heckl's approximation. However, it lacks the sophistication of the fully integrated infinite plate model, which predicts SRI with reasonable accuracy at mid and high frequencies. Clearly more work is required on the theory of finite orthotropic plates, if the acoustic behaviour of corrugated claddings is to be explained further.

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7. REFERENCES

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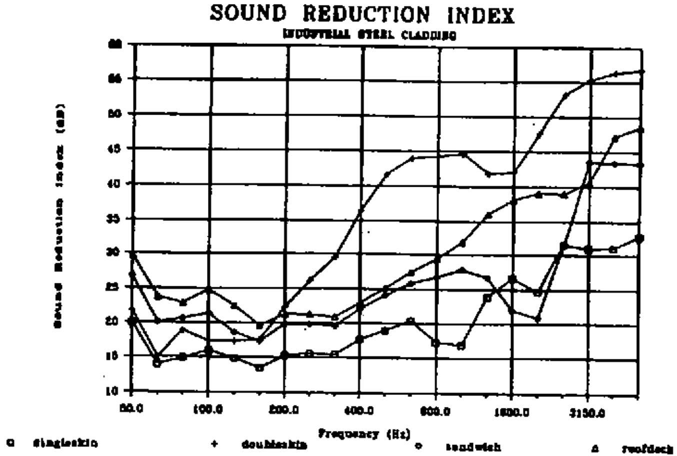

Fig 2a. Measured SRI of industrial cladding samples

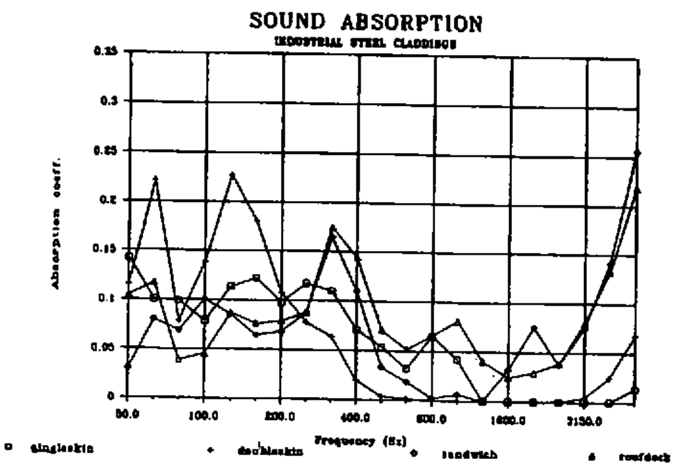

Fig 2b. Measured absorption coefficient of industrial cladding samples

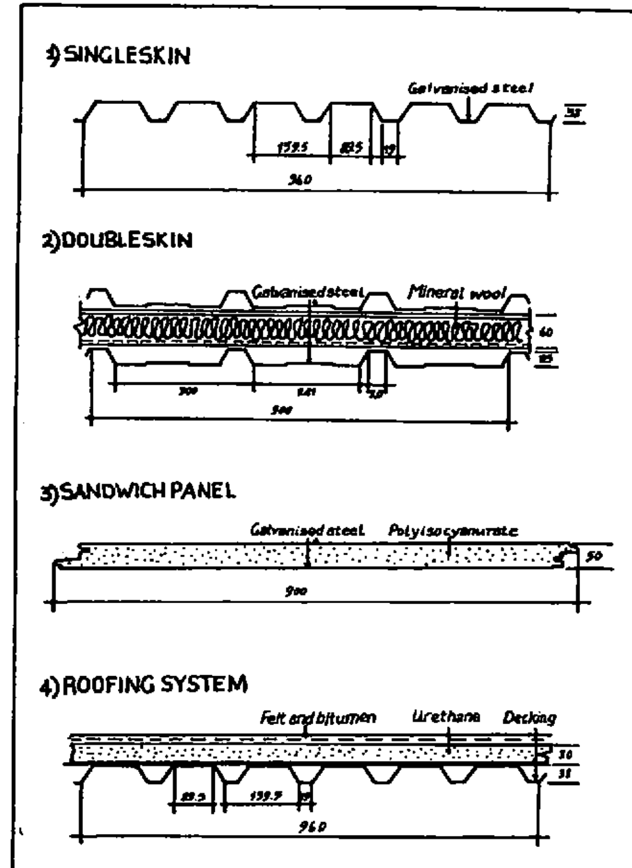

Fig 1. Cross-section of industrial cladding samples

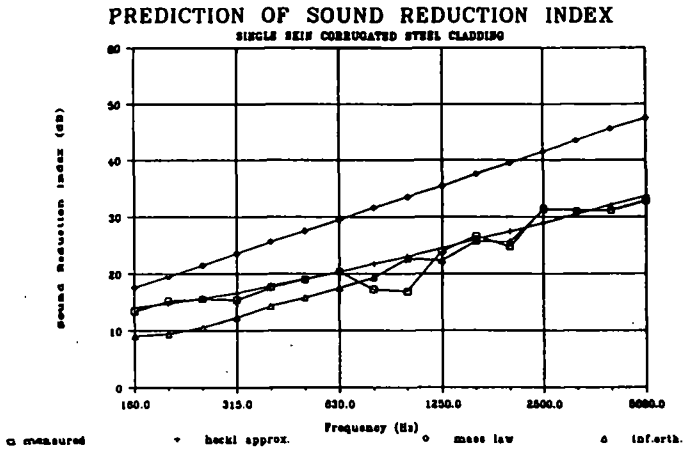

Fig 4. Predicted values of SRI of single skin cladding

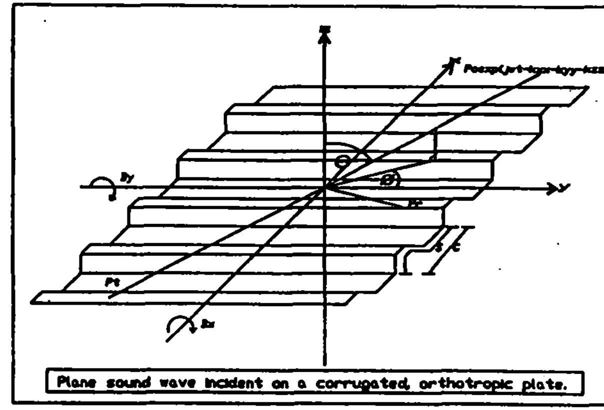

Fig 3a. Plane wave incident on a corrugated plate

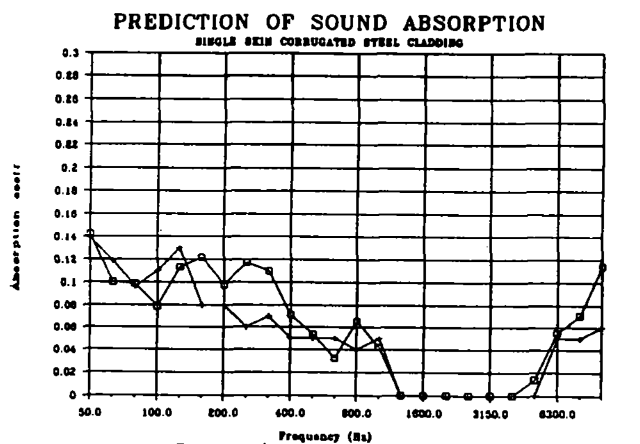

Fig 5. Predicted absorption coefficient of single skin cladding

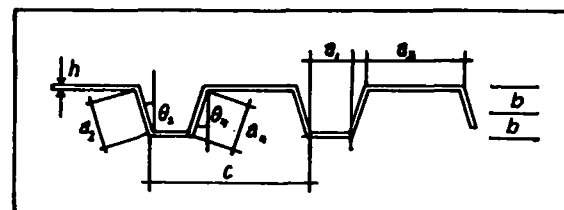

Fig 3b. Cross section of a corrugated plate