MEASUREMENTS OF SOUND ABSORPTION AND TRANSMISSION OF CORRUGATED STEEL PLATES

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1.0 Introduction

It has been well established that in order to use methods developed for accurately predicting noise levels experienced at positions both within and around factory buildings, the acoustic characteristics of typical industrial building materials are required (1,2).

In order to predict the propagation of sound within industrial buildings, it is necessary to determine accurate values for the internal surface absorption of the enclosure. With regard to the sound radiation from industrial buildings, the sound reduction index of the building's material is needed to predict the external noise level (3).

Lightweight claddings often form an integral part of industrial structures and a wide selection is produced in both profiled sheet and composite panel form. Their extensive use for industrial buildings presents the need to measure the absorption and transmission loss of cladding structures and to investigate possible methods for predicting these charadteristics.

2.0 Sheet metal and Composite Claddings Panels

There is a wide range of claddings from which industrial buildings can be constructed.

Sheet claddings range from simple single skin corrugated metal (galvanized steel or aluminium) sheets to complex double skin insulation and roofing systems, constructed from the single corrugated skins. Corrugation of the cladding imparts stiffness and hence strength to the relatively thin gauge and otherwise flexible metal sheets. Cladding thicknesses vary from 0.5 to 1.0mm. 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. The range of profile shapes available is large, with profile depths varying from 15 to 65mm.

In addition to these corrugated sheet claddings, there are composite sandwich panel claddings, constructed from metal sheets with a polyurethane foam core. These panels are generally profiled, but to a lesser degree than sheet claddings as a greater degree of stiffness is provided by the core material. The thickness of these panels ranges from 30 to 60mm.

All claddings require a support system, which usually takes the form of a steel beam structure. These steel beams are referred to as purlins. The purlins' thickness and span depends on the specified windload of the building and the type of cladding being used. Claddings are secured direct to the structural frame by means of self-drilling or self-tapping screws known generally as the primary fixings. The cladding side laps are secured with pop rivets or self-drilling/tapping stitching screws which are referred to as secondary fixings.

3.0 Methods of measuring acoustic characteristics of claddings

The methods for measuring the random-incidence absorption coefficient and sound reduction index of lightweight cladding samples complement one another and hence are carried out simultaneously in the transmission suite of the acoustic testing laboratories at Salford University.

3.1 Mounting of Samples

The cladding samples are mounted in an aperture between the two rooms of the test suite using the same structural support and fixings as typifies its use in an industrial construction. An acoustic acrylic sealant is used to seal the perimeter of the cladding sample. The seal prevents sound leakage at the edges of the sample while nominally allowing rotation at the cladding boundary, without movement in the x, y or z direction.

3.2 Reverberation room method for measuring diffuse field absorption

The method used complies with the British Standard method for the measurement of sound absorption coefficients in a reverberation room (BS3638:1987), except that the sample is mounted in the wall of the reverberation chamber as opposed to being placed within it.

In order to simulate the acoustic conditions generally found outside industrial buildings, the sound field on the outer facade of the cladding has to be non-reverberant. Therefore, the random incidence absorption coefficient of the cladding sample is measured with it mounted in the wall of the receiving room of the transmission suite (considered the reverberation chamber) with the interior surfaces of source room made absorbent in order to provide a free-field backing.

A real time analyser (RTA) is used to measure the absorption of the sample. Controlled by a PC microcomputer, the RTA measures the reverberant decay in the receiving room at ten microphone positions in third octave bands from 50Hz to 5kHz. The RTA and

PC software then calculate and tabulate the random incidence absorption. The empty room value is provided by reverberation time measurements made in the receiving room with the test aperture bricked and insulated. The measurement is repeated three times for each sample.

3.3 Measurement of SRI.

This method is undertaken in accordance with British Standard method of laboratory measurements of airborne sound insulation of building elements (BS2750:part3:1980).

A dual channel RTA is used to carry out the conventional two room method for measuring the sound reduction index. Controlled by a PC microcomputer, the RTA measures the average sound level in both the source and receiving room at ten microphone positions and the spatial-averaged reverberation time of the receiving room. The measurements are made in third-octave frequency bands from 50Hz to 5kHz. The SRI is then computed in accordance with BS2750 by the PC software. The measurement is repeated three times for each sample.

4.0 Measurements, Results and Features

Measurements of absorption and SRI were first made on one of the most common and simple types of cladding; single skin steel profiled sheet cladding, referred to as type E1. This sample was also used to investigate the effects of altering the mounting condition of samples.

4.1 The cladding sample, E1

The cladding sample consisted of four plastic-coated trapezoidal-profiled steel sheets mounted on the basic support structure described in 4.2. The profile and the technical data of the cladding sheets are shown in figure 1a. The measured absorption and SRI of the sample as function of frequency are shown as solid curves in figures 3a and 3b respectively.

As observed in measurements carried out previously, the absorption curve exhibits several strong peaks, particularly at low frequencies. These are due to the dissipation of energy by the vibration of the cladding sheets and tend to correspond to dips in the SRI curve.

Comparison of the measured absorption and SRI yields an apparent inverse relationship, which is particularly evident in the mid-frequency range.

The sound transmission loss of the sample exhibits a general increase with frequency, but with several distinct dips in the

SRI curve. At low frequencies these are due to plate and structural resonances. However, the most prominent drop in SRI is at around 1-1.25 kHz. This drop does not seem to be dependent upon the coincidence frequency (see 5.1), but may be due to resonances in the airspace formed by the corrugations and may therefore be related to the profile shape. The relationship is being investigated by carrying out more measurements on cladding sheets with different profiles.

The noise reduction coefficient of the sample was found to be 0.12 and the weighted sound reduction index, R_w, 22dB.

4.2 Variation in Mounting

A typical structure for mounting the cladding sample is achieved by horizontally bolting lightgauge steel purlins to wall brackets mounted within the aperture. The cladding sheets are fixed to the purlins with self-drilling screws and connected to one another along their seam overlap by pop-rivets.

The support structure adopted as standard for mounting the test samples consists of two ZETA purlins type 15018, illustrated in figure 1b, spaced 2m apart with the cladding fastened to the purlins at every other trough. This structure formed a basic mounting configuration which permitted the following variations to be investigated:

* Thickness of purlins (18mm,15mm).
* Number of purlins(2,3).
* Frequency of primary fixings (alternate/every trough).
* Use of secondary fixings on sheet overlap seams.
* Use of acrylic sealant on sheet overlap seams.
* Consistency of mounting.
* Consistency of sample.

Figures 3a and 3b show some of the effects of the above on the measured absorption and SRI of the sample. The curves show that both the absorption and the SRI are sensitive to changes in the mounting configuration, particularly at the upper and lower ends of the frequency range. In general, the absorption appears to be more sensitive to mounting variation than the transmission loss.

The addition of a third purlin appears to broaden the peak in absorption and increase the SRI at 100Hz and significantly reduce absorption at high frequencies. The effect of neglecting to fasten the side overlaps of the sheets with pop-rivets at intervals along the seam is to significantly increase SRI and reduce absorption at high frequencies. This is due to acoustic leakage at the seams when sheets are not forced to move coincidently. Interestingly, additional binding of the seams with sealant had little effect on the measurements, the pop-rivets are sufficient to ensure mutual vibration of neighbouring sheets. Repeating the measurement with a new sample showed a marked change in the absorption curve at low frequencies, but only a slight drop in SRI at high frequencies.

5.0 Theoretical analysis of acoustic characteristics of corrugated single skin claddings

The measurements of the samples are being compared with the following theories of plate behaviour in order to evaluate methods for predicting their acoustic characteristics.

5.1 Prediction of SRI of orthotropic plates

Platelike components of many practical structures are often neither homogeneous nor isotropic. As explained earlier, thin metal sheet claddings are corrugated or made into sandwich constructions in order to increase their static stiffness. Corrugated plates 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.

Analysis by Heckl of sound transmission through orthotropic plates (4) produced the following expressions for the diffuse field transmission coefficient:

$$\tau_d = \begin{cases} \dfrac{\rho_o c}{\pi \omega M_s} \cdot \dfrac{f_{c1}}{f} \cdot \left[\mathrm{Ln}\left(\dfrac{4f}{f_{c1}}\right)\right]^2 , & f_{c1} < f < f_{c2} \\[2ex] \dfrac{\pi \rho_o c}{\omega M_s} \cdot \dfrac{(f_{c1} f_{c2})^{1/2}}{f} , & f > f_{c2} \end{cases}$$

where M_s is the surface density and f_{c1} and f_{c2} are the critical frequencies based upon the maximum and minimum bending stiffness of the plate. Critical frequency is obtained from the bending stiffness as follows:

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{M_s}{B}}$$

The bending stiffness parallel to the corrugations of an infinite, unmounted orthotropic plate is a modification of that for an isotropic plate:

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

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. For the sample E1, this gave a maximum critical frequency of 22.698kHz.

The bending stiffness perpendicular to the corrugations is determined by:

$$B_x = E.I_{xx}$$

where I_{xx} is the second moment of area of the profile of the plate. For the sample E1, this gives a minimum critical frequency of 295Hz.

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

$$B_x = \frac{384EI_{xx}}{5L^3}$$

This equation gives a minimum critical frequency of 95Hz.

When the corrugated plate is mounted on purlins with overlaps, these simple equations do not suffice and the bending stiffness must be calculated from the predicted deflection of the complete structure. In this case, the lower critical frequencies for the sample E1 mounted on both two 15018 purlins and three 15015 purlins are found to be 84Hz and 80Hz respectively.

In assuming orthotropic bending, the critical frequency for bending waves travelling in the direction parallel to the corrugations is increased from that of a flat plate of the same thickness. The critical frequency for bending waves travelling in the direction perpendicular to the corrugations is greatly decreased. Thus the effect of corrugating is found to generally spread the effect of coincidence on transmission over a wider frequency range, lowering the average SRI. The effect of mounting an orthotropic plate on a support system is to increase the bending stiffness and reduce the minimum bending stiffness.

The SRI of the cladding sample E1 mounted on both two and three purlins was predicted using Heckl's expression for the diffuse field transmission coefficient of orthotropic plates and the values of maximum and minimum critical frequencies calculated above. The predicted and measured values of SRI of the sample mounted on two purlins compare favourably, as shown in figure 4. However, this Heckl's theory does not predict the drops in transmission loss due to plate resonances.

5.2 Prediction of random incidence absorption of orthotropic plates

For any point on the plate shown in figure 2, the equation of motion is:

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$$\frac{M_s\ddot{W}}{2} + \frac{j\omega\rho_o\dot{W}}{k_z} + \frac{(1+jn)}{2}\left(B_x\nabla_x^4 W + (B_x^{1/2}B_y^{1/2})^2\,\nabla_x^2 W\nabla_y^2 W + B_y\nabla_y^4 W\right)$$
$$= P_i \exp j(wt - k_x x - k_y y - k_z z)$$

where n is the loss factor (the fraction of energy dissipated per radian). By solving the equation of motion, the impedance of the plate, which is the complex ratio of pressure to normal velocity at its surface, can be written as:

$$Z(\theta,\phi) = nA + j\left(\frac{M_s\omega}{2} + \frac{\rho_o c}{\cos\theta} - A\right)$$

where $$A = \frac{\omega^3\sin^4\theta}{2c^4}\,.\,(B_x^{1/2}\cos^2\phi + B_y^{1/2}\sin^2\phi)^2$$

The reflection coefficient can be derived from the surface impedance and in turn yields the plane wave absorption coefficient of the orthotropic plate, $\alpha(\theta,\phi)$. For comparison with laboratory measured values of absorption a diffuse field value is obtained by use of Paris' formula:

$$\alpha_{diff} = 2\int_0^{2\pi}\int_0^{\frac{\pi}{2}}\alpha(\theta,\phi)\cos\theta\sin\theta\, d\theta d\phi$$

A computer program is being written to perform this prediction. The loss factor of steel structures is very sensitive to construction techniques and edge conditions, therefore it is measured for each sample construction. This can be done by exciting the cladding impulsively by mechanical impacts and using an accelerometer attached to the cladding to measure the vibration decay as a function of frequency (5).

$$n = \frac{2.2}{fT_{60}}$$

This measurement is being undertaken for each cladding sample mounted in the test aperture, so that the theory can be compared with the measurements of absorption.

The theory described can be extended to double plate models (6) by the use of an 'impedance transfer' technique.

5.3 Modal Analysis

Finite element analysis can be used to predict the resonant modes of corrugated plates (7). Using a finite element analysis software package, modal analysis of the cladding sample E1, mounted on both two and three purlins was obtained. The predicted modal behaviour can seen in figures 5a and 5b. The analysis shows some correlation with the values of absorption and SRI measured, encouraging further investigation into the modal behaviour of corrugated cladding panels.

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6.0 Conclusions

A programme of measurements of sound absorption and transmission of lightweight claddings has now been instigated at Salford University. Measurements are still being made on single skin claddings of varying profile and thickness. Measurements on samples of double skin insulation systems, special roofing systems and composite panels will begin later in the year. All the results will be included in a data base, which will be valuable for use with computer models which predict noise levels inside and around factory buildings.

The theories for predicting these characteristics show an encouraging correspondance to the measurements carried out. Study and development of the plate theories will continue and measurements of the claddings with the purlin support structure removed (leaving just the seal as a boundary support) will be made for comparison with these theories.

7.0 Acknowledgements

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8.0 References

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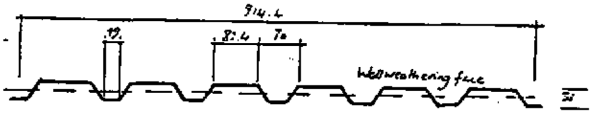


E1 Cladding profile Section properties (Steel):

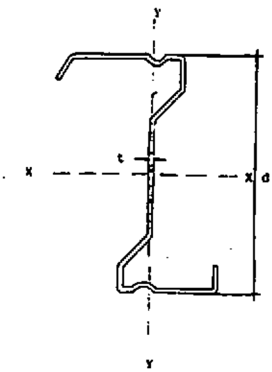
Nominal thickness, t = 9.7 mm

Surface density, M_s = 7.35 Kgm^{-2}

Moment of Resistance, R_{xx} = 0.878 KNm/m

Moment of Interia, I_{xx} = 14.608 Cm^4/m

Figure 1a. Profile of cladding sample E1.



Zeta Purlin Section Properties :

		15018	15015
Depth, d	=	150 mm	150 mm
Thickness, t	=	1.8 mm	1.5 mm
Moment of Interia, I_{xx}	=	103.8 cm^4/m	169.8 cm^4/m
Moment of Interia, I_{yy}	=	31.0 cm^4/m	[illegible] cm^4/m

Figure 1b. Cross-section of zeta purlin.

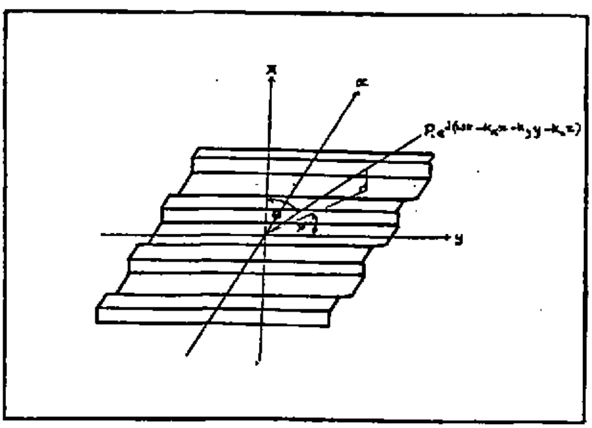


Figure 2. Plane wave incident on a corrugated plate.

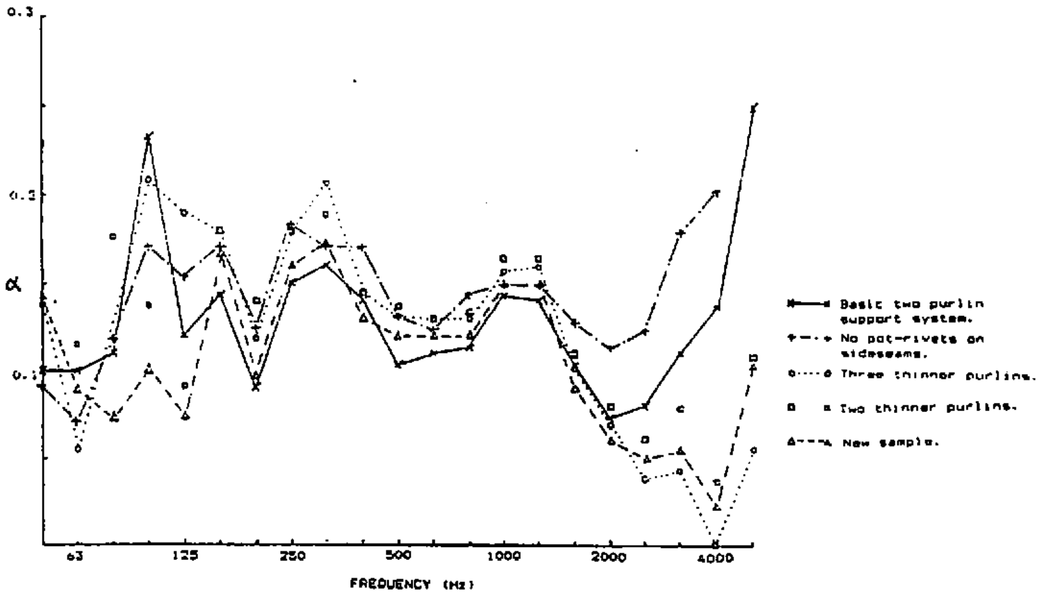


Figure 3a. Measured absorption coefficient of single skin profiled steel cladding E1.

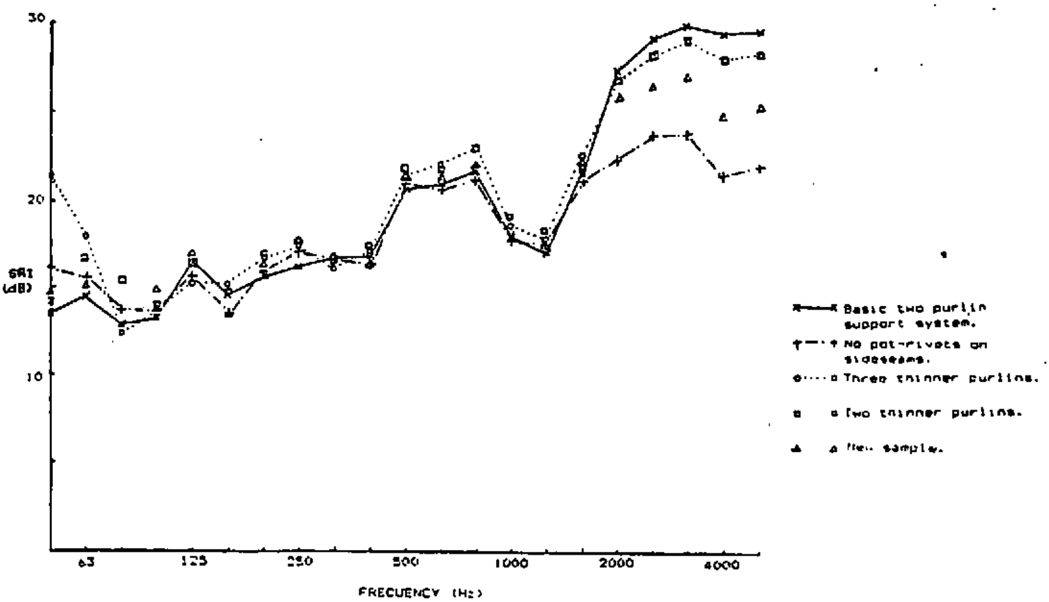


Figure 3b. Measured sound reduction index of single skin profiled steel cladding E1.

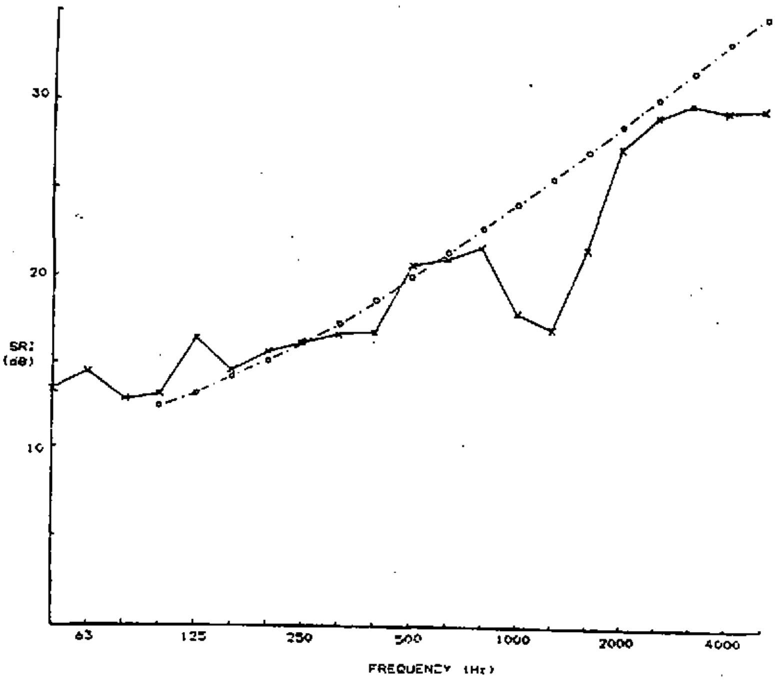


Figure 4. Measured and predicted value of sound reduction index of cladding E1.

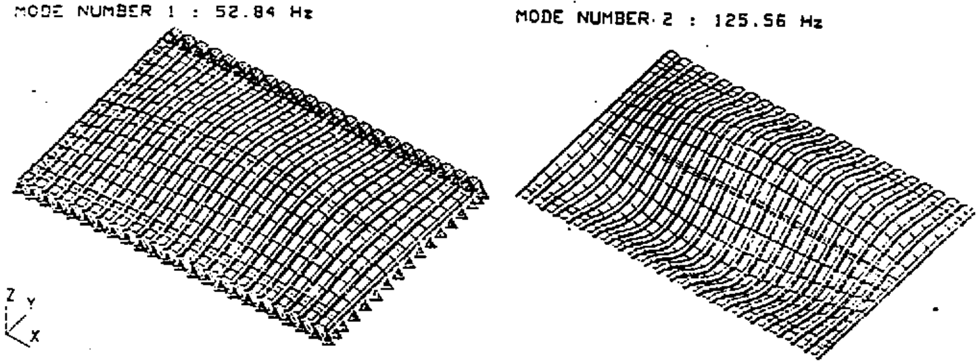


Figure 5a. Modal resonances of cladding E1 mounted on three purlins.

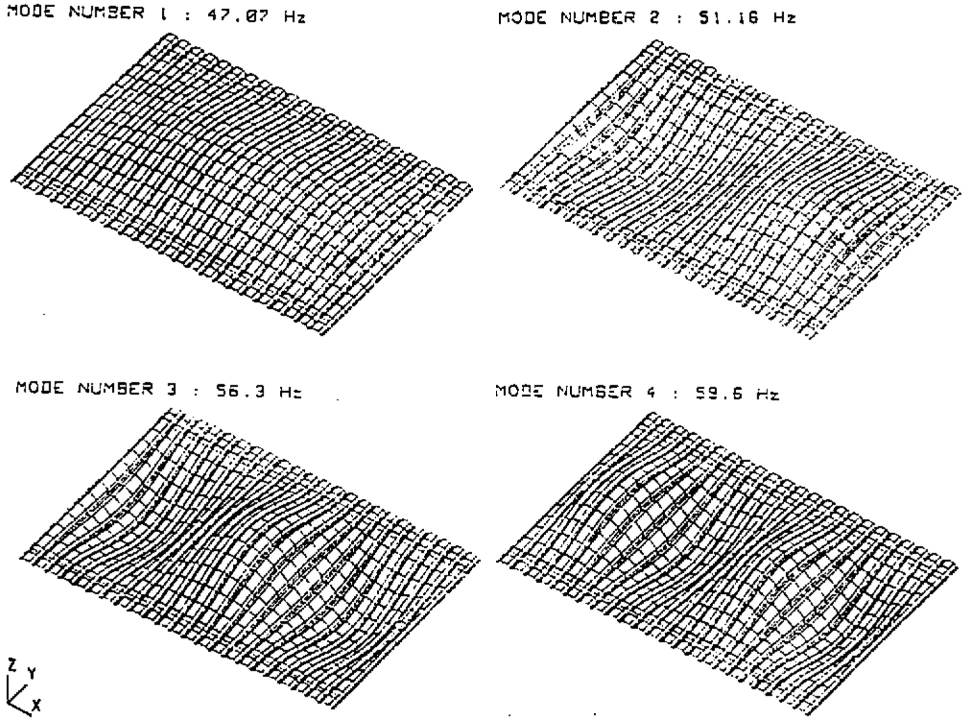


Figure 5b. Modal resonances of cladding E1 mounted on two purlins.