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A Study of Techniques to Increase the Sound Insulation of Building Elements

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16. Abstract

The principles and techniques that pertain to the design of building elements providing high values of sound transmission loss at low cost are presented. A comprehensive discussion of the principles of transmission loss for many different types of constructions is given and a series of analytical expressions derived. The techniques developed for obtaining high values of transmission loss are validated by means of a series of laboratory tests conducted on experimental and practical prototype constructions. The cost/effectiveness of the practical constructions is compared to that for existing constructions in common use today. It is shown that the transmission loss of single panels and multiple panels with sound bridges can be determined accurately by means of a set of simple expressions. These expressions can be applied directly to the optimum design of building elements providing high values of transmission loss. From the standpoint of acoustical performance, cost and total mass, the practical prototype constructions developed are superior to constructions that are in common use today.

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PREFACE

A program of the size and level of effort presented herein would have been impossible without significant contributions by many individuals. Of all those who participated in the project, however, the author wishes to give special acknowledgment to the contributions made by the late Mr. Robert Miller of HUD who not only overviewed the program but of more significance, set the goal which provided the impetus for its successful completion. Special thanks also to Mr. Maury Erkilla of HUD for his direction and patience in seeing the project through to its completion.

Sincere appreciation is also due Professor Lothar Cremer of the Technical University of Berlin, who provided invaluable assistance at the onset of the program in discussions on his most recent work and that of his colleagues.

Various members of the Research Staff at Wyle Laboratories provided much of the support in the program. In particular the author wishes to express his gratitude to Kenneth M. Eldred for his guidance and aid in overcoming seemingly difficult problems. Other members of the Wyle Research Staff who provided significant contributions include John W. Swing for his long and arduous work in managing the test program, Fancher M. Murray for his work on exterior structures, and Louis C. Sutherland, Manager of the Research Staff, for his continual guidance and enthusiasm.

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1.0 INTRODUCTORY SUMMARY

In recent years, significant advances have been made in building technology – both in the design of building components and in building methods themselves. The Department of Housing and Urban Development (HUD) has attempted to coordinate some of these technological advances in a major demonstration program – OPERATION BREAKTHROUGH – which at the time of this writing is still in progress. It is important, of course, that the technology in each of the many facets of the building process advance at approximately the same rate, so that the structural and environmental characteristics of a building system are compatible within themselves. One of the many environmental characteristics that must be considered is the sound insulation provided by the various building elements. This aspect of the building system is rapidly assuming a greater importance as people become more sensitive to the effects of noise impact and learn that certain steps can be taken to avoid it. Unfortunately, for the past several years there have been few significant advances in the theory and practice of sound insulation, with the result that designs appearing in modern acoustical handbooks differ little from those of two decades ago.

HUD has responded to the need for additional research and development by instigating this program which is designed to study techniques of increasing the sound insulation of building elements and lower the cost. Included in the program is a design goal requiring that the values of transmission loss for the constructions developed should exceed the values calculated according to the mass law by at least 20 dB in the frequency range 125 Hz to 4000 Hz. This unusual but intriguing goal was introduced into the program by the late Mr. Robert Miller of HUD, who by so doing provided the necessary challenge which was required to develop new design methods. Even with the knowledge gained from this program, it is hard in retrospect to define an alternative goal that would have inspired the same level of effort and still be within the bounds of possibility.

A cursory examination of existing common constructions showed that none satisfied or even approached the requirements for the acoustical goal of this program. The transmission loss of some constructions approaches a value that is 20 dB greater than the mass law at a few frequencies. To achieve the goal over the full frequency range, however, the new constructions required an order of magnitude increase in the transmission loss values. Moreover, it was required that low-cost materials be used in the designs.

The theory available at the time predicted that the majority of existing constructions were capable of providing significantly greater values of transmission loss than those measured in the laboratory. It was therefore necessary to examine and modify the basic theories so that more accurate prediction methods could be developed. Chapter 2 of this report contains a comprehensive discussion of the principles of sound transmission loss for many different types of constructions. The discussion covers the development of methods which make significant increases in the transmission loss of simple and complex structures possible. For convenience, this chapter concludes with a summary of the more important expressions developed, together with a description of methods by which constructions can be designed to meet specific acoustical requirements.

To test the validity of the new expressions, a series of experimental prototypes, and later a series of practical prototype constructions, were designed, built and tested. These prototypes cover all the different types of building elements. A discussion of the application of the design requirements, the practical constraints involved and the prototype test results are contained in Chapter 3. It is shown that the "20 dB requirement," as the acoustical requirement will be referred to, can be satisfied — but not always in a manner that results in a practical construction suited for wide use. However, the methods that had to be developed to achieve the goal were successfully applied to obtain subtantial increases in the transmission loss of more useful constructions.

To complete the study of noise reduction in buildings, a measurement program was conducted to determine the feasibility of using outdoor barriers to reduce noise levels both inside and outside buildings. Methods were examined for reducing the noise levels in the immediate vicinity of a dwelling by the introduction of various types of barriers. The effect of acoustic shielding by buildings is also discussed.

The principle conclusions from this study can be summarized as follows:

- The transmission loss characteristics of practical constructions can be determined to a high degree of accuracy by means of a set of simple expressions.

- The design expressions can be applied directly to the optimum design of building elements providing high values of transmission loss.

- With careful design, the 20 dB requirement can be achieved in a practical multiple panel construction; however, this is at the expense of high mass or great thickness. Consequently, constructions meeting the requirement are limited in use to high noise level areas.

- From the standpoint of transmission loss performance, cost and total mass, the practical prototype constructions developed in this program are superior to constructions that are in common use today.

2.0 PRINCIPLES OF SOUND TRANSMISSION LOSS

2.1 SINGLE PANEL STRUCTURES

The requirements of this program necessitate an unrestricted approach to the theory of sound transmission through panels in order to determine the principles from which building constructions exhibiting high values of transmission loss can be designed for high efficiency and low cost. Accordingly, a review of the basic theory for a general type of construction is in order and is presented in this section. Initially, the purpose of the discussion is to examine the process by which sound energy is transmitted from one area to another through a general type of intervening structure. Later sections deal with specific types of construction and their optimization.

2.1.1 Fundamental Concepts

In the general context, it is convenient to imagine a panel of infinite lateral dimensions situated in free space and subjected to acoustic radiation in the form of a plane wave produced by some undefined source. If the panel is perfectly rigid, the acoustic excitation produces no vibration, and all the incident energy is reflected in the form of a plane wave. A real panel, however, is never rigid; hence a portion of the incident energy is transferred to it, causing it to vibrate at a frequency identical to that of the excitation. The remainder of the energy is reflected as before. Since an airborne sound wave excites vibrations in such a panel, reasoning based on the reciprocity principle indicates that a vibrating panel will excite an airborne sound wave. As a result, a sound field will be established on the far side of the panel from the source. The intensity of this sound field will be less than that of the sound field incident on the panel by virtue of the energy reflected and dissipated. This is the basic mechanism by which sound energy is transmitted by all types of constructions. It is important to note that the energy is transmitted by the panel only because it is excited into vibration.

Qualitatively, the process of sound transmission through a panel is fairly straightforward. To calculate the transmission loss of a particular practical construction, however, requires much more information on the makeup of the construction together with a detailed understanding of its acoustical and mechanical properties. Just how the estimates of transmission loss are obtained for various construction configurations is described in the following sections.

2.1.2 Fundamental Expressions

Some aspects in the calculation of the transmission loss provided by a structure are readily analyzed in terms of a single general function that represents the physical properties of the structure. A convenient function to use in this context is "impedance," a term originating in electrical network theory. In the present case, it is the mechanical impedance of the structure that is required, relating the applied force (or pressure) to the resultant velocity. In these terms, the impedance of a structure is defined as the ratio of the sound pressure differential existing between the two faces of the structure to its normal velocity. This definition is completely analogous to that for the electrical impedance of a system, namely, the ratio of voltage differential to current, which sometimes makes it possible to simplify the solution of acoustical problems by forming what is known as an equivalent electrical circuit.

Using the concept of impedance, it can be shown either by classical methods (Reference 1) or by use of the equivalent electrical circuit (Reference 2) that for a plane wave incident at an angle θ to the normal of a structure of specific normal impedance Z, the ratio of sound power transmitted (W_t) to that incident (W_i) is given by the expression:

$$\frac{W_t}{W_i} = \left| 1 + \frac{Z \cos\theta}{2\rho c} \right|^{-2} \qquad (1)$$

where Z may be a complex quantity and ρc is the characteristic impedance of air. This ratio is sometimes called the "transmission coefficient" and given the symbol τ. Since τ is always less than unity, it is convenient to define the transmission loss provided by the panel in terms of its reciprocal. Furthermore, it is conventional to use a logarithmic scale. In this way, the sound transmission loss (TL) of the panel is defined as:

$$TL = 10 \log (\tau^{-1}) \qquad (2)$$

For a plane wave incident at an angle θ, the transmission loss is given by:

$$TL_\theta = 20 \log \left| 1 + \frac{Z \cos\theta}{2\rho c} \right| \qquad (3)$$

If the sound is incident normally to the panel, the transmission loss TL_o is given by:

$$TL_o = 20 \log \left| 1 + \frac{Z}{2\rho c} \right| \qquad (3a)$$

The general expression given in Equation (3) is sufficient to calculate the transmission loss of any structure with an overall specific normal impedance Z. The next step is to determine the impedance Z for various types of structures.

2.1.3 Thin Single Panels

The simplest type of structure to consider is the single panel whose thickness is small compared to the wavelength of the associated airborne and structure-borne waves. To determine the impedance of such a panel, it is necessary to obtain a relationship between the sound pressure acting on the panel and the resultant velocity. If it is assumed for the moment that the panel is of infinite lateral extent, this relationship can be obtained directly from the general wave equation for bending waves in a plate. In the present context, the term "infinite in lateral extent" means infinite compared to a wavelength, so that this condition is effectively satisfied in panels of finite dimensions at the higher frequencies but not necessarily at the lower frequencies.

The analytical procedure necessary to obtain an expression for the impedance of a thin panel is contained in Appendix A. Equation (A-8) of that Appendix gives the expression for the panel impedance as:

$$Z = j\omega m - j \frac{\omega^3 B}{c^4} \sin^4 \theta \qquad (4)$$

where

ω = angular frequency = $2\pi f$

m = mass of the panel per unit area

B = bending stiffness of the panel

c = velocity of sound in air

θ = angle of incidence of the incident plane sound wave

$j = \sqrt{-1}$

and a time dependence of $e^{j\omega t}$ is assumed.

The impedance Z is composed of two imaginary terms which, due to their signs, can be considered to represent the inertia, or mass, and bending stiffness of the simple panel. Equation (4) shows that the impedance of the panel is determined primarily by the mass at low frequencies, whereas at high frequencies it is the bending stiffness term that predominates. At some intermediate frequency, known as the coincidence frequency, the two terms are equal in magnitude, and, since they have opposite signs, the impedance is zero. This condition is illustrated in Figure 1.

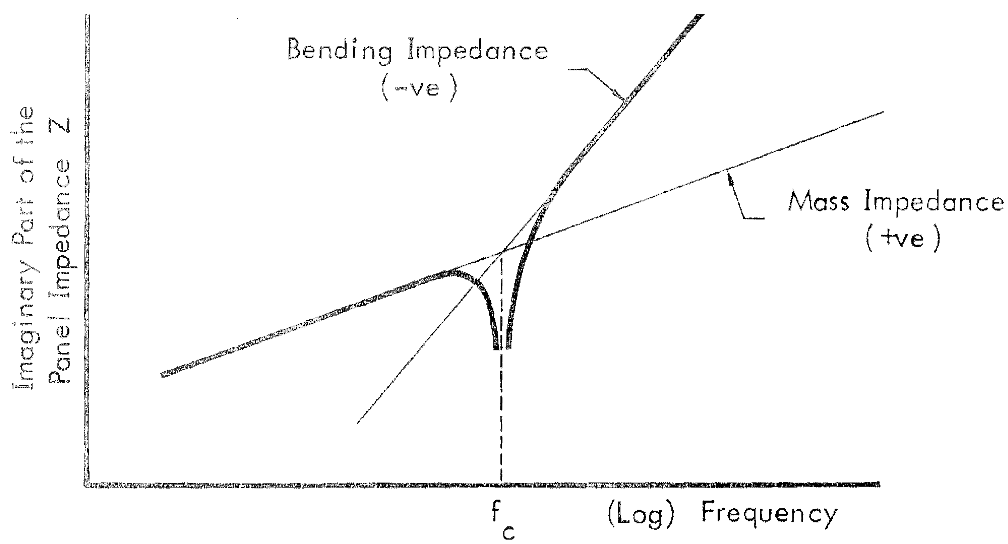


Figure 1. The Imaginary Part of the Transmission Impedance of a Thin Panel for Grazing Incidence ($\theta = \pi/2$) Showing the Effect of Coincidence

Cremer was the first to study this so-called coincidence effect (Reference 1) and show that the cancellation of terms occurs at a frequency given approximately by:

$$f \approx \frac{c^2}{2\pi h \sin^2 \theta} \left(\frac{12\rho_m}{E} \right)^{1/2}$$

where

h = the thickness of the panel

ρ_m = the density of the material

E = Young's Modulus of the panel material

Qualitatively, the coincidence effect can be understood when it is realized that the simple theory for determining the impedance is based on the assumption that pure bending waves are excited in the panel. Unlike compressional sound waves in air, which have a propagation velocity that is independent of frequency, the velocity of bending waves increases with increasing frequency. As a result, there is a frequency – the coincidence frequency – at which the trace velocity of sound waves in air is equal to the velocity of bending waves in the panel. At this frequency, energy is transferred easily from the airborne sound wave to the panel, resulting in a low transmission loss of the panel.

The frequency at which coincidence occurs depends on the angle of incidence of the sound waves; therefore, the panel impedance is zero at a different frequency for every angle of incidence. The lowest frequency at which the effect can occur corresponds to sound waves incident at grazing angle to the panel. This frequency is termed the "critical frequency" f_c and its value is given by the expression:

$$f_c = \frac{c^2}{2\pi h} \left(\frac{12\rho_m}{E} \right)^{1/2} \tag{5}$$

The value of the critical frequency increases with increasing material density and decreases with increasing panel thickness and material stiffness.

To calculate the transmission loss of a single thin panel, it is necessary to insert Equation (4) into (3). By itself this is not sufficient because in the standard test method for the measurement of transmission loss (Reference 3), it is assumed that all angles of incidence are equally probable, whereas Equation (3) gives the transmission loss for one angle only. Under diffuse sound field conditions, it would seem natural to average the transmission coefficient τ_θ over the range 0 to $\pi/2$. Unfortunately, this does not produce values that agree with those measured in the laboratory under supposedly the same conditions. The reasons for the discrepancy are to be found in the assumptions made with regard to the characteristics of the sound fields on both sides of the panel, and the coupling between these fields and the finite sized panel. A detailed discussion of the discrepancy, its causes and previous attempts made to obtain alternative solutions, is contained in Appendix B. At this point, it is sufficient to state that at frequencies less than the critical frequency, the transmission loss TL_m of a single thin panel is given by the expression: (Reference 4)

$$TL_m \approx 20 \log \left(1 + \frac{\omega m}{3.6 \rho c}\right) \approx 20 \log (m f) - 33.5 \text{ dB} \qquad (6)$$

provided that $\omega m >> 3.6 \rho c$. This is the familiar mass law, with the transmission loss increasing at the rate of 6 dB for a doubling of either the mass or the frequency. Equation (6) can also be rewritten in terms of the transmission loss TL_o for sound waves incident normally to the panel:

$$TL_m = TL_o - 5 \text{ dB} \qquad (6a)$$

where

$$TL_o \approx 20 \log \left(\frac{\omega m}{2 \rho c}\right)$$

The transmission loss predicted in this manner agrees well with measured values of the transmission loss of single panels at frequencies less than one-third of the critical frequency. An example of the agreement is shown in Figure 2 for a panel of 1/8-inch hardboard.

In considering finite sized panels, it is necessary to include an additional term in the expression for the impedance to account for the stiffness of the panel. This stiffness term Z_s is important only at low frequencies and for sound waves at normal incidence is given approximately by the expression:

$$Z_s = -j \frac{K}{\omega}$$

where

$$K = \pi^4 B \cdot \left[\frac{1}{a^2} + \frac{1}{b^2}\right]^2 \qquad \text{(Reference 5)}$$

and a, b = dimensions of the panel.

Examination of Equation (4) with this addition shows that the panel exhibits a resonance at a frequency f_r given by:

$$f_r = \frac{\pi}{2} \sqrt{\frac{B}{m}} \left[\frac{1}{a^2} + \frac{1}{b^2}\right] \tag{7}$$

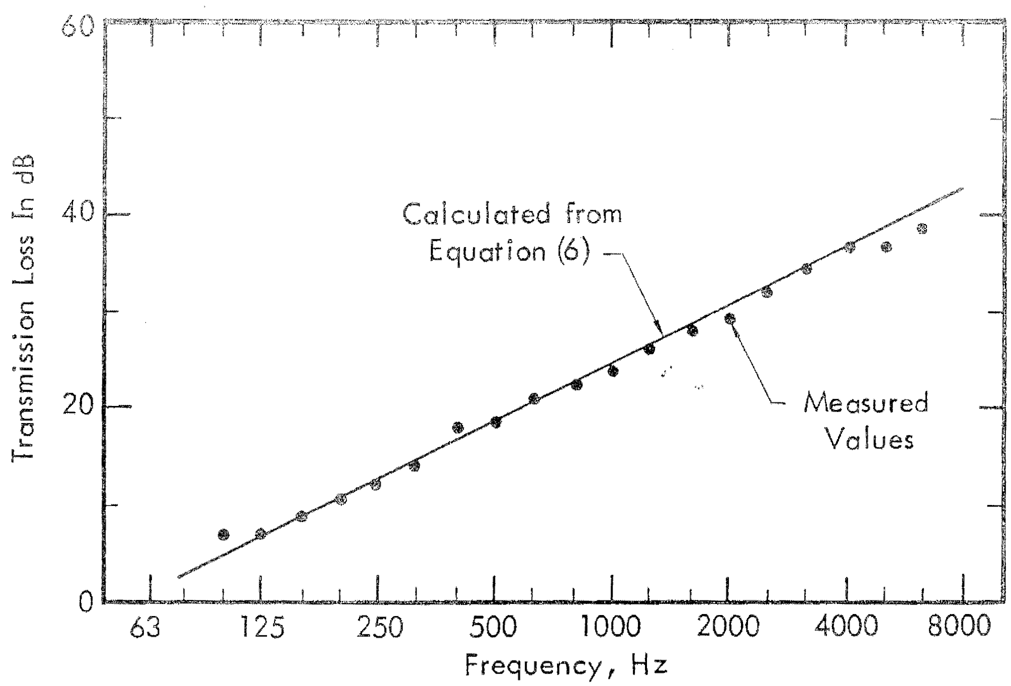


Figure 2. Measured and Calculated Values of the Transmission Loss of 1/8-inch Hardboard

There are in fact a number of panel resonances at frequencies greater than f_r; however, these are not normally evident in the measured values of transmission loss due to the effects of internal damping.

Since both Equations (7) and (5) include the bending stiffness term B, it is a simple matter to show that the product of the low frequency resonance f_r with the critical frequency f_c is given by:

$$f_r \cdot f_c = \frac{c^2}{4}\left[\frac{1}{a^2} + \frac{1}{b^2}\right] \tag{8}$$

In other words, the product is a function only of the dimensions of the panel. As a result, single panels having a high critical frequency exhibit a low mass-stiffness resonant frequency and vice versa. Normally, the magnitude of the quantities a and b ensures that this resonance occurs at very low frequencies – 10 Hz is typical for lightweight panels – so that the stiffness term can be neglected in dealing with large size building elements.

At frequencies approaching the critical frequency, the characteristics of the acoustic coupling between the sound field and the panel are different from those at lower frequencies, with the result that Equation (6) is no longer valid. In this frequency range, the transmission loss deviates below the predicted mass law values, exhibiting a minimum in the vicinity of the critical frequency f_c. At frequencies greater than f_c, the transmission loss increases and may exceed the mass law values. The general characteristics for the transmission loss of a single panel are shown in Figure 3 for a panel of 5/8-inch gypsumboard.

Existing simple methods for predicting the transmission loss of single panels at frequencies in the vicinity of and greater than the critical frequency prove to be inaccurate, often giving values that are as much as 10 dB too low (Reference 6). More exhaustive treatments – see Appendix A – (References 1, 4) show that a fair agreement with measured results is obtained with the following expression, valid only at frequencies greater than the critical frequency:

$$TL = TL_o + 10 \log \left(\frac{2\eta}{\pi} \frac{f}{f_c}\right) \qquad f > f_c \tag{9}$$

where η is the loss factor of the panel, including the energy losses due to radiation and dissipation at the perimeter of the panel. Using Equations (6) and (9), the predicted transmission loss of a 5/8-inch gypsumboard panel is included in Figure 3 to demonstrate the good agreement with measured results over the major part of the frequency range.

To a first approximation, the transmission loss in the frequency region between $1/2\ f_c$ and f_c can be obtained by describing a straight line between the transmission loss values $TL_m\ (1/2\ f_c)$ and $TL_m\ (f_c)$ for $f = 1/2\ f_c$ and f_c, respectively, as given by the expressions in Equations (6) and (9).

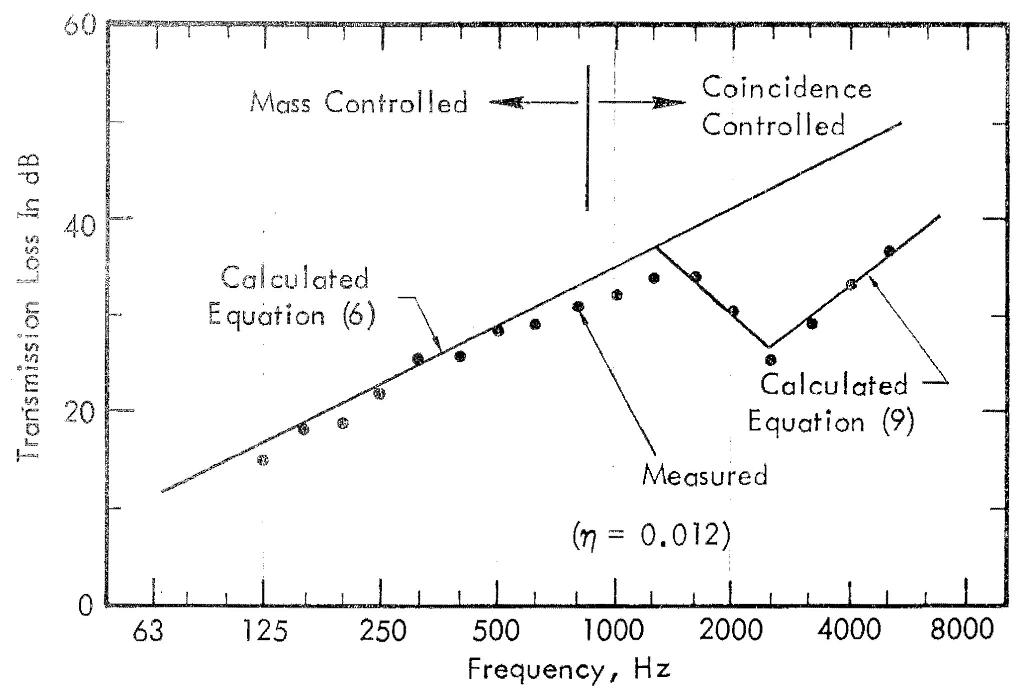


Figure 3. Measured and Calculated Values of the Transmission Loss of 5/8-inch Gypsumboard

It is clear that the effect of coincidence causes a significant reduction in the transmission loss of a single panel over a certain frequency range. Inspection of Equation (5) shows that there are two ways by which the significance of the effect can be reduced:

- The use of an extremely stiff panel – one having a high value for the Young's Modulus – so that the coincidence dip can be made to occur at frequencies below the frequency range of interest. For reasons that will become clear later, this is not normally a satisfactory solution.

- The use of an extremely limp panel, so that the coincidence dip will occur at frequencies above the frequency range of interest. This is the approach that is often taken when consistent with the structural requirements.

In summary, the acoustic behavior of thin single panels is fairly well understood. It is possible to predict the transmission loss by using the expressions given in this section. In the case of panels whose thickness is not small compared to the wavelength, however, further refinements are required in the derivation of the bending impedance.

2.1.4 Thick Single Panels

If the thickness of the panel is not small compared to the wavelength, then the assumptions made in the derivation of the expression for the impedance of the panel are not valid. The type of wave motion that is predominant in the panel at any given frequency is the one that presents the lowest impedance to the applied sound field. Examination of the panel impedance, as given by Equation (4), shows that the term representing the bending wave impedance assumes high values at high frequencies. Therefore, as the frequency is increased, it becomes more probable that the wave motion will change from pure bending to some other type that presents a lower impedance.

This change in the wave type is predicted by the theory for thick panels (see Appendix A) which provides for a more exact representation of the panel motion than does the simple theory for thin panels. The theory shows quite clearly that a change from bending to shearing waves occurs in a frequency range determined by the physical properties and thickness of the panel. Within this frequency range, the overall impedance of the panel changes from one dominated by the bending impedance to one in which the shearing impedance is of prime importance.

At frequencies where the shear wave is predominant, the impedance of the panel is given approximately by the expression (see Appendix A):

$$Z \approx j\omega m - j \frac{\mu h \omega}{c^2} \sin^2 \theta \qquad (10)$$

where

μ = shear modulus of panel material

h = panel thickness

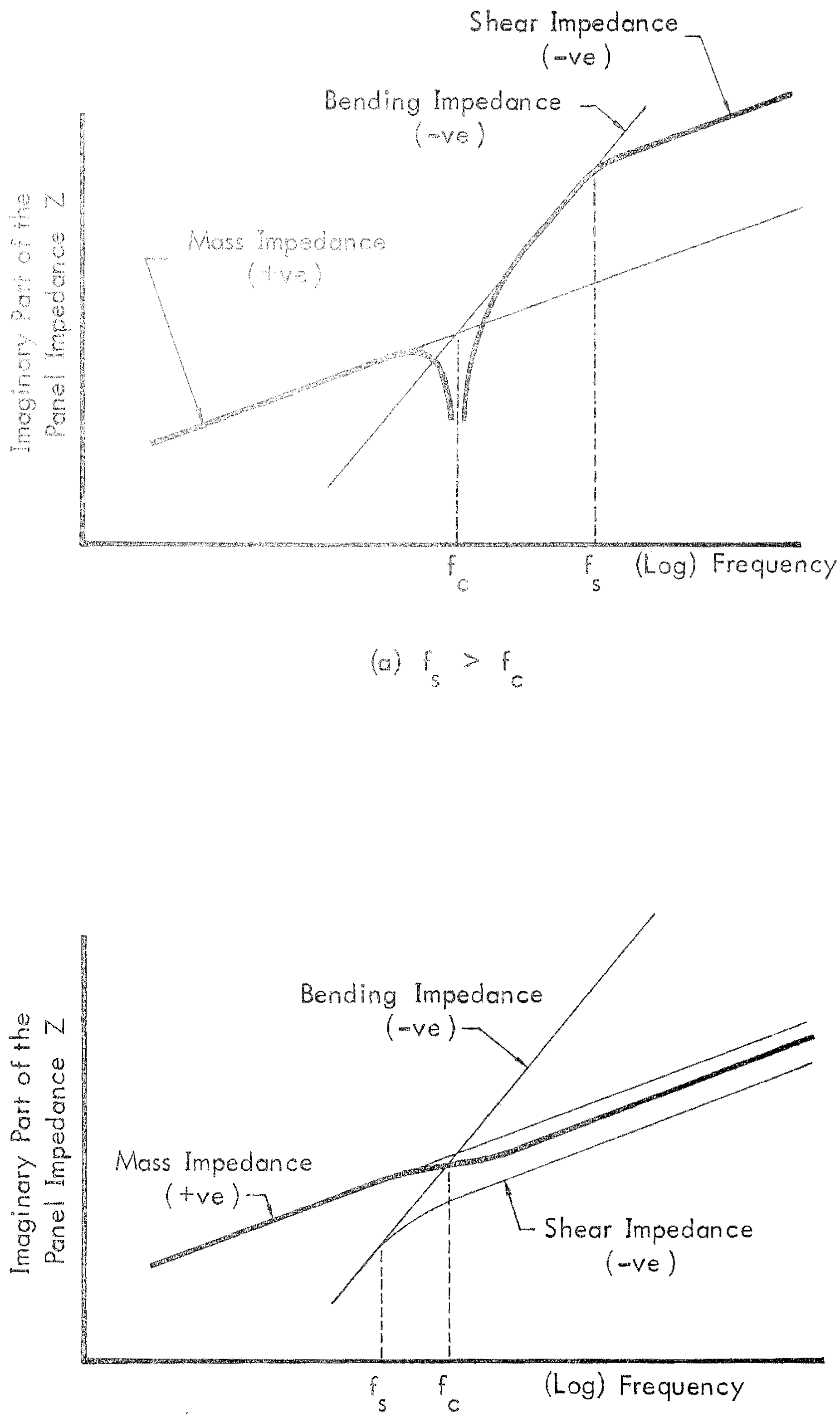
Inspection of Equation (10) shows that the shear impedance has the same dependence on frequency as does the mass impedance.

Equation (10) in conjunction with (4) describes the impedance of the panel over the full frequency range. If the change from bending to shearing waves occurs at a frequency greater than the critical frequency, the terms in the expression for the panel impedance cancel at the critical frequency – see Figure 4(a). At higher frequencies, where the change in wave type occurs, the impedance of the panel increases at a much lower rate than that predicted for thin panels with pure bending waves. Thus, the transmission loss at these frequencies will be less than that predicted by the theory for thin panels.

If the change in wave type occurs at a frequency less than the critical frequency, the coincidence effect will not occur at any frequency – see Figure 4(b). Additionally, if the shear impedance is low, the panel will be mass-controlled over the full frequency range and the transmission loss will obey the mass law as given in Equation (6).

The transmission loss of a hypothetical panel in which the parameters have been varied to represent the cases discussed above is illustrated in Figure 5. When the change in wave type occurs at a frequency f_s much greater than the critical frequency, i.e., $f_s >> f_c$, the transmission loss values are the same as those predicted by the theory for thin panels, except at the higher frequencies where shearing of the panel reduces the panel impedance. Lowering the value of f_s results in raising of the frequency at which coincidence occurs, i.e., the critical frequency is effectively increased. When $f_s = f_c$, coincidence occurs at grazing incidence at all frequencies greater than f_c, with the result that continually low values of transmission loss are obtained at higher frequencies. If f_s is reduced further, the transmission loss curve rapidly reverts to the familiar mass law line.

For the majority of lightweight building materials, such as gypsumboard, plywood, etc., the change in wave type occurs at such a high frequency that the effect is of minor concern. When it comes to considering more massive materials (concrete is a good example), the change in wave type may occur at frequencies well within the frequency range of interest, and in the process have a significant effect on the transmission loss. The effect is shown clearly in Figure 6 for a 6-inch concrete panel. The theory for thick panels –



(a) $f_s > f_c$

(b) $f_s < f_c$

Figure 4. The Imaginary Part of the Transmission Impedance of a Thick Panel for Grazing Incidence ($\theta = \pi/2$)

see Appendix A – gives good agreement with measured results for the 6-inch concrete panel, except in the vicinity of the critical frequency, whereas the application of the theory for thin panels gives results that are substantially in error. The effect of shear is represented by the difference between the two predicted curves and results in the concrete panel exhibiting a transmission loss approximately 6 dB less than the calculated mass law at frequencies greater than the critical frequency. This reduction of 6 dB is common to the majority of concrete and brick structures, and can be taken into account at frequencies above coincidence by assuming the effective mass of the panel is one-half that of the actual mass. The result is that concrete and brick structures provide lower values of transmission loss than would be expected for their mass.

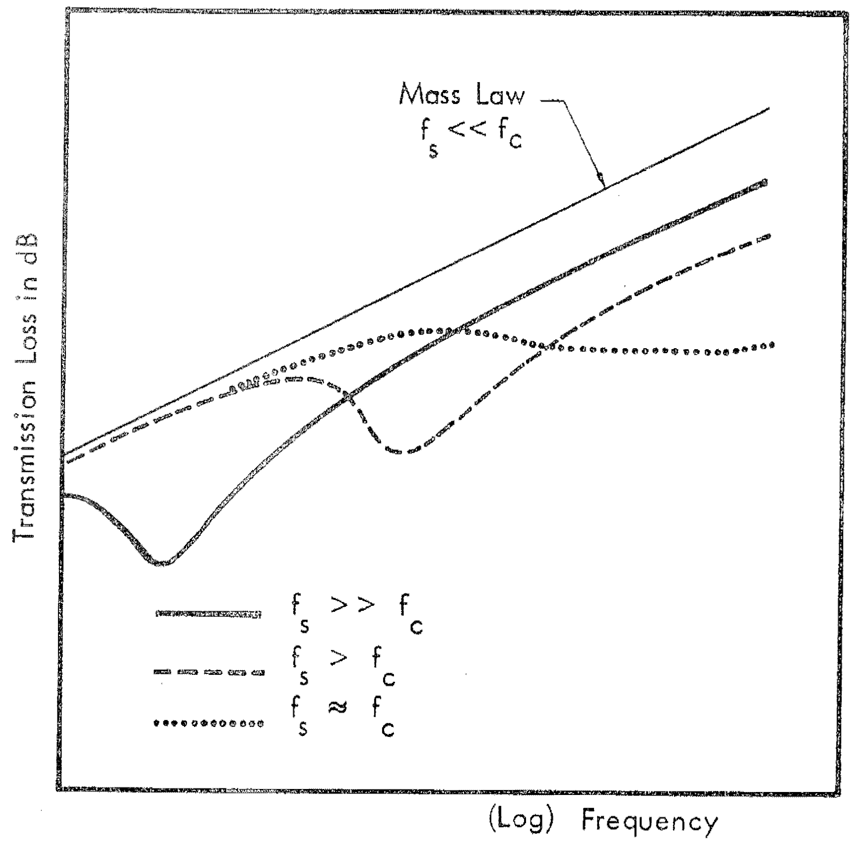


Figure 5. The Transmission Loss of a Hypothetical Panel as a Function of Frequency with the Ratio f_s (the Frequency at Which Shear Waves Dominate) to f_c (the Critical Frequency) as Parameter

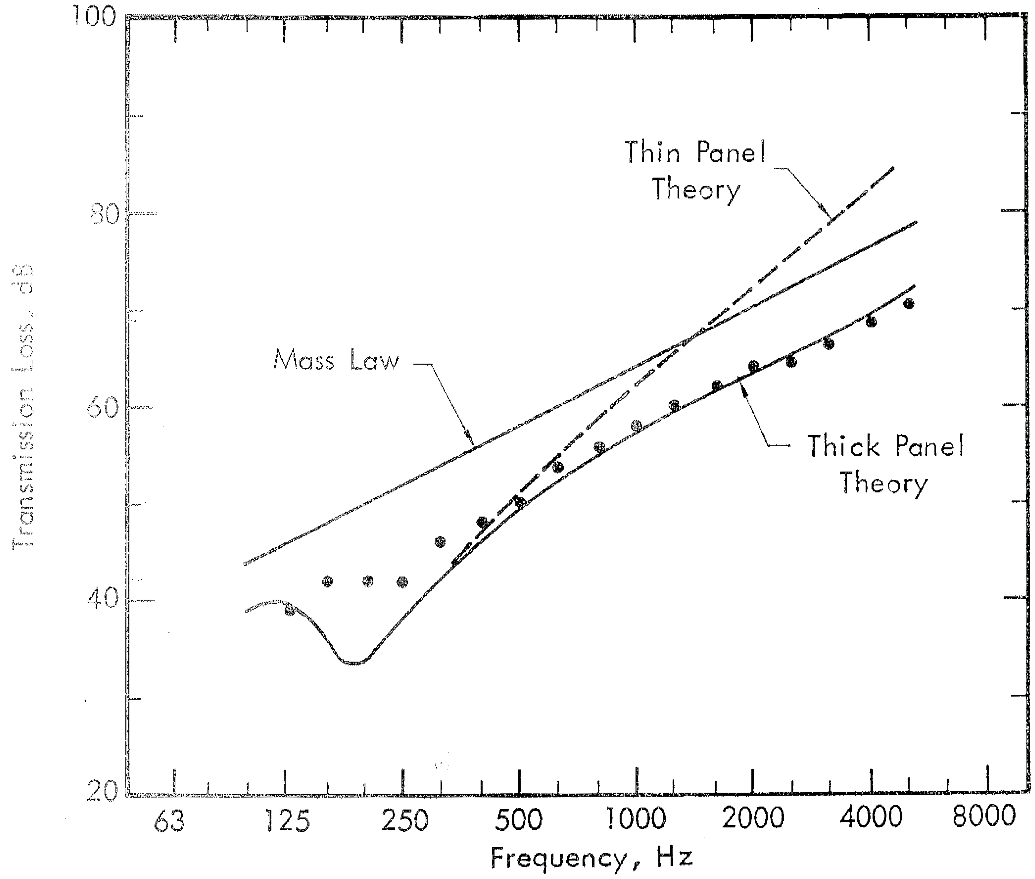


Figure 6. The Measured Values of Transmission Loss for a 6-inch Concrete Panel Compared to Values Predicted by Means of the Thin and Thick Panel Theories

2.1.5 Laminated Panels

To a great extent, the transmission loss of a single panel is determined by the mass of the panel; the greater the mass or the thicker the panel for a given material, the greater the transmission loss -- except at frequencies near the critical frequency. Since the value of the critical frequency is inversely proportional to the thickness of the panel, any attempt to increase the transmission loss of the panel by increasing its thickness automatically lowers the critical frequency, perhaps into a frequency region of major importance. As a result, the two most desirable properties for any single panel are high density and low stiffness -- properties that are normally incompatible in a single material. In practice, building elements are required to exhibit a high stiffness at low or zero frequencies in order to withstand lateral loads. Thus, the ideal panel would exhibit a stiffness that was high at low frequencies, reducing to a low value at high frequencies. Such a panel has been described by Kurze (Reference 7) and consists of a three-layer structure, the center layer of which exhibits a shearing motion at the higher frequencies.

The same effect can be obtained by the use of laminated panels in which the adhesive layer is designed to shear and provide a panel impedance lower than the bending impedance of the combination. At low frequencies, the two panels behave as though they were rigidly connected together, exhibiting a bending stiffness eight times that of either panel alone (the panels are assumed to be identical). At high frequencies, the shearing effect of the adhesive layer reduces the bending stiffness of the combination to that of each of the individual panels. As a result, the critical frequency of the combination can be increased by a factor of two without affecting the low frequency stiffness, provided that shearing of the adhesive occurs at a frequency less than the critical frequency of the combination.

The characteristics of such a multi-layer panel are determined largely by the properties and thickness of the adhesive layer. It is possible to remove this dependency by the technique of "spot" laminating, whereby the adhesive is applied in small discrete amounts on a square lattice over the surface of the panels. The general characteristics of such a multi-layer panel are the same as those described above, with the exception that the two panels decouple and move more or less independently at a frequency determined mainly by the relative spacing of the adhesive spots. It is therefore possible to design the decoupling frequency by correct choice of the adhesive lattice spacing, which can be determined in the following manner.

The wavelength λ_B of bending waves on a panel at a frequency f is given by the expression:

$$\lambda_B = \frac{c}{\sqrt{f f_c}} \tag{11}$$

where

c = the velocity of sound in air, and

f_c = the critical frequency of the panel.

In the case of laminated panels, f_c is the critical frequency of the combination in the absence of shearing. If the two laminated panels are identical and have critical frequencies f_c', then:

$$f_c \approx 0.5\, f_c'$$

At low frequencies, when the bending wavelength is much greater than the adhesive lattice spacing "a," the combination will act as a single panel having an effective critical frequency of f_c. Decoupling of the two panels will begin to occur at a frequency where the bending wavelength is comparable to the adhesive lattice spacing, i.e., when $\lambda_B \approx a$. Rearranging Equation (11) gives the approximate decoupling frequency f_D as:

$$f_D \approx \frac{2c^2}{a^2 f_c'} \tag{12}$$

For example, if the two panels are 1/2-inch gypsumboard ($f_c \approx 3000$ Hz) and the adhesive lattice spacing is 2 feet, the decoupling frequency is of the order of 210 Hz. This is considerably less than the critical frequency f_c of the combination, assuming no decoupling (i.e., 1500 Hz) so that the effective critical frequency of the combination with spot laminations will be of the order of 3000 Hz.

The effect of panel decoupling is demonstrated in Figure 7, where the measured values of transmission loss are given for two spot-laminated sheets of 1/2-inch gypsumboard and for a single sheet of 1/2-inch gypsumboard. No reduction is noted in the critical frequency from its value of approximately 3000 Hz. Similar results are shown in Figure 8 for laminated 3/8-inch gypsumboard panels. Common to both these transmission loss characteristics is a reduction in the measured results in the region of 1000 Hz. The cause is unknown at this time, but could possibly be the result of a double panel mass-spring-mass resonance with a very small air gap between the two laminated panels (see Section 2.2.2).

2.1.6 Mass-Loaded Panels

An alternative approach to the problem of designing panels of high mass and low stiffness is the so-called mass-loading technique. This involves the addition of discrete masses to a flexible base panel in such a way that the stiffness of the base panel is not substantially increased. The addition of any material

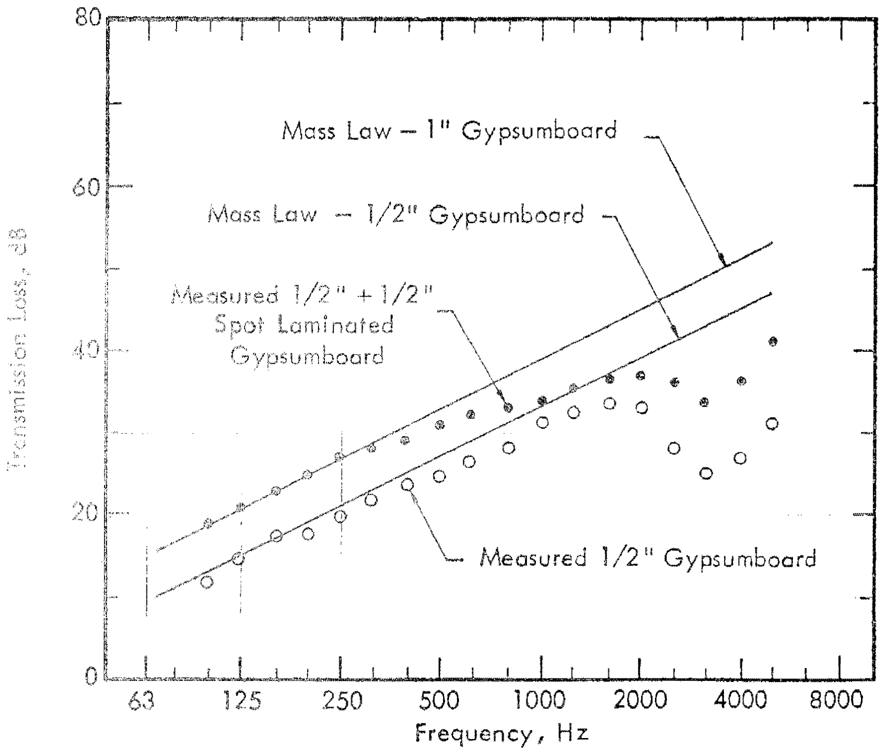


Figure 7. The Measured Values of Transmission Loss for a Single and Two 1/2-inch Spot Laminated Sheets of Gypsumboard

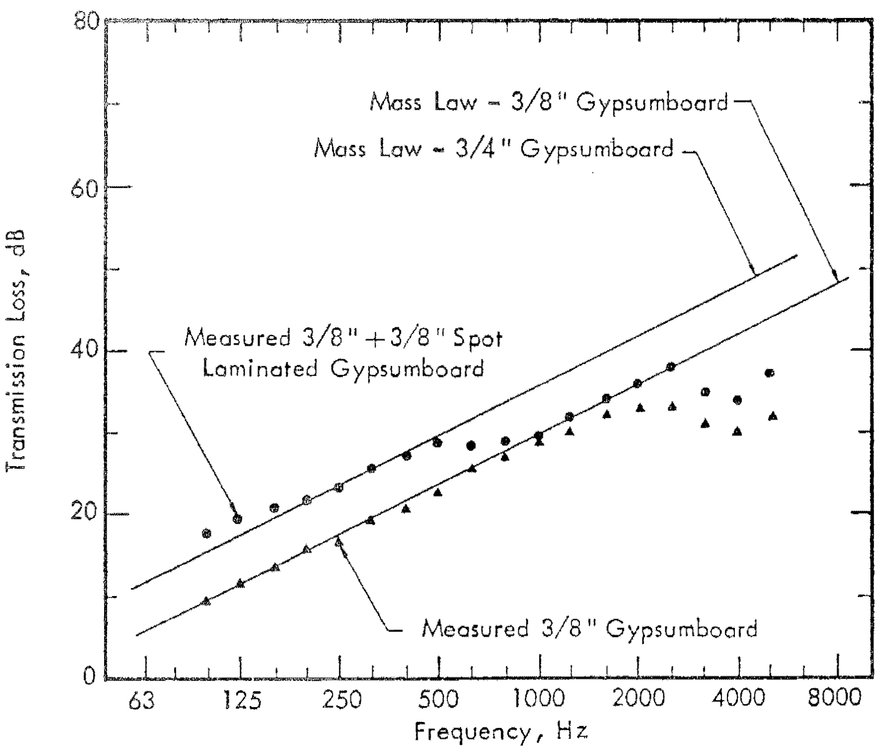


Figure 8. The Measured Values of Transmission Loss for a Single and Two 3/8-inch Spot Laminated Sheets of Gypsumboard

in any form will, of course, increase the stiffness of the base panel at some frequencies. The designer's task is to arrange for the increase in stiffness to occur at frequencies greater than the critical frequency. In other words, the size of the discrete masses must be less than the bending wavelength at the critical frequency. If the maximum lateral dimension of the discrete masses is "ℓ" this condition can be expressed as:

$$\ell < \frac{c}{f_c}$$

where

c = the velocity of sound in air

f_c = the critical frequency of the base panel.

An example of the acoustical performance of a panel loaded with discrete masses is shown in Figure 9. The panel is a 1/8-inch fiber glass sheet loaded to 4 lbs/ft^2 with 1-inch squares of a mixture of sand and vibration-damping compound (the compound being used in this case simply to hold the sand together and provide adhesion to the surface of the panel). The reduction in transmission loss at the higher frequencies indicates that stiffening of the base panel has occurred, probably due to insufficient spacing (1/2-inch) between the squares of added material. Clearly, spacing as well as size of the masses is important in retaining the original stiffness of the base panel.

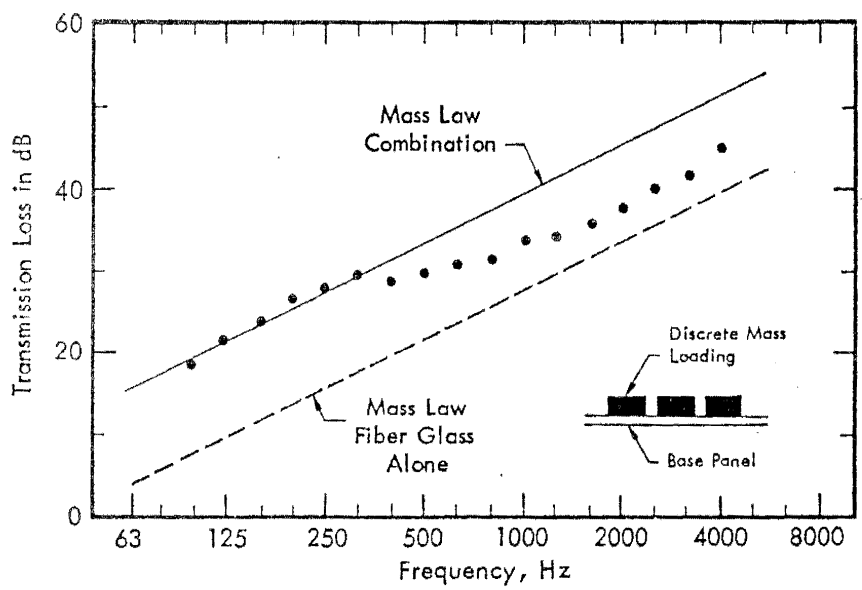


Figure 9. Measured Values of the Transmission Loss of a 1/8-inch Fiber Glass Panel Mass Loaded to 4 lbs/ft^2 with Sand

One of the problems associated with mass-loading by means of discrete masses concerns the amount of material that must be added. For example, if the discrete masses are square and spaced apart by a distance equal to their lateral dimension, the added mass can be applied over only 25 percent of the panel area. This means that the density of the added material must be high if the mass of the base panel — which normally will be of low mass if its critical frequency is high — is to be substantially increased. For this reason, it is often more efficient to provide complete coverage for the base panel using a limp but massive material such as sand. Sand is an almost perfect material for sound-attenuating structures, embodying all the most desirable features — high mass, low stiffness and high damping. The only reason that it is not used more often in building constructions is the difficulty of holding it in place. It is possible, however, to maintain loose sand in contact with a base panel by means of containers resembling egg cartons (see Section 3.3).

More convenient than sand for use as a continuous coverage is a flexible sheet of lead, lead-impregnated plastic, or something akin to asphalt roofing paper. Due to cost, the latter is a particularly desirable material. The transmission loss of a sheet of 1/2-inch plywood (1.5 lbs/ft^2) loaded to 4 lbs/ft^2 with three sheets of asphalt roofing paper stapled to the plywood surface is shown in Figure 10, compared with measured values for the plywood alone. The first point to be noticed is the virtual elimination of the coincidence effect due to the high added mass and damping. The predicted increase in transmission loss is obtained at the low frequencies, but a slight deviation is noticed at high frequencies due to a slight stiffening of the panel.

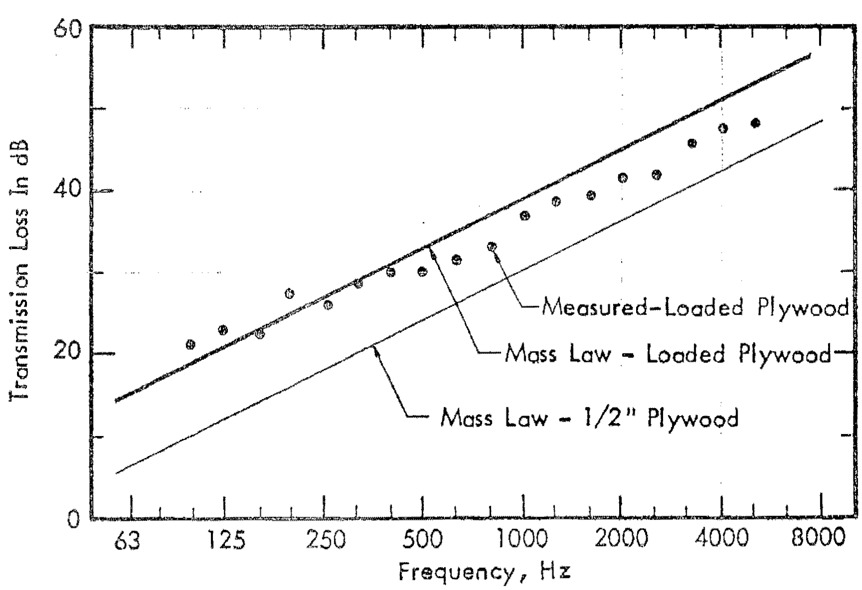


Figure 10. Measured Values of the Transmission Loss of a 1/2-inch Plywood Panel Mass Loaded to 4 lbs/ft^2 with Asphalt Roofing Paper

2.2 IDEAL MULTIPLE PANEL STRUCTURES

One method of obtaining higher values of transmission loss than that available from a single panel is by the introduction of one or more additional panels with intervening airspaces. The multiple panel construction formed in this manner is naturally more complex to analyze than the corresponding case for a single panel because the transmission loss is dependent on a greater number of construction parameters. The acoustical characteristics of multiple panels will be examined in this section and expressions will be derived for the transmission loss of double and triple panel constructions in various frequency ranges. In addition, a fairly complete study will be made on the effect of absorption in the airspaces between the panels.

2.2.1 General Theory for Multiple Panels

The simplest case to consider is a number (N) of single, infinite panels placed parallel to each other with intervening airspaces but no mechanical connections. It will be assumed for the moment that there is acoustical absorption in the cavity, so that sound waves propagating in the airspaces in a direction parallel to the panel faces are well damped. This means that the airspaces will act as stiffness elements at frequencies where the wavelength is much greater than the panel separations, the stiffness being that of the enclosed air. The multi-panel structure can then be represented by the electrical analog circuit using lumped parameters as shown in Figure 11, where the impedances of the individual panels are those given in Section 2.1.3. At high frequencies, where the panel separation is comparable to or greater than a wavelength, there is wave motion in the airspaces in a direction normal to the panel faces, and so distributed parameters have to be used in the representation.

With the assistance of the simple analog circuit of Figure 11, the general characteristics of a multiple panel structure can be derived. At low frequencies, the circuit shows that a combination of the impedances Z_n and Z_{n-1} of two adjacent panels, together with the stiffness k_{n-1} of the intervening air, will produce a resonance at a particular frequency. This will also be true for all the remaining pairs of elements, so if there are N panels in the structure, there will be N-1 resonances. In physical terms, these resonances are produced by the action of the individual panel masses on the stiffness of the air in the airspaces and are commonly referred to as the fundamental "mass-spring-mass" resonances, or simply the fundamental resonances. At frequencies less than the lowest fundamental resonant frequency, the motion of the structure is mass-controlled provided that the individual panels are mass-controlled. In

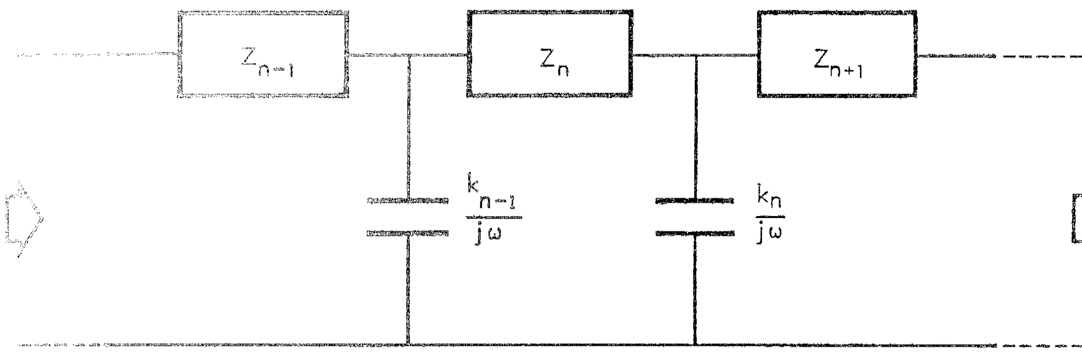


Figure 11. The Electrical Analog Circuit Representing a Multiple Panel Construction

this region, the transmission loss obeys the mass law, the mass being that of all the panels combined. The airspace has no effect on the transmission loss in this frequency range.

At frequencies greater than the fundamental resonances, the effect of the air stiffness is to provide a transmission loss that increases very rapidly with frequency. For a structure containing N panels, the rate of increase of transmission loss with frequency is 6(2N-1)dB per octave. This expression is also valid for a single panel (i.e., N = 1) where, it will be remembered, the rate of increase is only 6 dB per octave. In theory, then, high values of transmission loss can be obtained in this frequency region by the use of multiple panels.

At high frequencies, airborne resonances will be set up in the airspaces between the panels whenever any of the airspace dimensions are numerically equal to an integral number of half-wavelengths. This means that there will be an harmonic series of airborne resonances for each panel separation. The transmission loss curve is therefore characterized by a number of sharp dips descending from peaks that increase in value at the rate of 12(N-1)dB per octave for a structure containing N panels. Although this irregular behavior is predicted by the theory, a small amount of acoustical damping in the airspaces is sufficient to virtually eliminate the sharp dips from the measured results, so that the measured transmission loss increases at the rate of 12(N - 1) dB per octave.

In summary, the discussion of this section has concerned a general multiple panel structure containing N panels. It has shown that high values of transmission loss can be obtained at frequencies greater than the fundamental low frequency resonances, the rate of increase of transmission loss with frequency increasing as the number of panels increases. There is, of course, a limit to the number of panels that can be included in a structure. Practical problems of complex support systems, high cost and increasing floor area utilization quickly set an upper limit. For these reasons, and others which will become apparent, two particular cases are of interest, namely, double and triple panel constructions.

2.2.2 Transmission Loss of Ideal Double Panels

The expression for the transmission coefficient τ_θ of an infinite ideal double panel construction has been derived in the literature (Reference 8) using methods that are extensions of that outlined in Section 2.1 for single panels. A modification of these methods has been utilized (Reference 9) to arrive at a solution for the sound transmission coefficient of a multiple panel construction that is valid for the general case of N panels. From this solution, the transmission coefficient τ for a single angle of incidence θ can be obtained.

For a finite double panel construction that is excited by a reverberant sound field, it is necessary to employ modal methods to determine the transmission coefficient. Such methods involve many complications resulting from the numerous coupling factors between the airborne and structureborne modes. It is therefore more convenient to take the solution for the infinite panel transmission coefficient τ_θ and make use of the results obtained for single panels in Section 2.1.3 to determine the transmission loss for excitation by a reverberant sound field.

Taking this simplified approach, it is shown in Appendix C that the transmission loss of a finite double panel construction, with absorption in the cavity, at frequencies lower than the critical frequency of either panel is given by the expression:

$$TL_I = 10 \log \left\{ 1 + \left| \frac{\omega M}{3.6 \rho c} - \frac{\omega^2 m_1 m_2}{(3.6 \rho c)^2} \left(1 - e^{-2ikd}\right) \right|^2 \right\} \qquad (13)$$

where

m_1, m_2 = mass per unit area of the two panels

$M = m_1 + m_2$ = the total mass per unit area of the construction.

d = panel separation

The subscript I indicates that the expression for the transmission loss is valid for an ideal multiple panel, i.e., one with no interpanel connections. Equation (13) is an expression for the transmission loss with the general characteristics as shown in Figure 12. The frequency regions of major interest in this figure are those where the transmission loss of the construction is reduced by resonances. There are two such regions, one at low frequencies containing the fundamental panel resonance, the other at the higher frequencies with the cavity resonances. Knowing the frequencies at which these two types of resonances occur makes it possible to translate from the general characteristic shown in Figure 12 to the specific characteristics for any given construction without the need for evaluating Equation (13).

Examination of Equation (13) shows that at low frequencies, where the wavelength λ is much greater than the panel separation d, the transmission loss becomes zero at the fundamental resonance frequency f_o which is given by:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{3.6\rho c^2}{m' d}} \tag{14}$$

where

$$m' = \frac{2m_1 m_2}{m_1 + m_2} = \text{the effective mass of the construction} \tag{15}$$

Clearly, the frequency f_o becomes lower as the effective mass m' increases. An inspection of Equation (15) shows that for a given total mass M, the effective mass is greatest when there is an equal distribution of mass between the two panels. Thus, the optimum design for a double panel construction of given total mass is obtained when the panels are of equal mass.

At frequencies much less than the fundamental resonance, the airspace between the panels has very little influence on the transmission loss and the two panels vibrate essentially in phase and with the same velocity. From Equation (13),

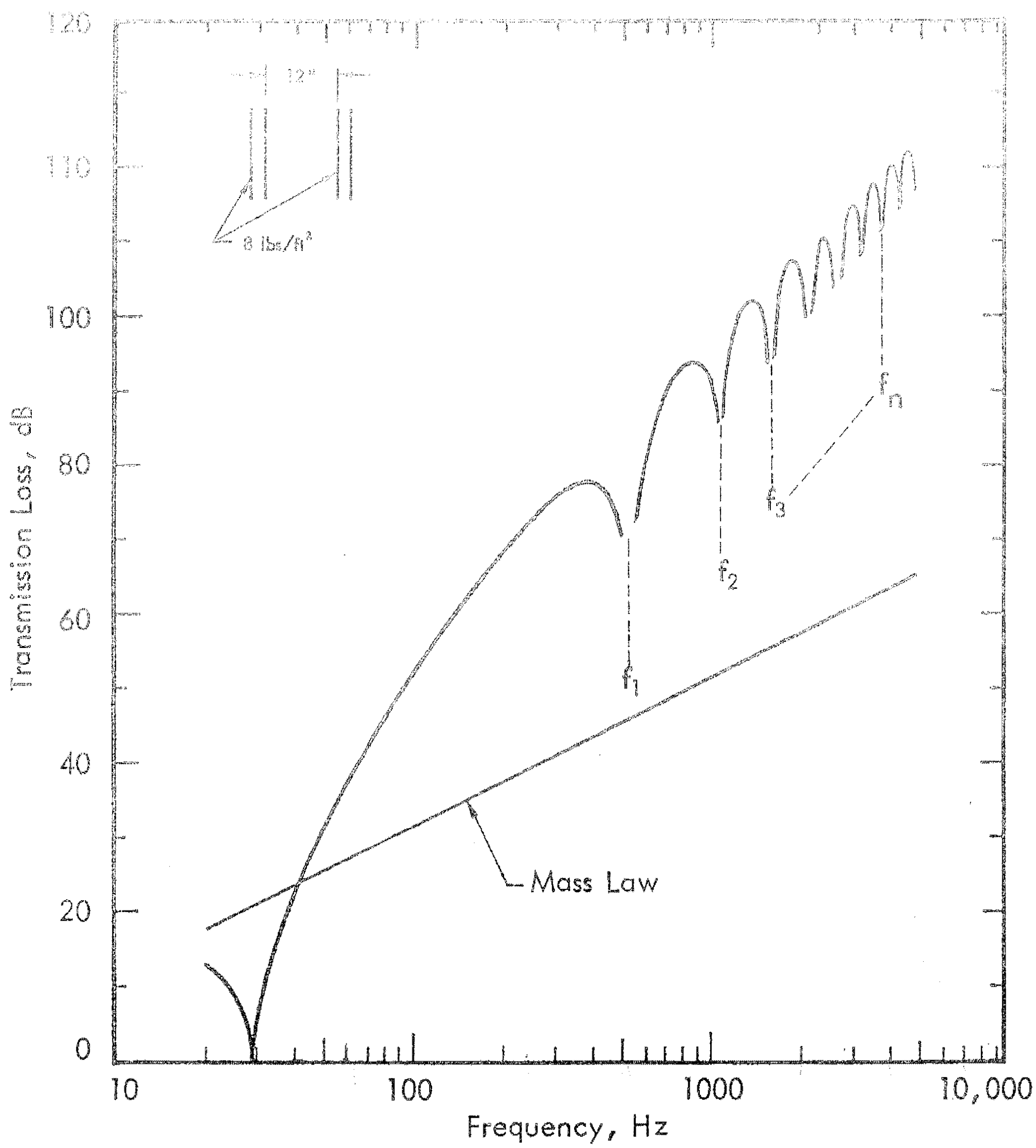


Figure 12. Exact Form for the Transmission Loss of an Ideal Double Panel

it can be deduced that the transmission loss in this frequency range is given approximately by the expression:

$$TL_I = 10 \log \left\{ 1 + \left(\frac{\omega M}{3.6 \rho c} \right)^2 \right\} \qquad f < f_o$$

If $\omega M >> 3.6 \rho c$, then

$$TL_I \approx 20 \log \left(\frac{\omega M}{3.6 \rho c} \right) = 20 \log (M f) - 33.5 \text{ dB} \qquad (16)$$

Equation (16) is the expression for the mass law transmission loss of the construction similar to that of Equation (6).

At frequencies greater than f_o, but still not sufficiently high for the wavelength to be comparable to the panel separation, the second term in the inner brackets of Equation (13) begins to dominate. In this frequency range, the transmission loss is given by the approximate expression:

$$TL_I \approx 20 \log \left[\frac{\omega^2 m_1 m_2}{(3.6 \rho c)^2} \; 2kd \right]$$

$$= TL_1 + TL_2 + 20 \log (2 kd) \qquad f_o < f < f_\ell \qquad (17)$$

where TL_1 and TL_2 are the transmission losses of the two panels calculated according to the mass law by means of Equation (6). The upper frequency limit f_ℓ of the frequency range for which Equation (17) is valid will be derived shortly. In this frequency range, the transmission loss of a double panel increases at the rate of 18dB per octave.

At frequencies greater than f_{ℓ}, where the wavelength becomes comparable to and less than the panel separation d, the transmission loss is characterized by an harmonic series of cavity resonances occurring at frequencies given by:

$$f_n = \frac{nc}{2d} \qquad n = 1,2,3 \ldots. \tag{18}$$

It was noted earlier that the full effect of these cavity resonances will not be observed if there is absorption in the cavity. However, the general slope of the curve reduces from 18 to 12 dB per octave. Thus the transmission loss in this frequency region is given by Equation (13) with the maximum value for the resonant term in parenthesis inserted.

$$TL_I = TL_1 + TL_2 + 6, \text{ dB} \qquad f > f_{\ell} \tag{19}$$

where TL_1 and TL_2 are as defined before.

The exact expression given in Equation (13) for the transmission loss of a double panel can therefore be approximated by means of Equations (16), (17), and (19) in the appropriate frequency regions. The value of the limiting frequency f_{ℓ} can be determined by equating the expressions given in Equations (17) and (19), whereupon:

$$f_{\ell} = \frac{c}{2\pi d} = \frac{f_1}{\pi} \tag{20}$$

It is thus possible to predict the transmission loss of an ideal double panel construction, provided the individual panels obey the mass law within the frequency range of interest. The accuracy of the approximate prediction method is good, as can be seen in Figure 13.

With the aid of the previous discussion and the approximate expressions that have been derived, it is now possible to examine the effects that coincidence will have on the transmission loss of a double panel. The values of the transmission loss of each of the individual panels will, of course, deviate from that calculated according to the mass law at frequencies in the vicinity of and greater than their critical frequencies (see Section 2.1.3). As a result, the

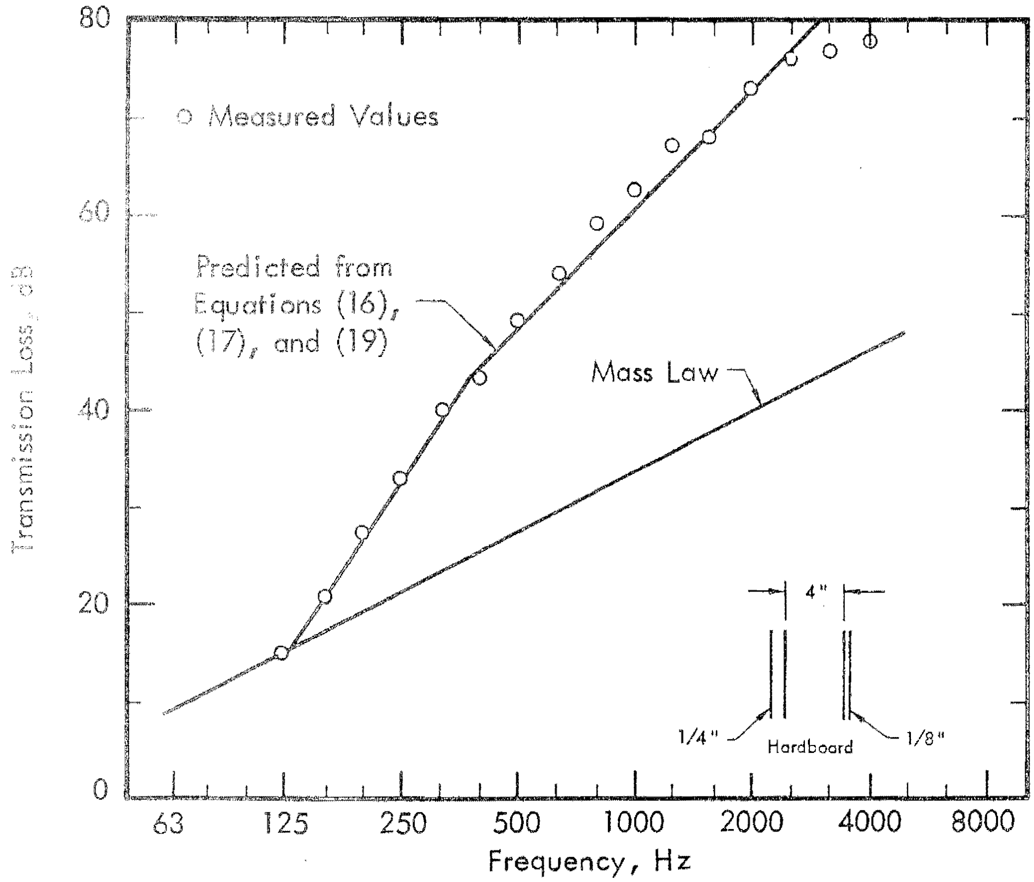


Figure 13. Measured Values of the Transmission Loss of a Double Panel Compared to Values Calculated by the Approximate Method

(second) panel that is not exposed directly to the source of noise will experience an increase in the level of excitation at the critical frequency of the first panel. Similarly, this second panel will transmit energy readily at its critical frequency. The increases in energy transmitted by the two panels at their critical frequencies are contained implicitly in their respective values of transmission loss. Equations (17) and (19) indicate that the two panels act independently in providing the overall transmission loss. Therefore, to a first approximation, the effect of coincidence in the double panel construction can be accounted for by taking the sum of the effects of coincidence in the transmission loss of each of the individual panels. As a result, it is possible to use Equations (17) and (19), with the values of TL_1 and TL_2 taken as the measured or calculated values of the transmission loss for the individual panels including the effects of coincidence.

This method of prediction using the approximate expressions is fairly accurate even for the case where the two panels are identical – see Figure 14. (In this example, mechanical connections between the two panels were minimized by locating the panels in the separate isolated rooms of the Transmission Loss Facility. It was necessary to seal the perimeter of the construction, and it is felt that this is the reason for the deviations between measured and predicted values in the region of 1000 Hz.) The predicted values were obtained by inserting measured values of transmission loss for the individual panels into Equations (16), (17), and (19). Note that the dip in the curve at the fundamental resonance has been eliminated by the introduction of acoustical absorption.

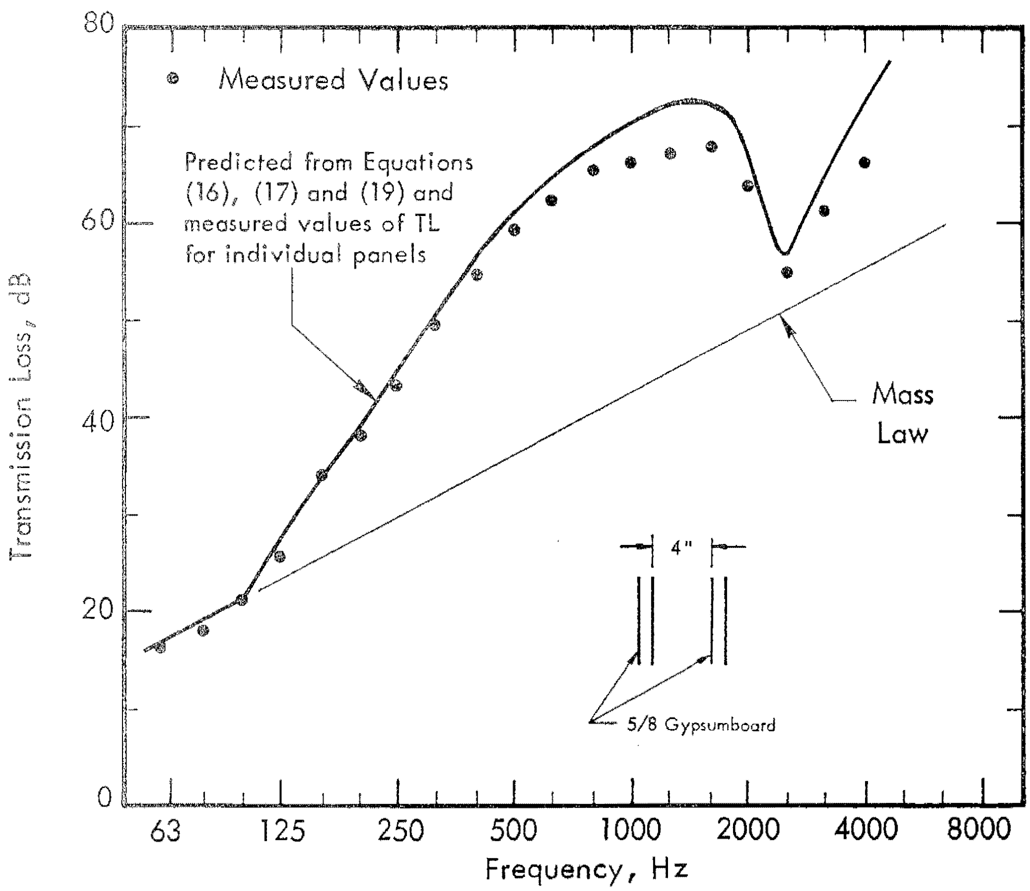


Figure 14. Measured and Calculated Values of the Transmission Loss of 5/8-inch Gypsumboard

If the critical frequencies of the individual panels are identical, then a large dip in the transmission loss curve is to be expected. If they are significantly different, then the transmission loss curve will exhibit two individual dips of lesser magnitude, or simply a flattening in the region in between. For all intermediate conditions, the result will be a broad, shallow dip in the curve. It is possible to gain more quantitative information of the effect of coincidence by computing the transmission loss of a number of double panel constructions in which the individual panels are given values of critical frequency that vary over a wide range. The computed values can then be plotted to determine the optimum ratio of critical frequencies for the two panels for the least reduction in transmission loss. Such a plot is shown in Figure 15 for panels of gypsumboard, where the values have been normalized for ease of comparison. The ratio of the critical frequencies for the two panels considered ranges from 1 to 2.5. The frequency f_{max} in Figure 15 is the one-third octave band center frequency at which the maximum transmission loss is obtained prior to the coincidence dip. Subsequent frequencies are spaced at one-third octave intervals.

The results show, as expected, that the acoustical performance of the construction improves as the ratio of the critical frequencies of the two panels is increased. It would appear that a ratio of 2 is adequate without introducing a reduction of more than 6 dB from the value at f_{max}. The results, of course, are dependent on the damping in the panels, the reduction being less for higher values of the damping. In the case of gypsumboard, the damping factor is in the order of 0.01, but this can be increased by using laminated panels. The reduction in transmission loss at coincidence for the same series of panels, with damping factors this time of 0.1, is shown in Figure 16.

One of the advantages of the approximate expressions given in Equations (16), (17), and (19) is that the effect of parameter changes on the transmission loss can be easily determined. The parameters of importance are the panel masses and separations. Examination of the three equations shows that the effect of varying the panel separation on the transmission loss of a double panel is:

- Zero for $f < f_o$ and $f > f_\ell$
- Proportional to 20 log (d) for $f_o < f < f_\ell$

where f_o in this case is the fundamental resonant frequency with the new value of d and f_ℓ is the limiting frequency with the original value of d. This behavior is illustrated in Figure 17(a). It is interesting to note that changing the panel separation has no effect on the transmission loss of a double panel at frequencies greater than f_ℓ, although the value of f_ℓ itself is changed. Thus for a double panel with a spacing of 4 inches increasing the separation only increases the transmission loss at frequencies below 500 Hz.

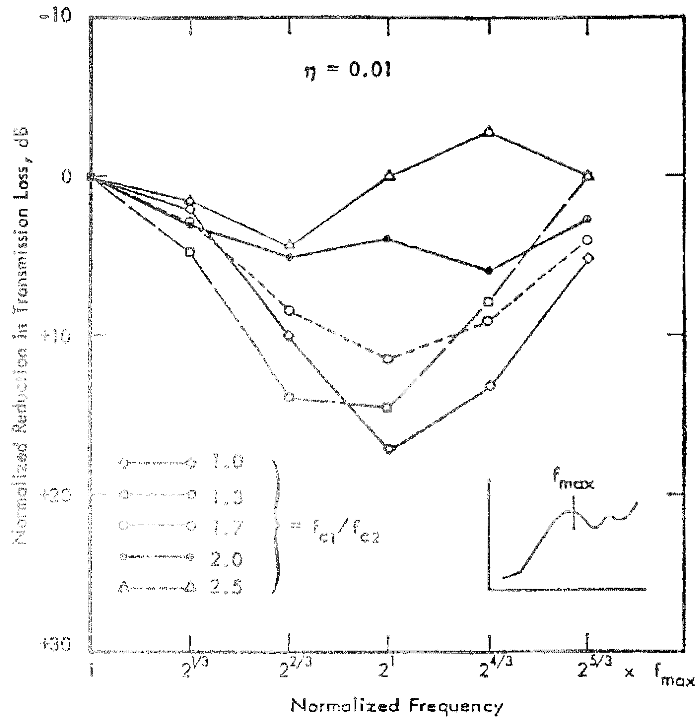


Figure 15. Normalized Reduction in Transmission Loss of an Ideal Double Gypsumboard Panel ($\eta = 0.01$) at Frequencies Near the Critical Frequencies of the Two Panels. The Parameter is the Ratio of the Critical Frequencies of the Panels

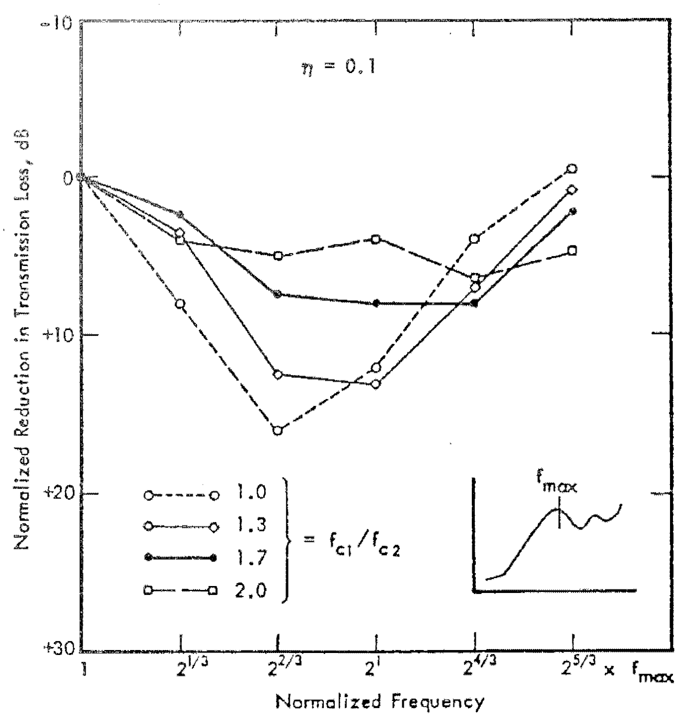
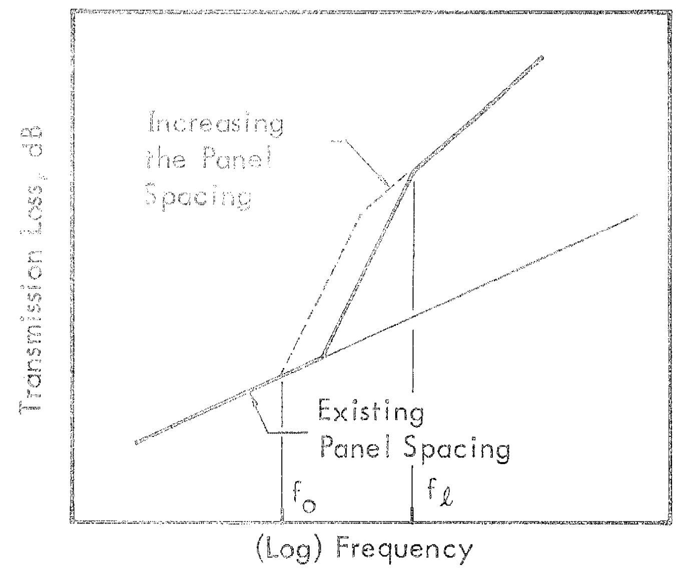
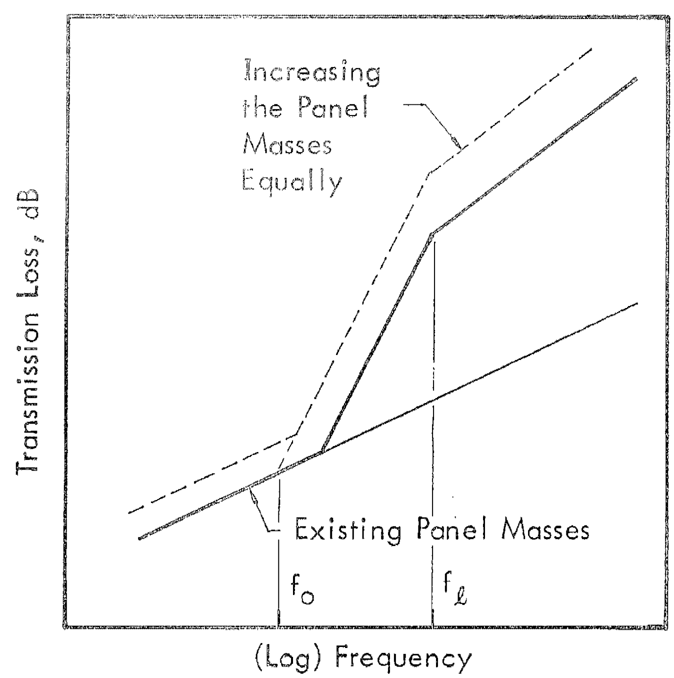


Figure 16. Normalized Reduction in Transmission Loss of an Ideal Double Gypsumboard Panel ($\eta = 0.1$) at Frequencies Near the Critical Frequencies of the Two Panels. The Parameter is the Ratio of the Critical Frequencies of the Panels



(a) Panel Spacing



(b) Panel Masses

Figure 17. The Effect of Varying the Panel Mass and Spacing on the Transmission Loss of an Ideal Double Panel

The effect on the transmission loss of changing the panel masses is more complex since it depends on how the mass is distributed between the panels. If the individual panels in a double panel construction are assumed to be identical (the optimum configuration for a given total mass), the effects of changing the masses of both panels equally is:

- Proportional to 20 log M for $f < f_o$
- Proportional to 40 log M for $f > f_o$

This is illustrated in Figure 17(b). At frequencies greater than f_o, the effect of doubling the mass of both panels is to increase the transmission loss by 12 dB.

2.2.3 Transmission Loss of Ideal Triple Panels

The possibility of obtaining transmission loss values in excess of the calculated mass law has been demonstrated in the discussion on double panel constructions. In an attempt to obtain even greater values of transmission loss from a construction, it is a natural extension to study the acoustical characteristics of triple panels. The general principles are just the same as those described in the previous section and, not surprisingly, the results prove to be remarkably similar. The exact expression for the transmission loss of a triple panel construction with no mechanical connections between the panels is given in Appendix D. Without repeating the individual steps involved, this exact expression can be simplified to provide straight line approximations for the transmission loss in various frequency ranges in the same manner as that described for the case of double panels:

$$TL_I = \left\{ \begin{array}{ll} 20 \log (Mf) - 33.5, \text{ dB} & f < f_- \\ \\ TL_1 + TL_2 + TL_3 + 20 \log (2kd_1) + 20 \log (2kd_2) & f_+ < f < f_\ell \\ \\ TL_1 + TL_2 + TL_3 + 12, \text{ dB} & f > f_\ell \end{array} \right\} \quad (21)$$

where

$$M = m_1 + m_2 + m_3$$

m_1, m_2, m_3 = mass per unit area of the individual panels

d_1, d_2 = panel separations

TL_1, TL_2, TL_3 = measured or calculated transmission loss of the three panels, including the effects of coincidence

$f_\ell = f_1/\pi$

f_1 = the lowest cavity resonant frequency

f_-, f_+ = lower and higher fundamental resonances of the construction.

It is shown in Appendix D that the optimum configuration for a triple panel construction of a given total mass and thickness is:

$$\left.\begin{aligned} m_1 &= m_3 = 1/2\, m_2 = m \\ d_1 &= d_2 = d \end{aligned}\right\} \tag{22}$$

Under these conditions, the fundamental resonant frequencies are given by the expressions:

$$f_+ = \frac{1}{2\pi}\sqrt{\frac{3.6\,\rho c^2}{m d}} \tag{23}$$

$$f_- = \frac{f_+}{\sqrt{2}} \tag{24}$$

The general approximated characteristic for the transmission loss of a triple panel is shown in Figure 18 where it is compared to that for a double panel construction of equal mass and thickness. With absorption material in both cavities, the effect of the fundamental resonances on the transmission loss is significantly reduced so that the mass law is valid at frequencies less than f_+. At frequencies greater than the higher of the two fundamental resonances f_+, but less than f_ℓ, the transmission loss increases at the rate of 30 dB per octave as compared to 18dB per ocatve for the double panel. In this frequency range, the transmission loss increases by 18dB if the mass of the construction is doubled.

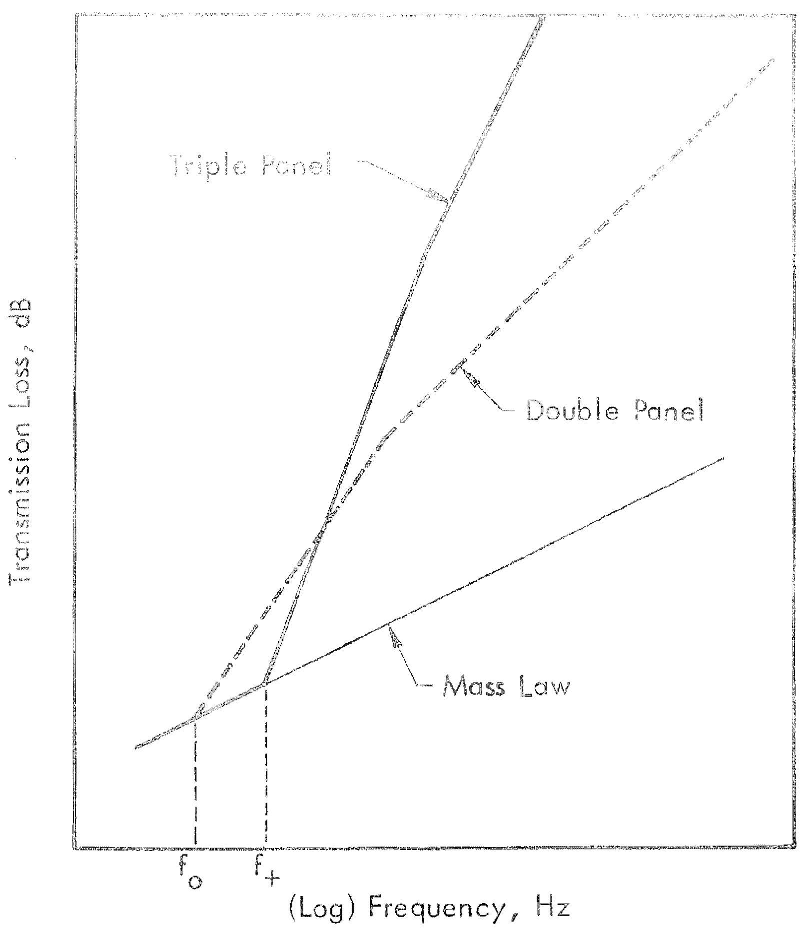


Figure 18. A Comparison of the Transmission Loss Provided by Double and Triple Panel Constructions of Equal Total Mass and Overall Thickness

2.2.4 Comparison of Double and Triple Panels

At this point, it is useful to examine the difference in acoustical performance of the double and triple panel constructions to determine which of the two is most efficient in terms of transmission loss for a given total mass and thickness. (It will be assumed that the same material is used in both types of constructions, so the thickness of the panels can be ignored in this comparison.)

One of the most critical frequency regions to be considered in the design of the construction occurs in the vicinity of the fundamental panel resonance f_o. Earlier in this chapter, it was shown that the value of this resonant frequency for both types of construction is proportional to $1/\sqrt{md}$ where m is one-half and one-quarter the total mass for the double and triple panels, respectively, and d is the panel spacing (assuming on optimum configuration). It readily follows that for a given total mass and thickness, the higher of the two resonances associated with the triple panel is exactly twice that for the double panel, i.e., $f_+ = 2f_o$. Introducing this relationship into the associated equations for the double and triple panels contained in Sections 2.2.2 and 2.2.3 shows that the transmission loss provided by the two constructions is equal at a frequency four times the resonant frequency for the double panel, i.e., $4f_o$. At this frequency, the transmission loss is 24 dB greater than the calculated mass law, assuming ideal conditions where there are no mechanical connections between the individual panels. Thus, the double panel provides higher values of transmission loss than the triple panel at frequencies less than $4f_o$, whereas the triple panel is superior at frequencies greater than $4f_o$.

2.2.5 Cavity Absorption in Multiple Panels of Finite Size

The basic acoustic theory for double panel constructions assumes that the air contained in the cavity separating the panels acts as a stiffness element at low frequencies. This implies that the air is unable to escape from the cavity and that the sound pressure is constant over the entire cavity volume. The lateral dimensions of practical double panel constructions, however, are sufficiently large compared to a wavelength for standing acoustic waves, or modes, to be set up in the cavity. Clearly, the cavity no longer can be represented as a simple stiffness element in the frequency range containing such standing waves. It is therefore natural to expect that the measured values of transmission loss will differ from the values predicted using the simple theory – that is unless the lateral modes are adequately damped. In a single 2 inch x 4 inch stud construction of height 9 feet with studs 24 inches on center, the lowest mode of vibration occurs at approximately 63 Hz or well below the lowest frequency of interest (125 Hz in this study). In this case the stiffness assumption is incorrect over the complete frequency range.

This is only part of the problem, however. If there is little or no acoustic absorption in the cavity, the standing waves may be of large amplitude and may transmit considerable energy to the panels. In fact, at the pressure antinodes in the cavity, the high values of sound pressure will produce an effect similar to that of direct mechanical connections. It would therefore be expected that the resulting strong acoustical coupling between the panels at the natural frequencies of the cavity would significantly reduce the transmission loss of a double panel construction. Furthermore, it is expected that the addition of acoustical absorption to the cavity would reduce the amplitude of standing waves and result in an increase in the transmission loss.

Much of the experimental work designed to study the effects of absorption has been performed on double panel systems in which some form of mechanical connection existed between the individual panels. It is to be expected, therefore, that such interpanel coupling would set an upper limit on the transmission loss that could be obtained. Nevertheless, a few of the results obtained are valid since they were obtained from experiments conducted on double panels that were shown to be capable of providing greater values of transmission loss by the introduction of more absorptive material. Some of the more important conclusions from previous work (References 10 and 11) are as follows:

- The position of a layer of absorption material in the cavity – whether it is against the panel surface or in the center of the cavity – is not important.

- Variation of the flow resistance of the material in the range 10 to 70 rayls per inch has little effect on the transmission loss.

- The density of the material has little effect on the transmission loss. (However, if the density is very high, the material may add mass to one of the two panels if it is attached and higher values of transmission loss may be obtained.)

These conclusions, while probably perfectly valid, unfortunately do not fully explain the action of the absorption material in the cavity. To obtain a greater understanding, it is necessary to consider the modal properties of the sound field that is set up in the cavity due to some external acoustic excitation and the coupling between this sound field and the panels.

Experimental evidence to support a modal coupling hypothesis has been obtained by measuring the transmission loss of a double panel in which the individual panels were completely isolated. In the experiments, one panel of the double panel construction was placed in the source room, the other in the receiving room, and the edges of the cavity were sealed. The panels used were of 1/8-inch and 1/4-inch hardboard, chosen so that the effects of coincidence were removed from the frequency range of interest. The results of the experiments are shown in Figure 19. In the absence of absorption, curve (c) of this figure shows that the strong acoustic coupling between the panels results in almost a single panel performance at frequencies less than the first cavity resonance perpendicular to the plane of the panels (i.e., 1100 Hz). At higher frequencies, the phase of the sound pressure varies over the thickness of the cavity and the acoustic coupling is weaker. In this frequency range, the transmission loss is seen to increase and behave more like that expected of a double panel, although the predicted values are not attained. The introduction of a 2-inch layer of fiber glass insulation board (density 3 lbs/ft^3) across the entire cavity width produces a remarkable improvement in the transmission loss — see curve (b) of Figure 19 — resulting in good agreement between theory and experiment. With a 4-inch layer of fiber glass in the cavity, the mass of the absorption material is comparable to the mass of the panels, which explains the additional increase in transmission loss over and above that predicted by the simple theory — see curve (a) of Figure 19.

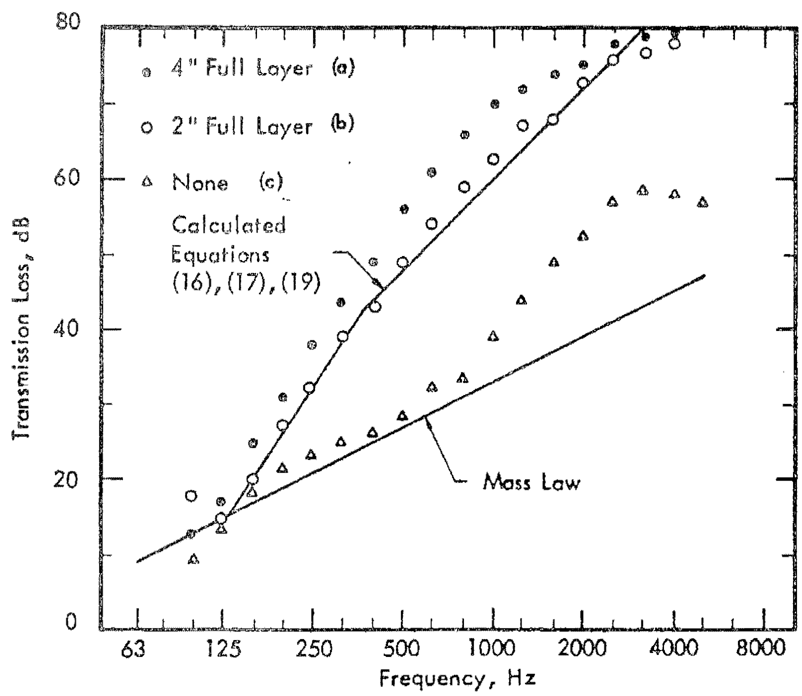


Figure 19. Measured Values of the Transmission Loss of an Isolated Double Panel Construction with and without Full-Layer Cavity Absorption. The Construction Consists of 1/4" and 1/8" Hardboard with a Spacing of 6-1/4 inches

It is normal, and less costly, to use foil-backed fiber glass batts in wall cavities rather than the fiber glass insulation board. As the density of the batts is lower than that of the board, their effectiveness in damping the cavity modes is lower. Measured results of the transmission loss of the double hardboard panel construction are given in Figure 20 for the two types of absorption material in the cavity. At low frequencies the values are essentially the same within experimental error, but a reduction on the order of 4 to 5 dB is noted at frequencies in excess of 500 Hz. It can be concluded that both types of material are equally effective in damping the low frequency lateral cavity modes, but that the batts are less effective than the board in the frequency range where the higher order cavity modes occur (i.e., those perpendicular to the surface of the panels) due to the lower density and flow resistance.

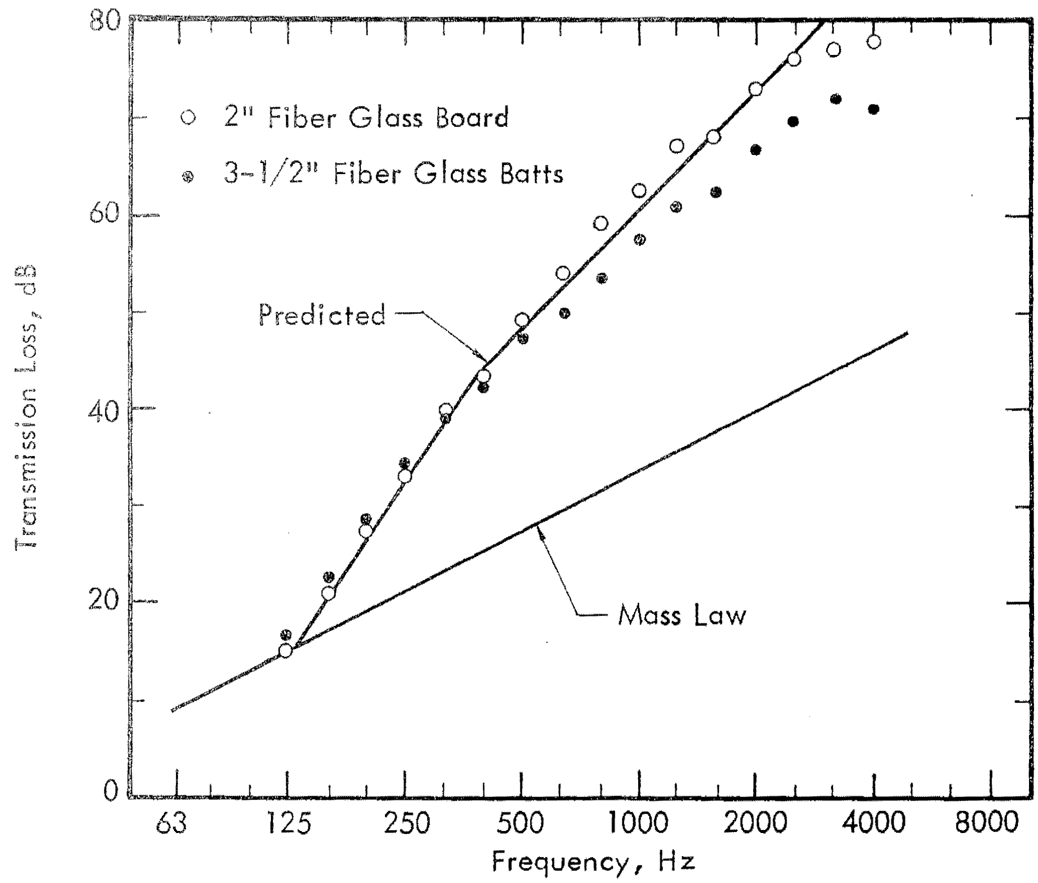


Figure 20. Transmission Loss Values for an Ideal Double Panel with a Full Layer Fiber Glass Insulation Board and Fiber Glass Batts

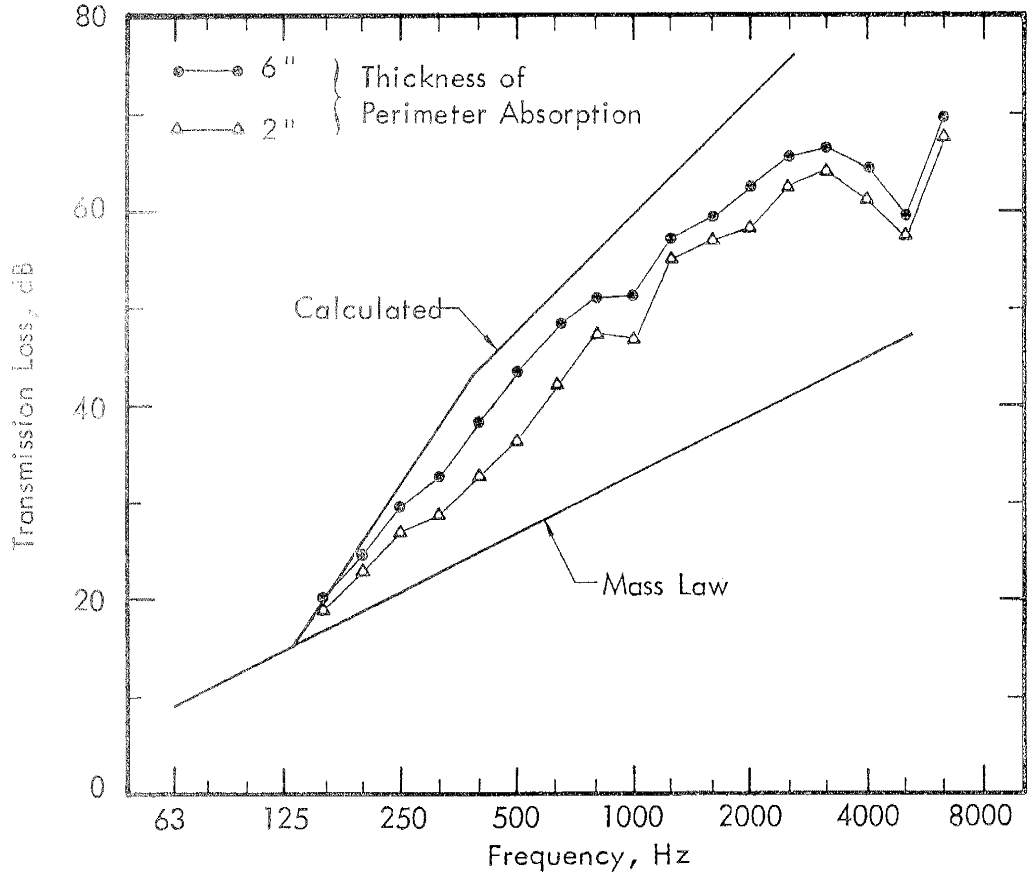


Figure 21. Measured Values of Transmission Loss of an Isolated Double Panel Construction with Perimeter Absorption. The Construction Consists of 1/4" and 1/8" Hardboard with a Spacing of 6-1/4"

If the modal coupling theory is correct, it should be possible to provide the acoustic absorption solely at the periphery of the cavity. This should, in fact, be the optimum position for the placement of the material. Figure 21 shows the result of introducing layers of fiber glass (density 3 lbs/ft^3), 2 inches and 6 inches thick, around the periphery of the cavity. The following points can be noted concerning the results:

- The transmission loss at low frequencies increases as the thickness of the absorbent material at the periphery is increased. The predicted values are not attained, but it is reasonable to assume that they would be approached more closely with thicker layers of material, i.e., more absorption.

- The slight dip in the curves at 1000 Hz corresponds to the first cavity resonance perpendicular to the plane of the panels. This will be evident since the damping at the periphery of the cavity will not be fully effective in damping this mode.

- At frequencies greater than the first cavity resonance, the presence of higher order cavity modes (again perpendicular to the plane of the panels) reduces the overall values of transmission loss. However, the individual resonances are not noticeable.

- At the critical frequency of the 1/4-inch sheet of hardboard (5000 Hz), there is a marked reduction in the measured values. Obviously, perimeter absorption has little effect on the transmission loss at the critical frequency.

The principles of modal coupling provide an interesting method by which the transmission loss of double panels can be increased without the use of absorption. If the cavity is divided into a large number of smaller cavities by means of a lattice network, the entrapped air will behave as a stiffness element up to high frequencies, i.e., up to the lateral modal frequencies of the individual elements in the lattice. This is demonstrated in the measured results of Figure 22, where the lattice dimension is 2 feet square. At low frequencies, the measured results follow the predicted curve closely. The strong coupling effect of the first and second lateral modes of the lattice (in the 315 Hz and 630 Hz one-third octave bands) is evident. The lattice has very little effect at high frequencies. If the lattice dimensions were 6 inches rather than 2 feet, it is anticipated that the predicted results would be approached at all frequencies up to 1000 Hz without the use of any absorption material.

The conclusion that can be drawn is that the modal coupling theory appears to be valid. The use of peripheral absorption alone apparently is not sufficient to attain the possible high values of transmission loss at the higher frequencies. Dividing the cavity into smaller individual cavities, while providing good results at low frequencies, again has similar limitations at high frequencies. At this point, it is interesting to return to the stated conclusions obtained from previous experimental work. These, it will be remembered, showed that the influence of the density and flow resistance of the absorption material on the transmission loss was negligible. This result is understandable when it is realized that of major importance is the damping experienced by sound waves traveling parallel and not perpendicular to the surface of the panels. With a full lateral layer of material in the cavity, the damping will always be high (unless the density or flow resistance of the material is very low indeed) since the complete propagation path is through the material.

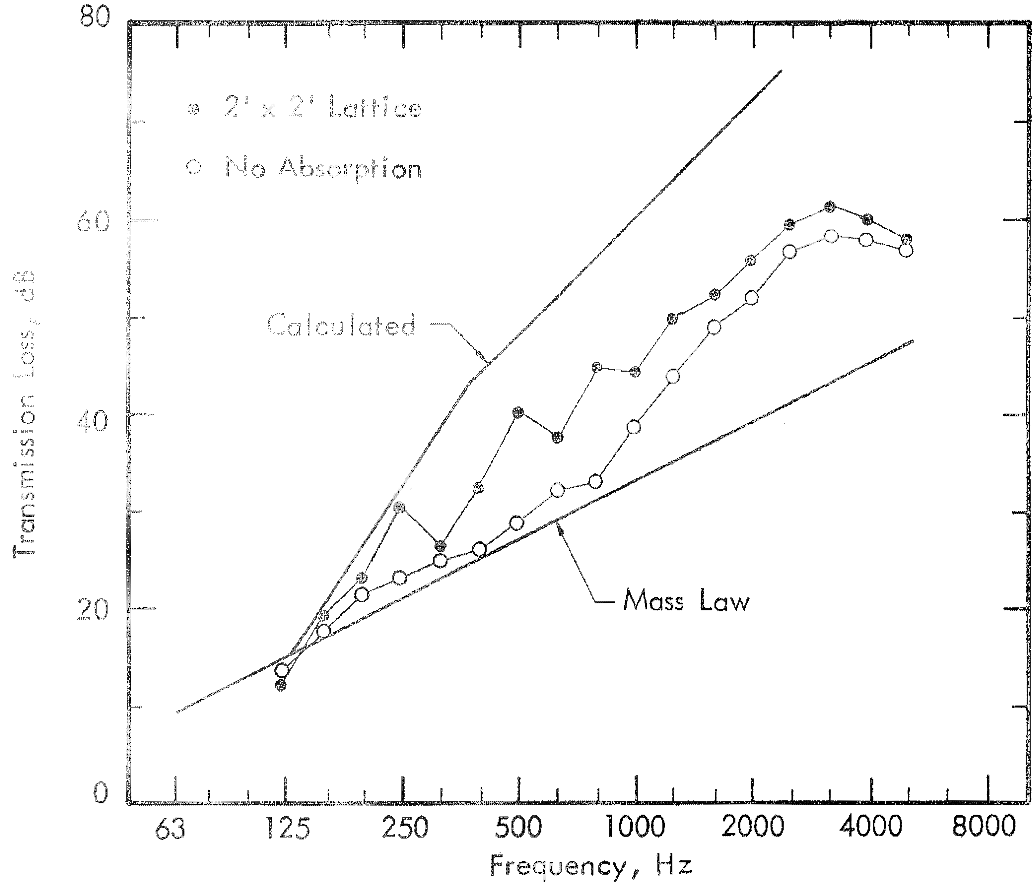


Figure 22. Measured Values of Transmission Loss of an Isolated Double Panel Construction with a 2' x 2' Lattice in the Cavity. The Construction Consists of 1/4" and 1/8" Hardboard with a Spacing of 6-1/4"

In double panels where the panel separation is small – say, less than 6 inches – it has been found (Reference 11) that the position of the material (assuming it is a full lateral layer) is not critical. For panel separations greater than this, as for example in floor/ceiling constructions, the lateral modes in the cavity may not be adequately damped if the material is attached to one of the panels. It is preferable in such cases to incline the material across the cavity wherever this is possible.

2.3 SOUND BRIDGES IN MULTIPLE PANELS

One of the major assumptions in the previous analysis of double panel structures is that the two individual panels are completely isolated from one another. This means that the only path of energy transfer between the two panels is an airborne path. In practice, it is necessary to have some form of connection between the panels to provide the added stiffness for the construction to withstand lateral loads. These connections usually take the form of wooden or metal studs in building structures and metal ribs and stringers in aerospace structures. Their effect is to provide an additional transmission path in parallel to the airborne path previously considered, with the result that acoustic radiation from the structure is increased and the transmission loss correspondingly reduced. It is not usually possible to eliminate these inter-panel connections, or "sound bridges" as they are called, and so it is necessary in the design of multiple panel structures to be able to determine the effect that they have on the transmission loss.

2.3.1 General Theory

There are basically two types of interpanel connections. One of these, the line connection, is commonly found in building constructions in the form of wooden or metal studs in which the two panels are connected along a line or a series of lines. The other, which is not so common, is the point connection and consists of a connection or a number of connections having a small cross-sectional area that approximates to a point. The method that will be used to determine the reduction in transmission loss of a double panel due to the insertion of a number of such sound bridges is to add together the acoustic power radiated by the action of the bridges and that radiated by the ideal isolated panel. The result will then be compared with the power radiated in the absence of sound bridges.

Consider a double panel construction that is subject to acoustic excitation from an unidentified noise source. The panel not exposed directly to the noise source will be exposed to the sound field created in the cavity between the two panels. If the resultant rms velocity of this second panel is v_2, then the sound power W_p radiated due to the forced response of the panel at frequencies less than the critical frequency is given by the expression:

$$W_p \approx \rho c S v_2^2 \tag{25}$$

where S is the area of the panel. This expression also holds for frequencies greater than the critical frequency for both free and forced wave radiation. To the power W_p must be added the power radiated by the action of the sound bridges which are assumed to connect the two panels. It has been shown by Heckl (Reference 12) that the sound power W_B radiated by a panel at frequencies less than the critical frequency, when excited by a mechanical force such as that provided by the action of the sound bridges, is given by the expression:

$$W_B = \rho c \varkappa v^2 \tag{26}$$

where v is the rms velocity of the area over which the force is acting, and $\varkappa$ is given by:

$$\left.\begin{aligned} \varkappa &= \frac{8}{\pi^3} \lambda_c^{\,2} && \text{for a point force} \\ &= \frac{2}{\pi} \ell \lambda_c && \text{for a line force} \end{aligned}\right\} \tag{27}$$

where

λ_c = the critical wavelength of the panel (c/f_c)

ℓ = the length of the line over which the force acts.

A comparison of Equations (25) and (26) shows that the quantity $\varkappa$ has the dimensions of an area and can be considered to be the effective area of radiation from either the point or line force. If the point force acts over a small but finite area A then as long as the lateral linear dimensions of this area are much smaller than the bending wavelength on the panel, Equation (26) can be rewritten approximately as:

$$W_B = \rho c \varkappa \left(1 + \frac{\pi^3 r^2}{2\lambda_B^{\,2}} \right) v^2 \tag{28}$$

where

$$r = \sqrt{\frac{A}{\pi}}$$

λ_B = wavelength of bending waves on the panel.

Also, $\varkappa$ is independent of frequency, which at first may seem to be a strange result. However, at frequencies less than the critical frequency, the area of the panel which is not in the immediate vicinity of the discrete point or line forces experiences free wave motion from which the sound power radiation is small. The only substantial radiation comes from the area of the force itself from the forced waves. The size of this effective area of radiation will decrease with frequency, but the power radiated per unit area will increase with frequency, so that the total radiation will remain constant. Since the size of the radiating area increases as the frequency is decreased, it is possible for overlapping to occur between deformations produced on the panel by neighboring point forces. It can be shown (Reference 13) that the effective radius of the radiating area is $\lambda_B/4$ where λ_B is the wavelength of bending waves on the panel. For the individual point forces to be independent of each other, the spacing "e" must be greater than $\lambda_B/2$. Using the relationship given in Equation (11), this criterion can be expressed as:

$$f > \frac{c^2}{4e^2 f_c} \tag{29}$$

For example, if the panel is 1/2-inch gypsumboard with a critical frequency of 3000 Hz, the forces can be considered to be independent at all frequencies greater than 27 Hz for a point spacing of 2 feet.

With these considerations, the total power W_T radiated by the second panel when $r << \lambda_B$ is given by:

$$W_T = W_p + W_B$$

$$= \rho c S v_2^2 \left[1 + \frac{n\varkappa}{S} \left(\frac{v}{v_2}\right)^2 \right] \tag{30}$$

where n is the number of point or line forces acting on the panel. Comparing Equations (30) and (25) gives the result that the decrease TL_B in transmission loss of the double panel construction due to the introduction of the sound bridges is given by:

$$TL_B = 10 \log (W_T/W_p)$$

$$= 10 \log (1 + \delta) \tag{31}$$

where

$$\delta = \frac{n\varkappa}{S} \left(\frac{v}{v_2}\right)^2$$

The overall transmission loss TL of a bridged double panel is then given by the expression:

$$TL = TL_I - TL_B \tag{32}$$

where TL_I is the transmission loss of an ideal double panel with no connections, as given by the exact expression in Equation (13) or the approximate expressions in Equations (16), (17), and (19). To calculate the reduction in transmission loss it is necessary to determine the velocity ratio v to v_2, which is the ratio of the panel velocity at the position where the line or point force acts, to the velocity of the panel at a point well removed from this position. To a first approximation, it can be assumed that:

- The velocity of the first panel (that exposed to the sound field) is unaffected by the introduction of the point or line connection.

- The velocity of the second panel at the position where the point or line force acts is the same as the velocity of the first panel (assumed constant over its surface), i.e.,

$$\frac{v}{v_2} \approx \frac{v_1}{v_2}$$

With these assumptions, it can be shown (see Appendix E) that the velocity ratio is given by:

$$\left.\begin{aligned} \frac{v}{v_2} &= \frac{\omega^2 m_2 d}{1.8\rho c} && f_o < f < f_\ell \\ &= \frac{\omega m_2}{1.8\rho c} && f > f_\ell \end{aligned}\right\} \quad (33)$$

where f_ℓ is given by Equation (20).

Under conditions where the second term in the brackets of Equation (31) is much greater than unity, the rate of increase of TL_B (the detraction in transmission loss) with frequency is 12 dB per octave for $f < f_\ell$ and 6 dB per octave for $f > f_\ell$. The transmission loss of an ideal double panel increases at a rate of 18 dB per octave and 12 dB per octave in the two frequency ranges, respectively. Thus, the transmission loss of a double panel with sound bridges will increase at a rate of only 6 dB per octave over the entire frequency range where the transmission loss is governed by the bridges. The curve will thus be parallel to the mass law line.

At lower frequencies, when the value of the second term (δ) in Equation (31) is less than or comparable to unity, the slope of the curve will vary between the limits 18 dB and 6 dB per octave. Thus, the general form of the transmission loss for a bridged double panel is as illustrated in Figure 23. The frequency at which the sound bridges begin to determine the transmission loss is called the "bridging" frequency f_B which for the case where the two panels are of equal mass is given by:

$$\left.\begin{aligned} f_{BP} &= f_o \left(\frac{e}{\lambda_c}\right)^{1/2} && \text{for point connections} \\ f_{BL} &= f_o \left(\frac{\pi b}{8\lambda_c}\right)^{1/4} && \text{for line connections} \end{aligned}\right\} \quad (34)$$

where

e^2 = the area (in square feet) associated with each point connection

f_o = fundamental resonance of the double panel

b = the spacing (in feet) between the line connections.

The more general case where the distribution of mass between the panels is not even is discussed in Appendix E.

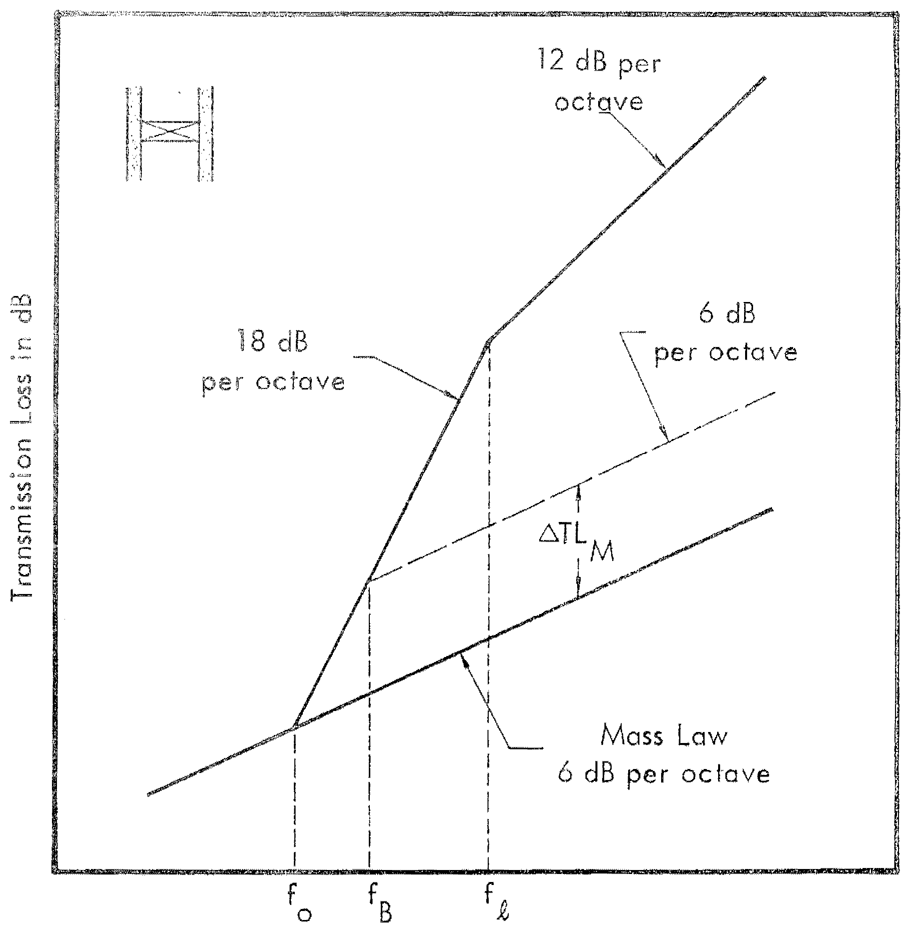


Figure 23. General Form for the Transmission Loss of a Double Panel with Sound Bridges

Since, the curve of the bridged transmission loss as a function of frequency is parallel to the mass law line, a convenient method for specifying the transmission loss is in terms of the increase ΔTL_M in transmission loss over and above that predicted by the mass law for the entire structure. It is a fairly simple matter to show (see Appendix E) that the value of ΔTL_M can be obtained from the following expressions:

For point connections (to one panel only) –

$$\Delta TL_M = 20 \log (e f_c) + 20 \log \left(\frac{m_1}{m_1 + m_2} \right) - 55, \quad dB$$

$$= 20 \log (e f_c) - 61, \quad dB \qquad \text{for } m_1 = m_2 \qquad (35)$$

For line connections –

$$\Delta TL_M = 10 \log (b f_c) + 20 \log \left(\frac{m_1}{m_1 + m_2} \right) - 28, \quad dB$$

$$= 10 \log (b f_c) - 34, \quad dB \qquad \text{for } m_1 = m_2 \qquad (36)$$

where

e = point lattice spacing in feet

b = line stud separation in feet

m_2 = mass per unit area of the panel supported by point connections

f_c = critical frequency of panel supported by point connections or, in the case of line connections, the highest critical frequency of the two.

It must be recognized, however, that Equations (35) and (36) do not account for the effects of coincidence in either of the two panels. Thus, the method of adding the quantity ΔTL_M to the calculated mass law transmission loss TL_M in order to obtain the overall transmission loss of the bridged double panel is valid only when the critical frequencies of both panels are either outside the frequency range of interest or staggered sufficiently in value (see Section 2.2.2) for their individual effects to be reduced. Otherwise, it is necessary to compute the reduction TL_B in transmission loss as a result of the sound bridges and subtract this from the transmission loss of the ideal double panel, calculated from Equations (16), (17), and (19).

Whichever method of calculation is required, however, the expressions given in Equations (35) and (36) give an indication as to the required design parameters for an optimum double panel construction incorporating sound bridges. Not surprisingly, it is found that the transmission loss increases as the number and/or length of the interpanel connections is reduced and as the critical frequency (or flexibility) of the panels is increased.

The value of ΔTL_M is plotted in Figure 24 as a function of the construction parameters $e\,f_c$ and $b\,f_c$. In a practical construction, it is to be expected that the point lattice (assumed square) spacing "e" normally will be equal to the stud spacing "b". Figure 24 therefore shows that a value of ΔTL_M equal to 10 dB can be obtained with a panel seven times less flexible if it is mounted on points than if it is mounted conventionally on line studs.

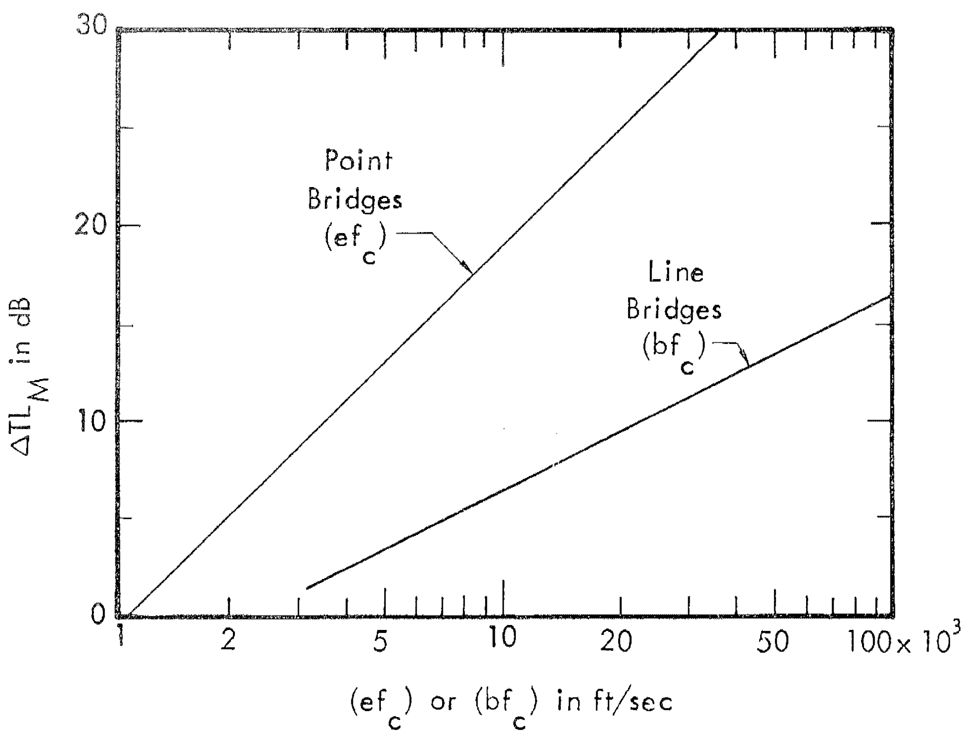


Figure 24. The Increase in Transmission Loss TL_M with Reference to the Mass Law as a Function of the Quantities (ef_c) and (bf_c) for a Double Panel with Sound Bridges

2.3.2 Experimental Verification of Sound Bridging Theory

A series of experiments was designed to check the validity of the above expressions. A double panel consisting of two sheets of 5/8-inch gypsumboard was placed in the transmission loss testing facility. As before, the panels were located in separate rooms, ensuring that no mechanical connections existed. A layer of 2-inch fiber glass (density 3 lbs/ft^3) was placed in the cavity to provide absorption. The transmission loss of the double panel was measured; the measurement was then repeated with the addition of one, three, and nine point connections between the panels. The point connections used were made of wood and had a cross-sectional area of 4 square inches. These connections were placed on a square lattice with a spacing of 2 feet. The area of the connections was one-tenth of the radiating area of the panel at 1000 Hz, and could therefore be neglected in considering the effective radiating area. The results of the measurements are shown in Figure 25, where they are compared with computed results using Equations (16), (17), (19), (31), (32), and (33). The agreement is good, even at frequencies approaching and above the critical frequency. This perhaps is surprising, since the expressions are supposedly valid only at frequencies below the critical frequency. In any event, it would appear that the predicted effects of point bridging in double panels are confirmed by the measurements – at least for this ideal laboratory case.

The experiment was repeated with a line connection replacing the points. The line connection consisted of an 8-foot long wooden stud, 2 inches x 4 inches, which was screwed firmly to both panels along its length. The measured results and the predicted values are shown in Figure 26. It can be seen that the prediction method gives values that are approximately 3 dB too low. This discrepancy can be explained by remembering that in the theory, the introduction of the connection is assumed to have no effect on the motion of the panel directly exposed to the sound excitation. With point connections, this is a reasonable assumption which is justified to a certain extent by the good agreement obtained between predicted and measured results. The continuous line connection, however, will exert an influence on the motion of the first panel, due partly to its mass and partly to the reaction of the second panel. Since these are rather indeterminate quantities in an already approximate theory, an empirical correction to Equations (31) and (36) may be necessary to obtain predicted results for line connections.

To see if the above results applied equally well to practical structures, further experiments were conducted on a single wood stud partition built in the test facility. The material applied to both sides of the studs was 5/8-inch gypsumboard. The studs were mounted 24 inches on center. The results of the measurements are shown in Figure 27. The three curves in this figure are:

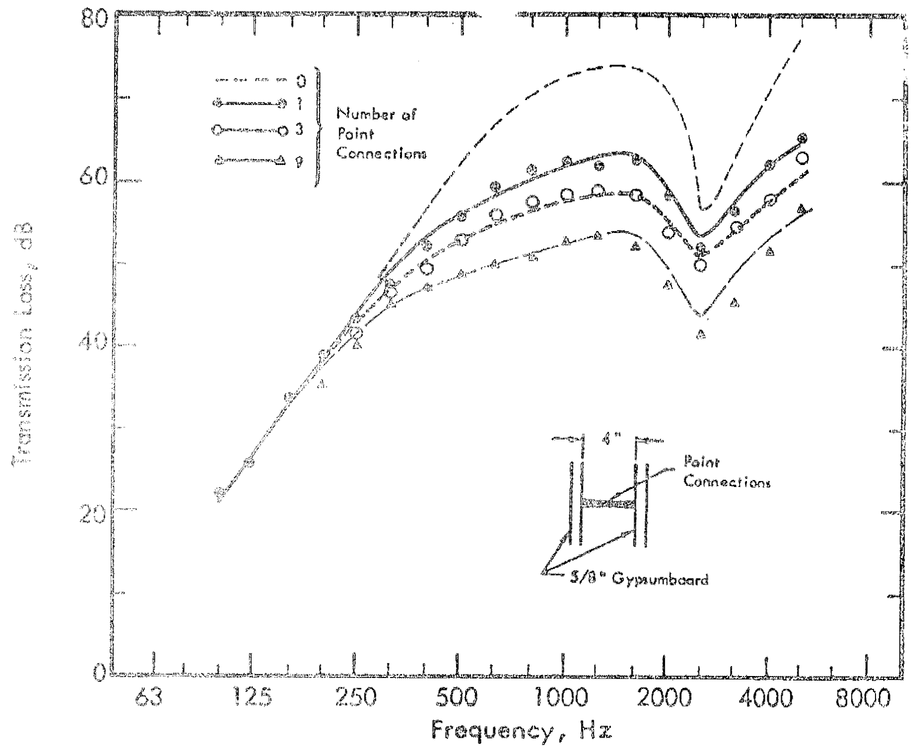


Figure 25. Measured and Calculated Values of Transmission Loss for a Double Panel with a Number of Point Connections

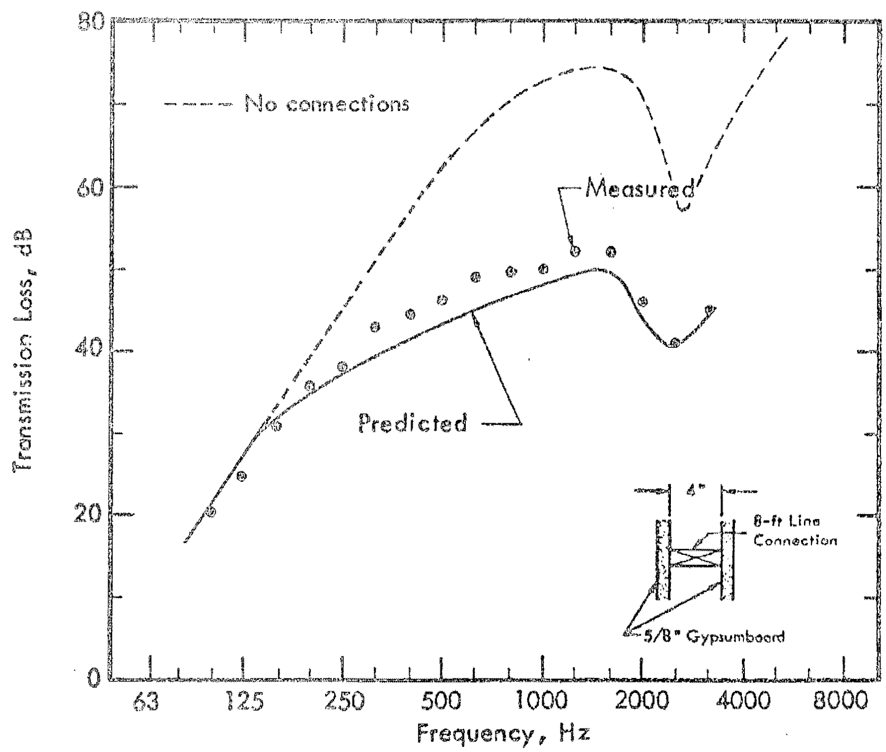


Figure 26. Measured and Calculated Values of Transmission Loss for a Double Panel with a Line Connection Between the Panels

- The values of transmission loss for the basic structure
- The modified structure with one of the panels mounted on points 24 inches on center
- The modified structure with both panels mounted on points 24 inches on center

The points consisted of 1 inch x 1 inch x 1/4-inch pieces of plywood nailed to the studs; the panel(s) were subsequently nailed to the plywood points. The figure also depicts the predicted values for the line and point connections. The agreement between predicted and measured results is good for point connections, but a discrepancy is noticed in the case of the line connections. The reason for this additional discrepancy is the same as that discussed earlier regarding line connections. In this case, however, the presence of many wooden studs is most likely to significantly affect the validity of the theory. As a result, it would appear that the empirical correction factor that has to be applied to Equations (31) and (36) for line connections should be 5 dB to account for typical practical constructions. The practical version of Equation (36) thus becomes:

$$\Delta TL_M \approx 10 \log (b f_c) - 29 \text{ dB} \tag{37}$$

Note that in both cases the accuracy of the theory at frequencies approaching coincidence is less than in the previous more ideal structures, as is to be expected.

The increase in transmission loss produced by mounting just one of the panels on point connections is in the order of 5 dB over a fairly wide frequency range. Of particular interest is the small increase (in the order of 1 dB) in transmission loss produced by introducing point connections on both sides of the wood studs. It appears that this is an unnecessary complication.

The experiments were repeated using the same wood stud system as before, but with 3/8-inch gypsumboard mounted on one side and 5/8-inch gypsumboard on the other. The results of the measurements are given in Figure 28. The agreement between the predicted and measured values is good at frequencies lower than the critical frequency for both the point and line connections, if the 5 dB empirical correction is applied to the latter. Again, little or no significant increase in values was obtained by mounting both panels on point connections. Examination of Equation (34) shows that the value of f_{BP} – the bridging frequency – and hence the transmission loss, increases as the

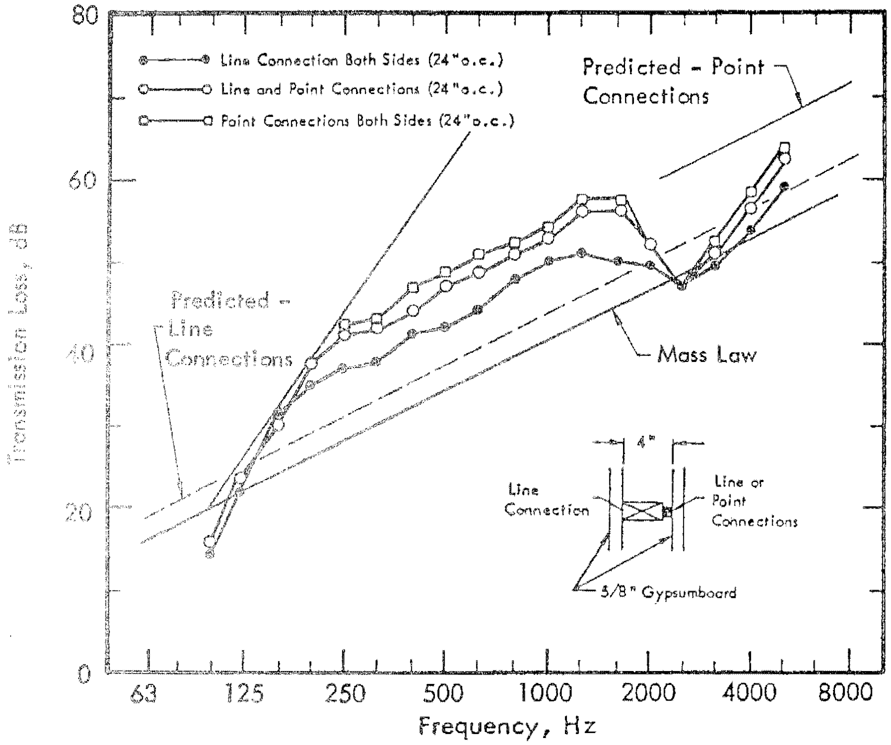


Figure 27. Measured Values of Transmission Loss for a Double Panel with One and Both Panels Mounted with Point Connections

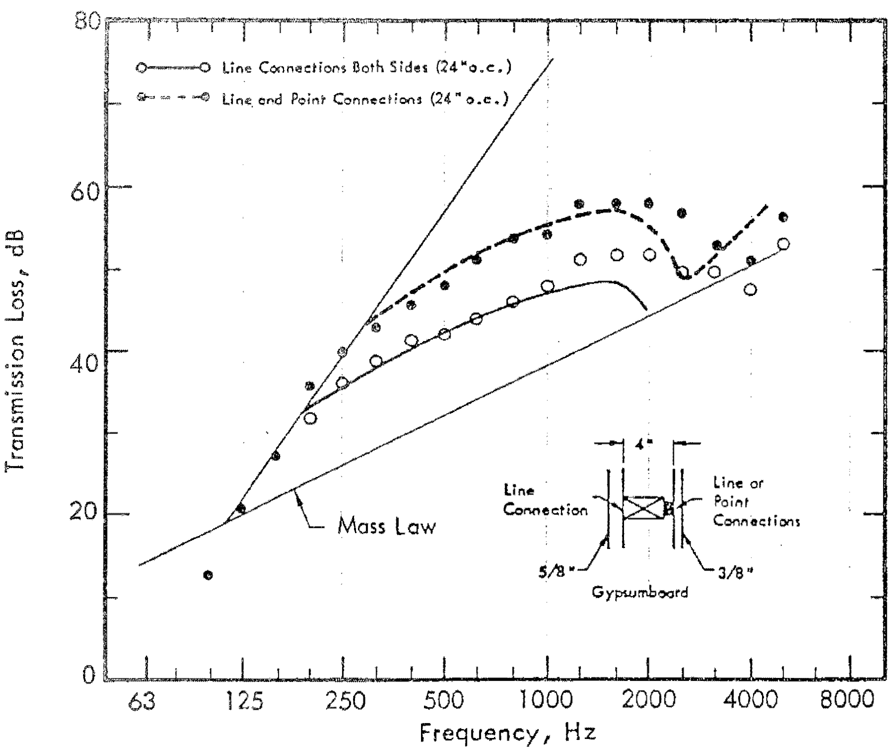


Figure 28. Measured and Calculated Values of Transmission Loss for a Double Panel with One of the Panels Mounted with Point Connections

critical frequency is increased. It therefore follows that the panel having the highest critical frequency, i.e., the more flexible panel of the two, should be attached by means of point connections.

The expressions given in Equations (35) and (37) show that in the frequency region dominated by the sound bridges, the increase in transmission loss for the above two constructions obtained by attaching one of the panels on point connections is given by:

$$10 \log (e f_c) - 32 \tag{38}$$

where it is assumed that the line study spacing b is equal to the point spacing e. The additional 5 dB is included as the empirical correction factor for the line connection calculation. Evaluation of this expression gives increases of 5 dB and 7 dB for the 5/8-inch and 3/8-inch gypsumboard panels, respectively, which agrees very well with the measured increases shown in Figures 27 and 28.

In summary, it can be stated that the simplified theory discussed above provides results that are a considerable improvement over those obtained using prediction methods previously available. The accuracy of the predicted results is high at frequencies less than the critical frequency. At frequencies in the vicinity of and greater than the critical frequency, the theory is no longer strictly valid. However, it is interesting that the predicted results in this frequency region are conservative (i.e., low) at worst and often agree surprisingly well with those measured. It is useful to take advantage of this unexpected outcome, but extreme caution naturally must be taken in interpreting the results in the frequency region above coincidence.

2.3.3 Isolated Panels

The preceding discussion has demonstrated the benefits of point connections between the panels of a double panel structure. The connections used in the series of measurements were solid in the sense that the two opposite faces that connected directly to the panels moved in phase and had essentially the same velocity. It is to be expected that the introduction of a resilient connection between the panels and the connections would lessen the amount of energy transferred from one panel to another, and hence increase the overall transmission loss. An examination of Equation (31) supports this idea, since the decrease in transmission loss depends on the velocity ratio between the two ends of the connection.

In practical constructions, it is not feasible to connect the panels together by means of a resilient element such as a spring, because of the requirements for a support system. Neither is it feasible to employ simple point connections in the form of a rod, since the support system needs to be attached firmly to the base plate or floor to be of any practical use. It is possible, however, to obtain the point connection and the isolated point connection by the method illustrated in Figure 29. This illustration shows that the normal stud system is still being used, but that the panels are attached to points protruding from it. Such a system is likely to be acoustically superior to one containing connections in the form of rods due to the additional mass introduced by the line studs. In addition, it is a simple matter to introduce a resilient material between the panel and the points.

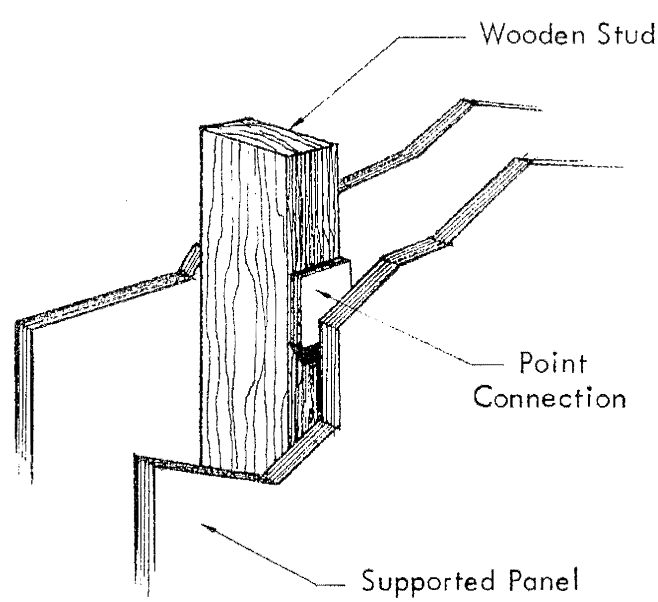


Figure 29.

Method of Providing a Point Connection to One Panel in a Double Panel Construction

Sound bridging between the two panels of a double wall construction occurs not only through the vertical studs, but also through the top and bottom plates. It is to be expected that the transmission of energy through the plates will be less (per unit length, say) than that through the studs, since the plates are supposedly connected firmly to the floor and ceiling, respectively. Nevertheless, it can result in an appreciable decrease in the transmission loss. This is demonstrated in Figure 30 for the case of a double 5/8-inch gypsumboard wall mounted on a 2-inch x 4-inch wood perimeter in the test facility (total panel dimensions 10 feet x 8 feet), with a 2-inch layer of absorption in the cavity. It is to be noticed that the effect of the perimeter is to reduce the transmission

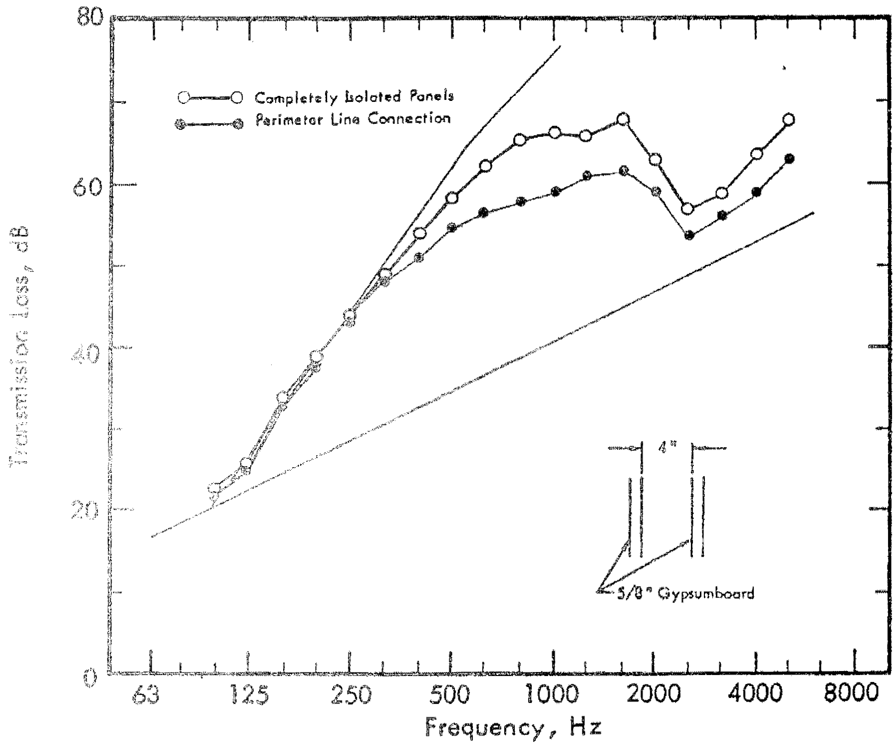


Figure 30. Measured Values of Transmission Loss for a Double Panel with no Connections and with Perimeter Connections

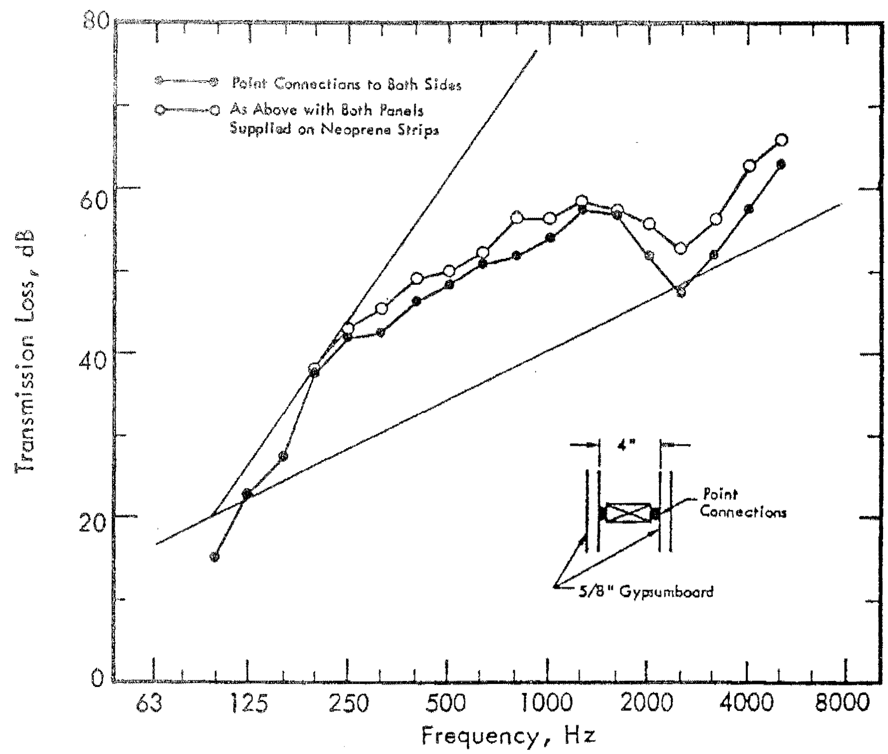


Figure 31. Measured Values of Transmission Loss for a Double Panel with Both Panels Mounted with Point Connections on Resilient Base Strips

loss by amounts up to 8 dB at some frequencies. In a practical construction, the vertical portion of the perimeter introduced into the test assembly is just another vertical stud. In this respect, the above test is not truly representative. On a simple length basis, however, the additional bridging by the vertical portions of the perimeter accounts for only 2 to 3 dB of the total decrease in transmission loss, which may be considered as fairly insignificant.

The importance of sound bridging by way of the top and bottom plates in a practical double wall construction depends, of course, on the amount of bridging that is provided by the stud support system, which in turn depends on the way the individual panels are attached to the studs. In a conventional construction, with the panels nailed or screwed directly to the studs, the amount of energy transmitted by means of the plates will be small compared to that transmitted through the studs. The concept of attaching the panels to the studs with point connections, however, will result in a significant reduction in the importance of the studs as a transmission path. This applies equally well to the plates since the panels can also be connected to them by point connections. Consequently, the only path of concern, other than that through the point connections, is through the line where the panels contact the floor. A reduction of the amount of energy transmitted by way of this path can be obtained by supporting the panel on a thin layer of resilient material. The effect of this measure on the overall transmission loss depends on the critical frequency of the panel that is being supported. For example, the increase in transmission loss for the case of a 5/8-inch gypsumboard panel construction, with point connections due to the addition of a neoprene resilient base support for both panels, is shown in Figure 31 to be 1 or 2 dB over much of the frequency range. The benefit of providing the resilient base support for just one of the panels is presumably less than this. Similar experiments with a 3/8-inch gypsumboard panel showed less improvement (if any), as would be expected with the increased value of the critical frequency. The benefits of this form of isolation increase in the frequency region near and above the critical frequency of the panel that is isolated.

It is to be expected that the optimum application of a resilient isolator material would be at the points where the panels are attached to the studs. Accordingly, the simple experiment described in the previous section that was conducted to determine the effect of nine point connections between two otherwise unconnected 5/8-inch gypsumboard panels was extended to include the effect of isolating the point connections to a certain degree by means of the insertion of a 1/4-inch layer of resilient PVC foam tape. The measured increase in the transmission loss of the panel resulting from the insertion of "isolators" is evident over the complete frequency range, as can be seen in Figure 32. It

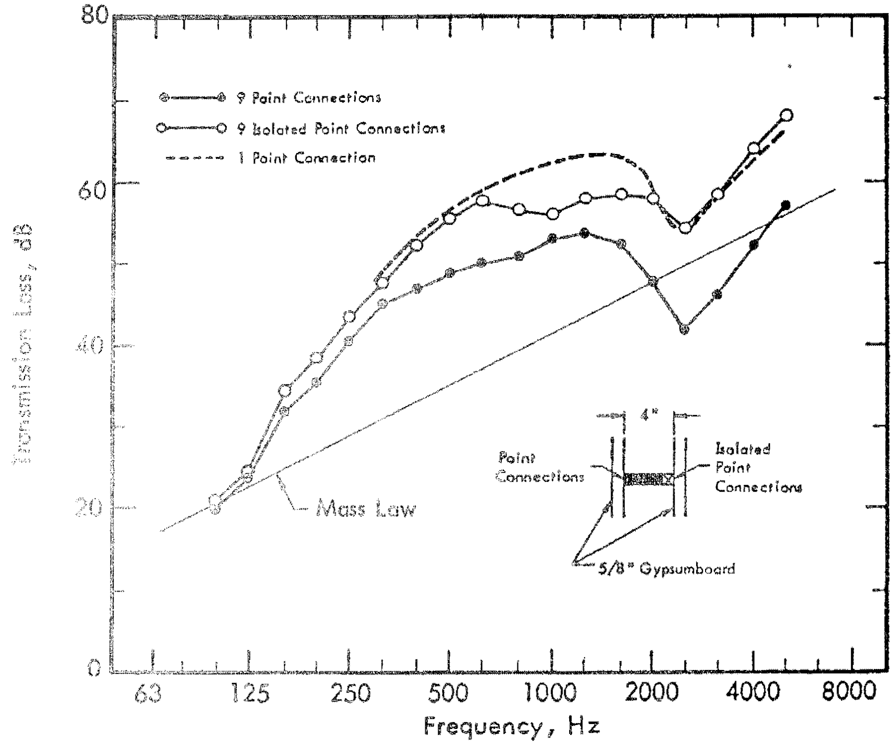


Figure 32. Measured Values of Transmission Loss for a Double Panel with a Limited Number of Isolated Point Connections

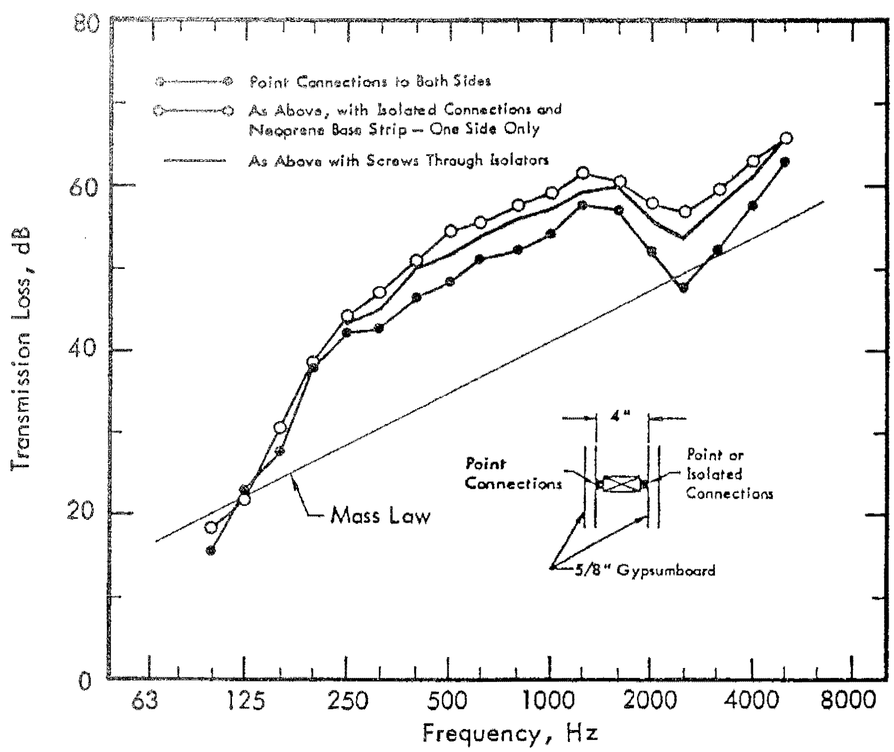


Figure 33. Measured Values of Transmission Loss for a Double Panel Construction with Identical Panels Both Mounted on Isolated Point Connections

is a significant increase at medium frequencies; perhaps most interesting of all, the addition of the isolators substantially reduces the effect of coincidence. For comparison, the transmission loss of the double wall with just one solid point connection is also included in Figure 32. The stud-isolator-panel system exhibits a resonance phenomenon in the 1000 Hz frequency region that results in a reduction of the overall transmission loss. However, at frequencies near and above the critical frequency, it appears that the introduction of the isolators has the effect of reducing the sound power radiated by a factor of approximately 9, i.e., increasing the transmission loss by approximately 10dB.

In a practical construction, the effect of introducing a degree of isolation between the panels and the point connectors is less than that obtained in the above experimental tests. This is illustrated in Figure 33 where one of two 5/8-inch gypsumboard panels has resilient base and point stud supports (located on a 2-foot x 2-foot square lattice). The reduction in transmission loss caused by placing screws firmly through the stud isolators also is shown in this figure. With this construction, there are obviously benefits from both stud and base isolation.

Similar measurements conducted with 3/8-inch gypsumboard replacing the isolated 5/8-inch panel indicated that the introduction of a resilient base support had no significant effect on the measured values of transmission loss. Figure 34 shows, however, that there is a significant increase in transmission loss as a result of introducing resilient point stud supports, particularly in the critical frequency region. Again, the acoustical performance is slightly impaired in the 1600 to 2000 Hz region due to what appears to be a resonance phenomenon. It is interesting to compare the measured results using the point isolators with values of the transmission loss predicted by Equation (35), neglecting the effects of coincidence in the panels. Normally, significant errors are introduced by neglecting coincidence, but with the introduction of isolation between the point supports and the panel, the agreement between the approximate theory and measurements is fairly good. In Figure 34, the approximate theory – which does not account for the effect of the isolators – is conservative in the mid-frequency range.

The reduction in the transmission loss of a double panel due to the introduction of a line connection between the two panels has already been discussed and is shown in Figure 26. The effect of resiliently isolating a line connection from one of the two panels by means of a complete layer of 1/4-inch PVC foam is shown in Figure 35. It is interesting to note that the resultant values of transmission loss are only slightly superior to those for a conventional steel stud of equal length, confirming the existing beliefs regarding the benefits of steel studs for noise control purposes.

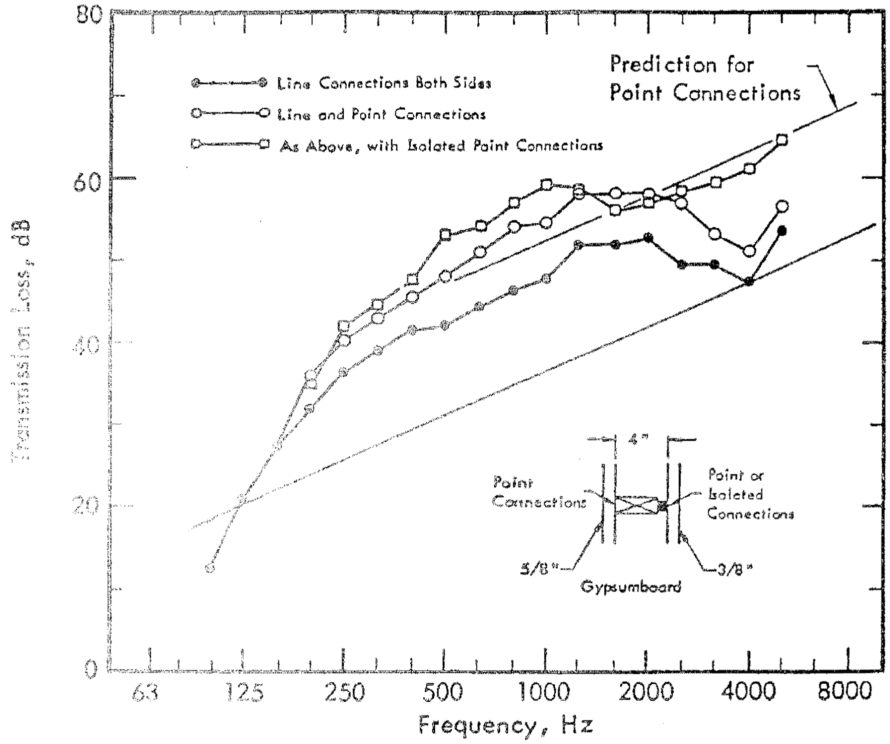


Figure 34. Measured Values of Transmission Loss for a Double Panel Construction with Dissimilar Panels Mounted on Isolated Point Connections

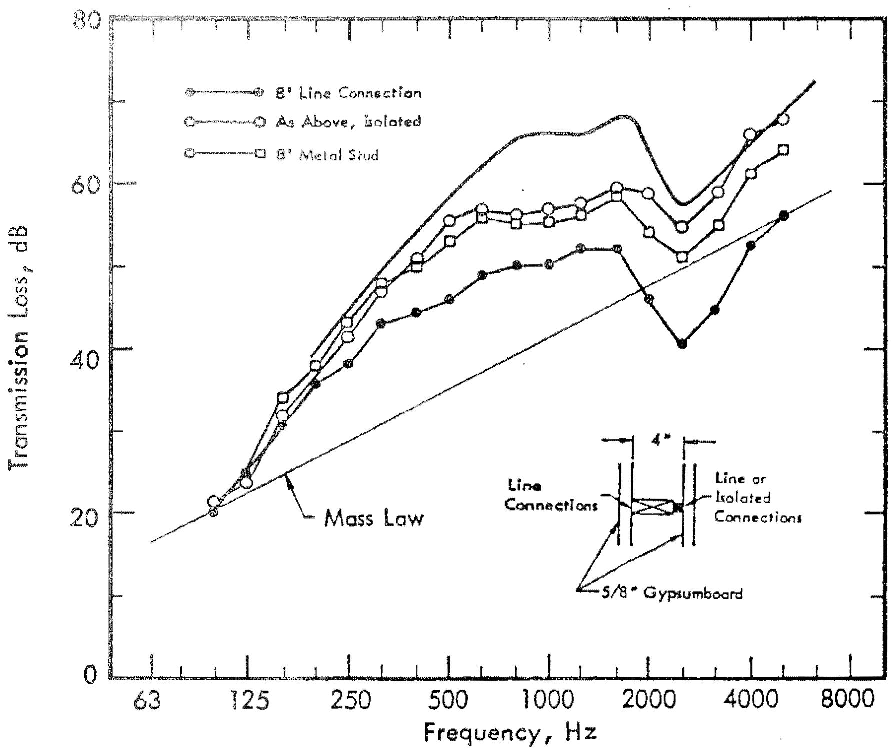


Figure 35. Measured Values of Transmission Loss for a Double Panel with an Isolated Line Connection

On the basis of the theory and the experimental results described above, the following general conclusions can be made concerning the partial isolation of wall panels from their support system:

- The introduction of a resilient mount at the base of a panel is beneficial only for the case when the panel has a low value for the critical frequency. In the experiments conducted, base resilience ceased to have any significant effect on the overall transmission loss when the critical frequency of the panel was in the order of or greater than 3000 Hz.

- The isolation of point connections results in a significant increase in the transmission loss, the increment depending upon the critical frequency of the panel, and being especially noticeable at and above the critical frequency.

2.4 SUMMARY OF DESIGN METHODS

The acoustic principles that have been discussed and presented in the preceding sections form a comprehensive basis for the design of sound attenuating structures using single or multiple panel constructions. In the course of the discussions, a series of expressions have been derived with which the transmission loss of many types of construction can be determined. The majority of these expressions are simple in form and provide values of transmission loss that are generally in good agreement with measured values.

In the process of designing new types of construction to meet specific acoustical goals, there is a definite requirement for a standard method of approach that makes proper use of the correct expressions for each particular case. Moreover, it is necessary to consider tradeoffs between parameters so that the final design provides good performance at low cost within specified constraints. This section is designed to fulfill these requirements – first, by restating the relevant expressions developed in the preceding sections, and second, by indicating how these expressions may be used to arrive at optimum designs for specific sound insulation requirements.

2.4.1 Design Expressions

The expressions derived in the preceding chapters can be divided conveniently into the categories of single and multiple panels. They are repeated here for use in the discussions on the optimum design of sound attenuating structures and for convenience in future references. The symbols used in this section are as follows:

a, b	dimensions of panel (ft)
b	spacing of line studs (ft)
c	velocity of sound in air = 1128 (ft/sec)
d	separation of panels in a double panel construction (ft)
d_1, d_2	separation of panels in a triple panel construction (ft)
E	Young's Modulus ($lbs/ft/sec^2$)
e	square root of area associated with a point connection, or the lattice spacing constant if square (ft)
f	frequency (Hz)
f_B	bridging frequency (Hz)
f_c	critical frequency (Hz)
f_L	limiting frequency for single panel (Hz)
f_ℓ	limiting frequency for double panel (Hz)
f_o	fundamental double panel resonance (Hz)
f_r	fundamental single panel resonance (Hz)
h	thickness of panel (inches)
k	wave number = $2\pi f/c$ (ft^{-1})
log	logarithm to the base 10
M	total mass of multiple panel per unit area (lbs/ft^2)
m	mass of panel per unit area (lbs/ft^2)
m_1, m_2, m_3	mass of panels 1, 2 and 3 per unit area (lbs/ft^2)
m'	effective mass of double panel for determining f_o (lbs/ft^2)
$TL(f)$	transmission loss of construction at a frequency f (dB)
$TL_1(f)$, $TL_2(f)$, etc	transmission loss for panels 1, 2, etc. at a frequency f (dB)
$TL_B(f)$	reduction in transmission loss at a frequency f for a double panel due to sound bridges (dB)
$TL_I(f)$	transmission loss at a frequency f of a multiple panel with no interpanel connections (dB)
$TL_m(f)$	transmission loss at a frequency f according to the mass law (dB)

ΔTL_M	increase in transmission loss over that calculated according to the mass law (dB)
η	loss factor of panel (dimensionless)
λ_B	wavelength of bending waves (ft)
ρ	density of air = 0.0745 (lbs/ft^3)
ρ_m	density of panel material (lbs/ft^2)

Expressions in which the dimensions are stated have been determined using the foot, pounds, seconds system of units. To convert from the foot, pounds, seconds system to the SI system of units, the following factors can be used:

1 lb	=	0.454 kg
1 ft	=	0.3048 m
1 inch	=	0.0254 m
1 lb/ft^2	=	4.88 kg/m^2
1 lb/ft^3	=	16.0 kg/m^3

a. Single Panel

The single panel is defined as a homogeneous panel having no cavities. The transmission loss characteristic of a single panel can be divided into two frequency ranges where the ratio of limiting frequency is given approximately by the expression:

$$f_L \approx \frac{0.03\,(1-\sigma)^2}{h} \sqrt{\frac{E}{\rho_m}} \qquad (39)$$

This is equivalent to the condition $\lambda_B = \left(\frac{7.7}{1-\sigma}\right) h$ – See Appendix A.

- Thin Single Panels ($f < f_L$)

The transmission loss of a thin single panel as a function of frequency is illustrated in Figure 36.

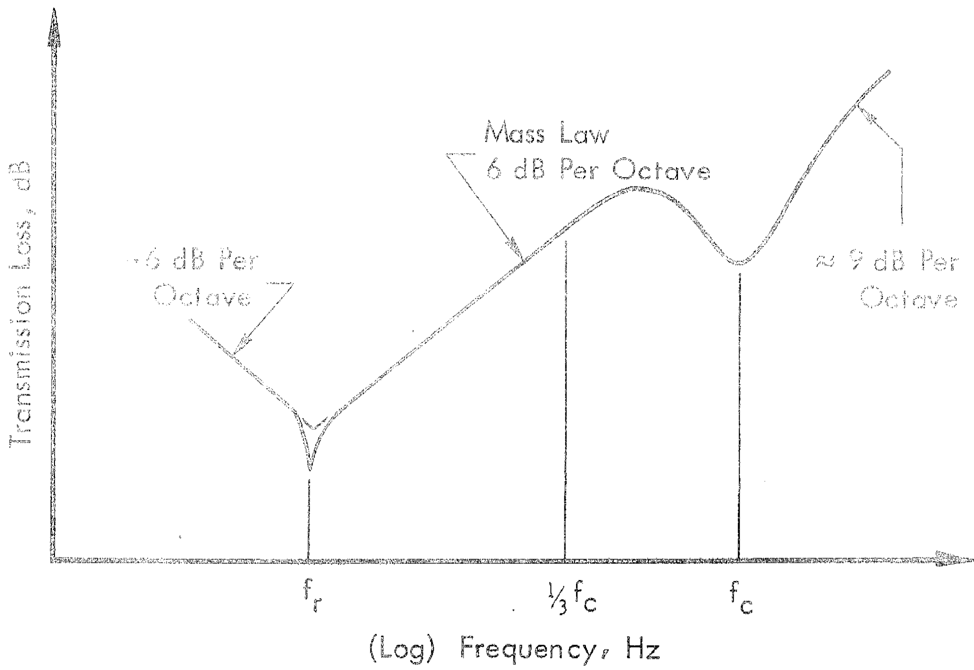


Figure 36. The General Form of the Transmission Loss as a Function of Frequency for a Thin Single Panel

The transmission loss characteristic can be divided into frequency ranges where the limiting frequencies are given by the expressions:

$$f_r \approx \frac{\pi h}{2} \sqrt{\frac{E}{12 \rho_m}} \left[\frac{1}{a^2} + \frac{1}{b^2} \right] \tag{40}$$

usually low enough to be of little concern.

$$f_c \approx \frac{c^2}{2 \pi h} \sqrt{\frac{12 \rho_m}{E}} \tag{41}$$

At a given frequency, the transmission loss is given by:

$$
\bullet \quad TL(f) = \begin{cases} TL_m(f) + 40 \log \left(\frac{f_r}{f}\right), & dB \quad f < f_r \\ TL_m(f) & f_r < f < \frac{1}{3} f_c \\ TL_m(f) + 10 \log \left(\frac{2\eta}{\pi} \frac{f}{f_c}\right) + 5, & dB \quad f > f_c \end{cases} \tag{42}
$$

where

$$
\bullet \quad TL_m(f) = 20 \log (m f) - 33.5, \quad dB \tag{43}
$$

To a first approximation, the transmission loss in the frequency region between $1/2 f_c$ and f_c can be obtained by describing a straight line between the transmission loss values $TL_m(1/2 f_c)$ and $TL(f_c)$ for $f = 1/2 f_c$ and f_c, respectively, as given by the expressions in Equation (42).

Measured values of the transmission loss for some conventional building materials are shown in Table 1.

- Thick Single Panels $(f > f_L)$

See Appendix A.

b. Double Panel

The double panel is defined as consisting of two single panels (of any thickness) with an intervening airspace or cavity. It is assumed that there is a full layer of absorption material – at least equal to 3-1/2 inch fiber glass batts – in the cavity. There may also be mechanical connections or sound bridges between the two panels.

The transmission loss of a double panel with sound bridges as a function of frequency is illustrated in Figure 37.

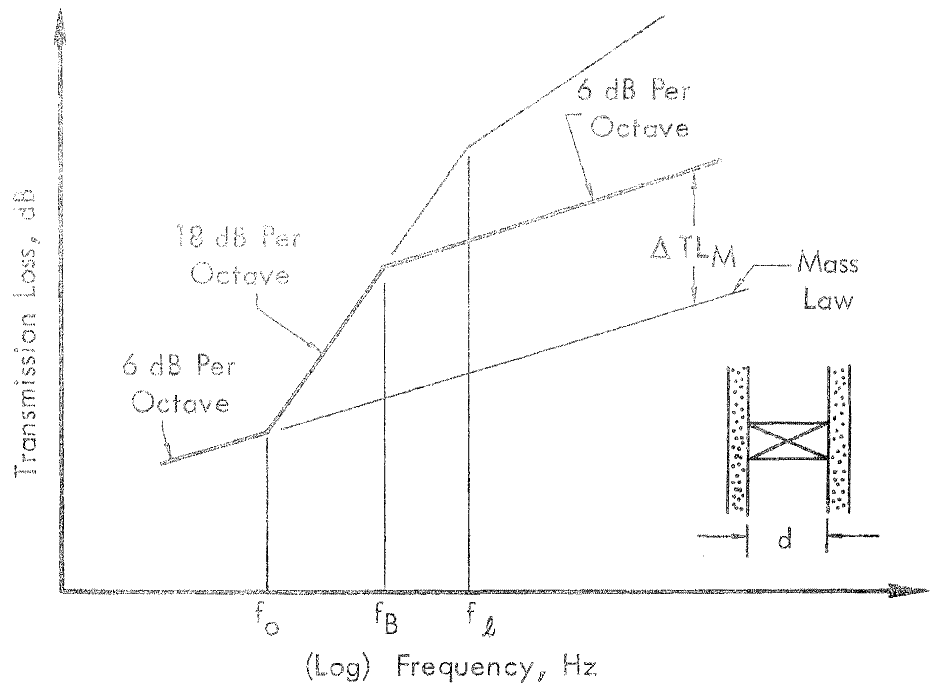


Figure 37. The General Form of the Transmission Loss as a Function of Frequency for a Double Panel with Sound Bridges

The transmission loss characteristic can be divided into frequency ranges where the limiting frequencies are given by the expressions:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{3.6 \rho c^2}{m' d}} \qquad \text{(see Figure 38)} \qquad (44)$$

where $m' = \dfrac{2 m_1 \, m_2}{m_1 + m_2}$

TABLE 1

MEASURED VALUES OF TRANSMISSION LOSS (dB) FOR A NUMBER OF CONVENTIONAL BUILDING MATERIALS

Construction	Mass lbs/ft^2	Critical Frequency, Hz[3]	One-Third Octave Band Center Frequency, Hz																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
1/4" Gypsumboard	1.0	6,300	7	9	10	12	14	16	17	19	21	23	25	27	28	30	32	33	32	25
3/8" Gypsumboard	1.5	4,000	10	12	14	16	17	19	21	23	26	27	29	30	32	33	33	29	25	28
1/2" Gypsumboard	2.0	3,150	12	15	17	18	20	22	24	25	27	28	31	32	33	33	29	25	27	31
5/8" Gypsumboard	2.6	2,500	14.5	16.5	18.5	20.5	22.5	24.5	26.5	28	29.5	31	32	33.5	34	30.5	25.5	29	33	35.5
Lamination[1] of 1/4" and 1/4" Gypsumboard	2.0	5,000	13	15	17	19	20	22	24	26	27	29	31	32	34	35	36	37	37	33
Lamination[1] of 1/2" and 1/2" Gypsumboard	4.0	3,150	19	21	23	25	27	28	29	31	32	33	34	35.5	36.5	37	36.5	33.5	36	41
Lamination[2] of 1/2" and 5/8" Gypsumboard	4.6	2,500	21	23	25	27	29	31	33	33.5	35	35.5	35	35.5	36	34	32	34	36.5	4.0
Lamination[2] of 5/8", 1/2" and 5/8" Gypsumboard	7.2	2,000 to 2,500	23	25	27	29	31	33	35	34	35	35	36	38	40	39	39	41	43	47
1/8" Hardboard	0.7	10,000	7	7	9	10.5	12.5	14	18	19	21	22.5	23.5	26	27.5	29	32	34.5	36.5	36.5
1/4" Hardboard	1.4	5,000	10	12	14	15	17	20	21.5	23	25	27	29	32	33.5	35	36	36.5	37	35
2" Reinforced Concrete	≈ 24[4]	630	34	35	36	38	37	36	38	39	41	43	46	49	51	52	54	56	58	59
4" Reinforced Concrete	≈ 48[4]	315	39	42	42	42	42	43	43	46	50	53	54	55	57	59	60	64	66	68
6" Reinforced Concrete	≈ 72[4]	200	39	39	42	42	42	46	48	50	53.5	55.5	58	60	62	64	64	66	68	70

[1] Spot laminations – 12" on centers.

[2] Spot laminations – 24" on centers.

[3] Center of the One-Third Octave Band within which the critical frequency lies.

[4] Assuming a density of concrete of 144 lbs/ft . This will vary according to the aggregate.

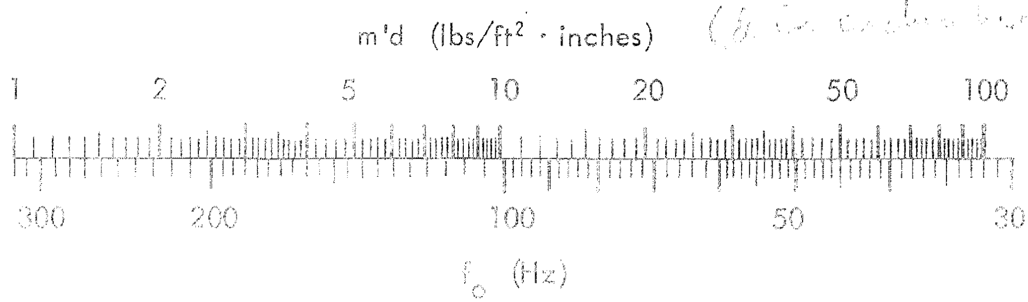


Figure 38. Relationship Between the Product $m'd$ and the Fundamental Double Panel Resonant Frequency f_o

$$f_B = f_o \text{ antilog} \left(\frac{\Delta TL_M}{40} \right) \tag{45}$$

$$\Delta TL_M = \begin{cases} 20 \log (e f_c) - 61, & \text{dB} \quad \text{for point bridges spaced } e \text{ feet apart on one panel only} \\ 10 \log (b f_c) - 29, & \text{dB} \quad \text{for line bridges spaced } b \text{ feet apart} \end{cases} \tag{46}$$

for $m_1 = m_2$. For other combinations of mass, see Equations (35) and (36).

$$f_\ell = \frac{c}{2 \pi d} \tag{47}$$

$$f_c \approx \frac{c^2}{2 \pi h} \sqrt{\frac{12 \rho_m}{E}} \tag{48}$$

At a given frequency, the transmission loss is given by:

$f < \frac{1}{2} f_c$ (for either panel)

$$TL(f) = \begin{cases} TL_I(f) & f < f_0 \\ TL_M(f) + \Delta TL_M & f > f_B \end{cases} \qquad (49)$$

Note: The expression given in Equation (49) is fairly accurate for all frequencies if isolators are inserted – see Section 2.3.3.

$f > \frac{1}{2} f_c$ (for either panel)

At frequencies approaching or greater than the critical frequency of the panel mounted on points or lines, the following expressions must be taken with discretion.

$$TL(f) = TL_I(f) - TL_B(f) \qquad (50)$$

where

$$TL_I(f) \approx \begin{cases} TL_M(f) & f < f_o \\ TL_1(f) + TL_2(f) + 20 \log (fd) - 39, \quad dB & f_o < f < f_\ell \\ TL_1(f) + TL_2(f) + 6, \quad dB & f > f_\ell \end{cases} \qquad (51)$$

(d in feet)

and $TL_1(f)$, $TL_2(f)$ can be measured or calculated values of transmission loss.

For point connections to one panel only:

$$TL_B(f) = \begin{cases} 20 \log\left(\dfrac{m_2 d}{e\, f_c}\right) + 40 \log(f) - 17.5, & \text{dB} \quad f_o < f < f_\ell \\ \\ 20 \log\left(\dfrac{m_2}{e\, f_c}\right) + 20 \log(f) + 27.5, & \text{dB} \quad f > f_\ell \end{cases} \tag{52}$$

m_2 = mass of panel on point connections. For line connections:

$$TL_B(f) = \begin{cases} 10 \log\left(\dfrac{m_2^2 d^2}{b\, f_c}\right) + 40 \log(f) - 44, & \text{dB} \quad f_o < f < f_\ell \\ \\ 10 \log\left(\dfrac{m_2^2}{b\, f_c}\right) + 20 \log(f) + 1, & \text{dB} \quad f > f_\ell \end{cases} \tag{53}$$

$$TL_M(f) = 20 \log(M f) - 33.5, \quad \text{dB} \tag{54}$$

where $M = m_1 + m_2$

CAUTION: – The transmission loss of a double panel, calculated by the method described above, in some cases may not be obtained in practical installations because of flanking transmission through adjoining elements.

For design purposes, Equation (49) can be combined with Equation (46) to give an expression for parameter requirements for $f > f_B$:

$$M e f_c = \frac{1}{f} \cdot \text{antilog}\left[\frac{TL(f) + 94.5}{20}\right] \quad \text{for point connections} \tag{55}$$

$$M^2 b f_c = \frac{1}{f^2} \cdot \text{antilog}\left[\frac{TL(f) + 62.5}{10}\right] \quad \text{for line connections} \tag{56}$$

c. Triple Panel

The triple panel is defined as consisting of three single panels (of any thickness) with two intervening airspaces or cavities. It is assumed that there is a full layer of absorption material — at least equal to 3-1/2 inch fiber glass batts — in each cavity. There may also be mechanical connections or sound bridges between the individual panels.

The transmission loss of a triple panel as a function of frequency is illustrated in Figure 39.

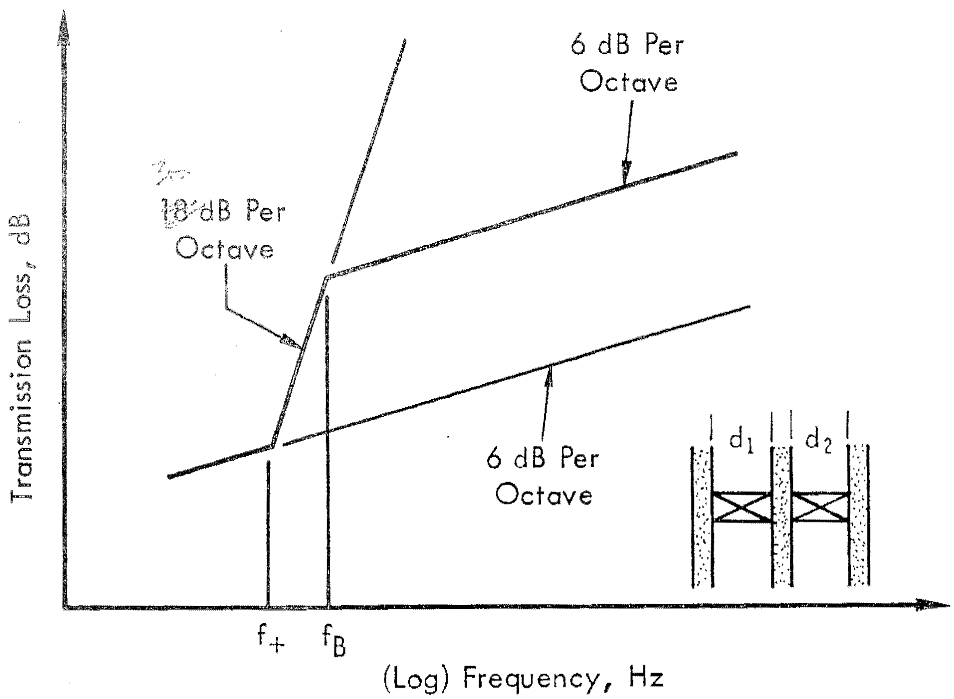


Figure 39. The General Form of the Transmission Loss as a Function of Frequency for a Triple Panel with Sound Bridges

The transmission loss $TL_I(f)$ of a triple panel with no sound bridges is given by the expression:

$$TL_I(f) \approx \left\{ \begin{array}{ll} TL_M(f) & f < f_+ \\ & \\ TL_1(f) + TL_2(f) + TL_3(f) & f_+ < f < f_\ell \\ + 40 \log(fd) - 78, \quad dB & \\ & \\ TL_1(f) + TL_2(f) + TL_3(f) + 12, \quad dB & f > f_\ell \end{array} \right\} \qquad (57)$$

$$TL_M(f) = 20 \log (Mf) - 33.5, \quad dB \qquad (58)$$

where $\quad M = m_1 + m_2 + m_3$

$$f_+ = \frac{1}{2\pi} \sqrt{\frac{3.6 \rho c^2}{m_1 d_1}} \qquad \text{(See Figure 38)} \qquad (59)$$

where $\quad m_1 = m_3 = \frac{1}{2} m_2$

and $\quad d_1 = d_2 = d$

(See Appendix D for other configurations.)

$$f_\ell = \frac{c}{2\pi d} \qquad (60)$$

The transmission loss of a triple panel construction with sound bridges depends on the configuration of the bridges. If they are in line, as illustrated in Figure 39, then at frequencies less than the critical frequency of all the three panels, the transmission loss of the construction is given approximately by Equation (49), where $TL_I(f)$, $TL_M(f)$ and ΔTL_M are given in Equations (57),

(58) and (46). At frequencies greater than the critical frequency of any of the panels, the expression for the transmission loss becomes too complex to be of practical use although it is possible to make conservative estimates.

CAUTION: – The transmission loss of a triple panel calculated by the method described above may not be obtained in practical installations because of flanking transmission through adjoining elements.

2.4.2 Special Design Methods

The expressions given in the preceding section are sufficient for the design of a construction that is required to satisfy a specific transmission loss requirement. In many cases where the requirement is not severe, a simple single panel may suffice, provided, of course, the mass required to achieve the transmission loss is not too high. If a practical single panel does not provide sufficient transmission loss, a brief review of the HUD Noise Control Guide (Reference 14) or the prototypes given in Section 3.3 will show if there is any existing construction that will satisfy the requirement. If both of these approaches fail to come up with a desirable construction or if the requirement itself is for a construction having low cost and/or high transmission loss, then it is necessary to design a construction by means of the expressions in the preceding section.

As an example, suppose the transmission loss requirement shown in Figure 40 is required for an internal load-bearing wall construction. To define a construction that will satisfy this requirement, the steps in the calculation are as follows:

1. Draw a straight line with a slope of 6 dB per octave tangential to the required transmission loss characteristics. See Figure 40.

2. Note the value of the transmission loss given by this line at a certain frequency – say, 1000 Hz for convenience – and insert the value into Equation (43) to determine the mass of the single panel that would provide the straight line characteristic. In this case, TL_M at 1000 Hz is equal to 58 dB; hence a mass of 38 lbs/ft^2 is required.

3. Determine the feasibility of using a single panel of mass 38 lbs/ft^2 to satisfy the requirement. Such a high mass can be obtained only by using concrete or masonry walls which invariably exhibit low values for the critical frequency. For example, a 3-inch concrete panel of mass 36 lbs/ft^2

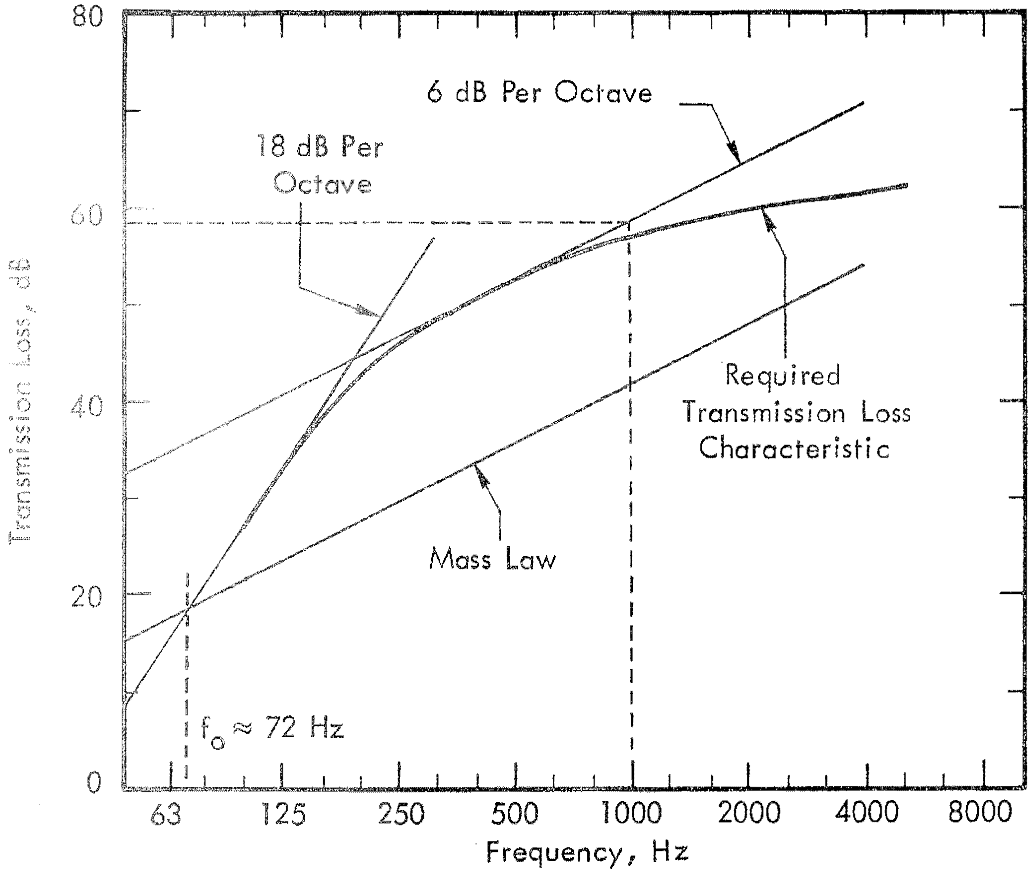


Figure 40. Required Transmission Loss Characteristic for Design Example

has a critical frequency of approximately 400 Hz. At frequencies greater than 400 Hz, the concrete panel will provide a transmission loss approximately 6 dB less than that calculated according to the mass law – Equation (43). That is, its effective mass is one-half of its actual mass. Thus, a 6-inch concrete panel of mass 72 lbs/ft^2 is required to satisfy the transmission loss requirement shown in Figure 40. Examination of the measured values of transmission loss for a 6-inch concrete panel as given in Figure 6 show that this panel would in fact satisfy the requirement. If the 6-inch panel is too massive or undesirable for other reasons, it is necessary to consider a double panel construction.

4. Consider the possibility of a double panel with line connections, i.e., a common wooden or metal stud wall. Insert the value of the required

transmission loss (58 dB) at a given frequency (1000 Hz) in Equation (56) to determine the required value of the quantity $M^2 b f_c$. In this case, the minimum requirement is given by:

$$M^2 b f_c = 1.1 \times 10^6 \qquad (\text{lbs}^2/\text{ft}/\text{sec})$$

If the stud spacing b is taken as 2 feet, the requirement becomes:

$$M^2 f_c = 5.5 \times 10^5 \qquad (\text{lbs}^2/\text{ft}^2/\text{sec})$$

Using gypsumboard, it is possible to obtain values of the critical frequency in the range 2500 Hz for 5/8-inch thickness to 6000 Hz for 1/4-inch thickness. Taking a median value of 4000 Hz (3/8-inch gypsumboard), the minimum requirement for the total mass of the construction, excluding the studs, is then:

$$\underline{M \approx 12 \text{ lbs/ft}^2}$$

5. Consider the possibility of a double panel with one of the panels mounted on point connections. Repeating the general method described in (4.), but this time using Equation (55), shows that for a panel having a critical frequency of 4000 Hz mounted on points with a lattice spacing of 2 feet the minimum requirement for the total mass of the construction, excluding the studs, is:

$$\underline{M \approx 5.3 \text{ lbs/ft}^2}$$

This is significantly less than the 12 lbs/ft^2 required with the same panel mounted directly to the studs. The remainder of this example therefore assumes the presence of point connections for the panel of critical frequency 4000 Hz, although the method for the case of line connections is exactly the same.

6. Calculate the transmission loss for the total mass of 5.3 lbs/ft^2 according to Equation (43) and insert the mass law line onto the diagram – see Figure 40.

7. Draw a straight line with a slope of 18 dB per octave tangential to the required transmission loss curve as shown in Figure 40.

8. Determine the frequency f_o at which the mass law line intersects the line at 18 dB/octave. In this case $f_o \approx 72$ Hz.

9. Using Equation (44) determine the spacing d of the two panels in a double panel construction with each panel of mass $1/2 \times 5.3$ lbs/ft^2 (the optimum condition) for the frequency f_o to be 72 Hz. In this case d = 7.5 inches.

It would appear from this result that the requirement would be satisfied by 8-inch wooden studs (actual dimensions 7.5 inches) with 5/8 inch gypsumboard (m = 2.6 lbs/ft^2) mounted on both sides. However, the critical frequency of 5/8-inch gypsumboard is 2500 Hz, which is well below the required value of 4000 Hz. The critical frequency can be raised by using 3/8-inch gypsumboard (f_c = 4000 Hz); however, since the mass of this material is only 1.5 lbs/ft^2, it is necessary to use two laminated panels. Checking back through the calculations shows that this combination of materials with a spacing of 5-1/2 inches in place of 7.5 inches would provide a value of 80 Hz for f_o, which is close to that required. To obtain an increase in the transmission in the vicinity of the critical frequency of the two panels, the point connection can consist of 1/4" x 1" x 1" squares of PVC foam tape through which the laminated panel is nailed. Thus the final construction is as follows:

> 2" x 6" wooden studs, 24" on center; 5/8" gypsumboard nailed to one side; on the other side, two laminated panels of 3/8" gypsumboard mounted on point connections 24" on center. Fiber glass batts (3-1/2") to be included in the cavity.

This construction is one of the prototypes that was tested in the program – see the results for prototype 2. It is interesting to compare the total mass of this construction (5.6 lbs/ft^2 excluding studs) to that of the single panel with equivalent performance (72 lbs/ft^2).

The design method described above is based on the simplified expressions given in Section 2.4.1, without considering the effect of coincidence on the individual panels. On completion of this approximate method, the transmission loss of the final construction can be checked more accurately by using

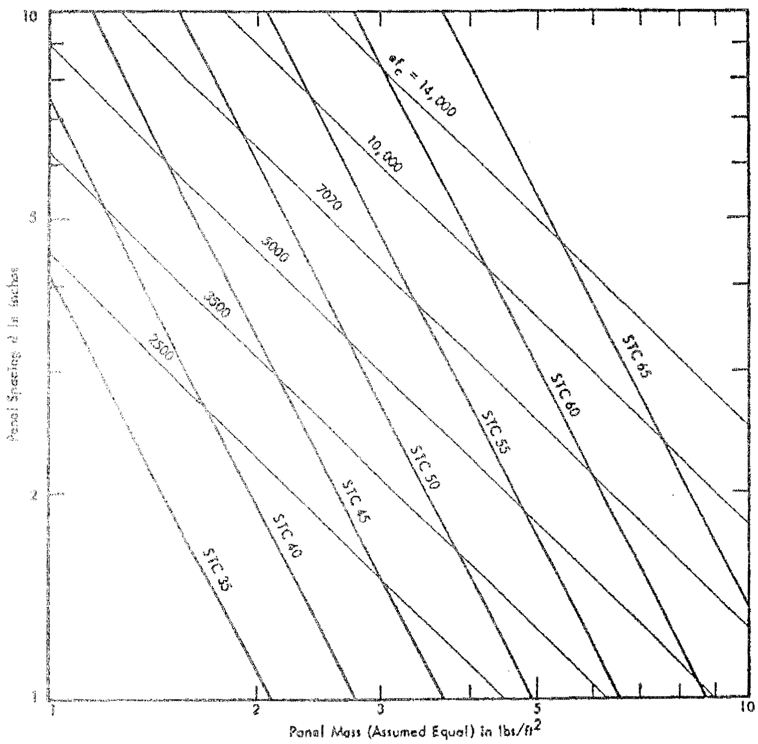
Equations (49) and (50) in the appropriate frequency ranges. In some cases, iterative calculations may be necessary to obtain the required characteristic within stated parameter constraints.

2.4.3 STC Design Method

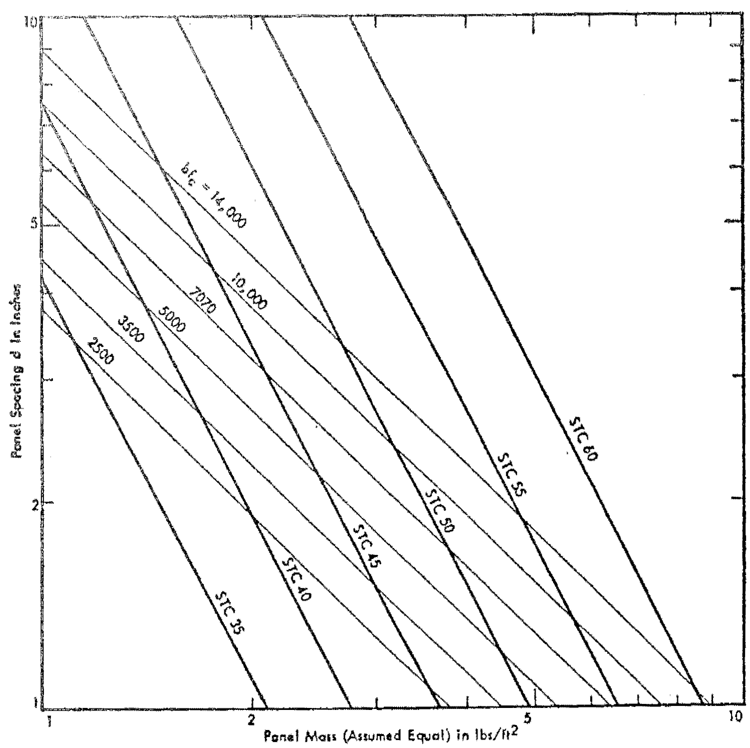
The parameters that determine the transmission loss of a double wall can be varied independently to provide almost any acoustical characteristic that may be desired. Practical limitations on the size and weight of the construction help to set bounds on the degree of variation possible in each of the parameters, but the optimum configuration for a specific application can still be obtained only by means of iterative calculations (see Section 2.4.2). Clearly, it would be of value to combine the independent parameters in the form of an expression or chart so that the effects of perturbations of any one parameter could be readily observed. It is possible to do this in terms of the STC rating.

To determine the STC rating of a construction (Reference 15), the STC weighting contour is superimposed upon the measured values of transmission loss and adjusted so that the sum of the deficiencies (i.e., deviations of the transmission loss values below the STC weighting contour) does not exceed 32 dB, with the additional constraint that no single deficiency exceeds 8 dB. With the contour adjusted to its highest value that meets these requirements, the STC rating of the construction corresponds to the value of the transmission loss in dB given by the weighting contour at a frequency of 500 Hz.

The general form of the transmission loss curve for a double panel with bridging as a function of frequency is characterized by a slope of 18 dB per octave at the low frequencies and 6 dB per octave at higher frequencies, neglecting for the moment the effects of coincidence. The changeover between the two distinct slopes occurs at the bridging frequency f_B. Since the shape of the curve is well defined, it is possible to determine its STC rating in terms of the important parameters of the construction. The derivation of the expressions necessary for this to be accomplished is contained in Appendix F. It is assumed in this derivation that the maximum allowable deviation of 8 dB is taken at 125 Hz. The results have been simplified and incorporated into the design charts shown in Figures 41 (a) and (b) for cases involving point connections to one panel and line connections to both panels respectively. This chart contains two sets of diagonal lines which provide information on the required value of the parameters such that the portions of the transmission loss curve both above and below the bridging frequency f_B are compatible with a given STC rating. The solid lines have the panel mass m (assumed equally distributed between the panels) and the separation d as abscissa and ordinate, respectively, with STC rating as the parameter, and represent the criterion for the portion of the



(a) Point Connections



(b) Line Connections

Figure 41. STC Design Chart for a Double Panel

transmission loss curve at frequencies less than f_B. For example, Figure 41(a) shows that a mass of 3.5 lbs/ft^2 and a panel separation of 3.5 inches are required to complete the requirement at low frequencies for an STC rating of 55. To achieve the rating, however, the dashed lines which have the product $e\,f_c$ as parameter indicate that a minimum value of $e\,f_c = 7070$ is required. Thus the two sets of curves on the chart are used to determine the design parameters for a double panel in the low and high frequency ranges. It is of course necessary to ensure that the critical frequencies of the two panels are either sufficiently high or spaced sufficiently far apart – see Figures 15 and 16 – so as not to affect the STC rating.

The STC rating of the construction is dependent on the transmission loss at 125 Hz, so any perturbations in the product "md" will directly affect the rating in a manner that can be determined from the chart. The chart does not give the direct STC rating for a construction where the quentity "$e\,f_c$" is incompatible with the same rating as that given by the product "md". It is difficult to state an exact method for calculating the change in STC rating due to such a condition; in general, however, it can be assumed that the reduction (ΔSTC) in the rating is given approximately by the expression:

$$\Delta STC \approx 20 \log \left\{ (e\,f_c)_{STC} \Big/ (e\,f_c)_{DES} \right\}$$

where

$(e\,f_c)_{STC}$ = the value of the product required to be compatible with the product "md" in giving a specific STC rating (e.g., 7070 in the example given above)

$(e\,f_c)_{DES}$ = the value of the product actually used in the design of the construction.

Because the STC rating as determined from the chart of Figures 41(a) and (b) are dependent on the transmission loss of the construction at 125 Hz, it is not possible to increase the rating by increasing the value of the product "$e\,f_c$".

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3.0 DESIGN OF BUILDING ELEMENTS FOR HIGH TRANSMISSION LOSS

3.1 THE 20 dB REQUIREMENT

As defined in the contract statement of work, the acoustical goal for the building elements to be designed in this study is that the transmission loss must exceed the calculated mass law values by at least 20 dB in the frequency range 125 Hz to 4000 Hz. In addition, it is required that the elements perform satisfactorily with respect to the environment and be lower in cost (per STC value) than other constructions presently known. A cursory examination of the acoustical requirement indicated that existing techniques in the theory and practice of sound transmission loss were insufficient for the design task. For example, the requirement -- which will be referred to simply as the "20 dB requirement" in all future discussions -- is not satisfied by any of the common construction types such as those listed in the HUD Noise Control Guide (Reference 14). Additionally, a fairly intensive search has shown that nowhere in the main published literature is there mention of a construction satisfying the requirement over the entire frequency range 125 Hz to 4000 Hz. As a result, it was necessary to return to the fundamentals of sound transmission loss to develop new techniques by which the 20 dB requirement could be satisfied. The results of this study are summarized in Section 2.4.

This section contains an examination of the design parameters necessary to satisfy the 20 dB requirement and a discussion on the practical realization of these parameters.

3.1.1 Design Parameters for the 20 dB Requirement

Single panels alone cannot be used to satisfy the 20 dB requirement since their transmission loss exceeds the mass law only at frequencies below the natural panel resonance and above the critical frequency. It is therefore necessary to consider double and triple panel constructions.

Section 2.2.4 shows that for a given total mass and thickness, the double panel provides a greater transmission loss at low frequencies than the triple panel. The transmission loss of the two types of constructions are equal at a frequency ($4f_o$) which is four times the fundamental resonant frequency of the double panel, where the value is 24 dB in excess of the mass law. The double panel is therefore slightly superior to the triple panel in achieving the 20 dB requirement at the lowest frequency of interest. At frequencies greater than $4f_o$, the transmission loss of the triple panel is greater than that of the double panel, provided there are no mechanical connections between the individual panels. When the cost and complexity of the support system required for a triple panel construction are also taken into account, however, it turns out that double panels provide the most cost-effective method of achieving the 20 dB requirement. If more than 20 dB in excess of the mass law is necessary, it might be necessary to use a triple panel construction.

The minimum design for a multiple panel construction that just satisfies the 20 dB requirement is depicted in Figure 42.

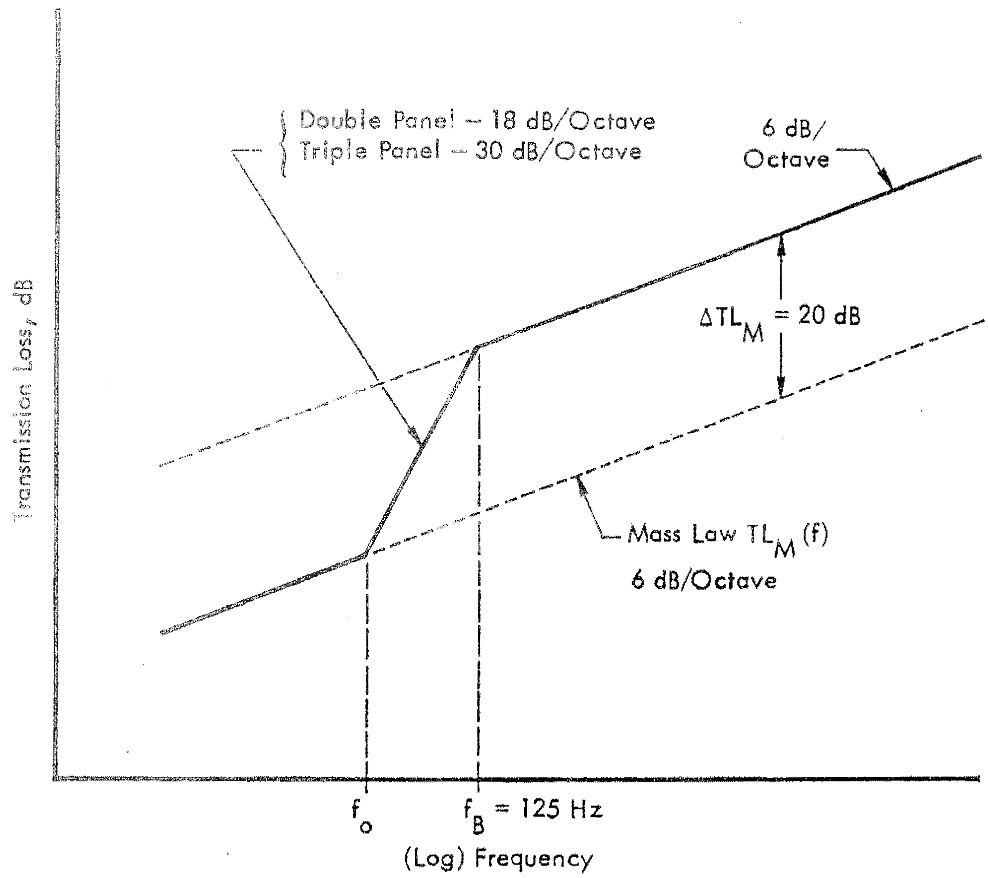


Figure 42. Minimum Design Requirement for a Multiple Panel Construction with Sound Bridges to Satisfy the 20 dB Requirement

It is necessary in the design to arrange for the fundamental panel resonance (or resonances in the case of more than two panels) to occur at a sufficiently low frequency so that the transmission loss is 20 dB greater than the calculated mass law at 125 Hz. Equations (14) and (17) of Section 2.2.2 can be rearranged to show that the increase ΔTL_M in the transmission loss over and above that predicted by the mass law is obtained at a frequency $f_{\Delta TL_M}$, where:

$$\Delta TL_M = P \log (f_{\Delta TL_M}/f_o) \qquad (61)$$

and

$$P = \begin{cases} 40 \text{ for a double panel} \\ 80 \text{ for a triple panel} \end{cases}$$

and f_o for the triple panel is taken as the higher of the two fundamental resonances (f_+).

Inserting the values of ΔTL_M and $f_{\Delta TL_M}$ into Equation (61) shows that the requirement for the fundamental resonant frequency f_o is:

$$f_o \leq \begin{cases} 40 \text{ Hz for a double panel} \\ 70 \text{ Hz for a triple panel} \end{cases}$$

The corresponding values for the product "md" are given by Equation (44) as:

$$md \geq \begin{cases} 65 \ \ (\text{lbs/ft}^2) \text{ ins. for a double panel} \\ 21 \ \ (\text{lbs/ft}^2) \text{ ins. for a triple panel} \end{cases} \qquad (62)$$

The above design figures are the minimum allowable to satisfy the 20 dB requirement and apply in the case of optimum mass distribution between the panels, namely:

$m - m$ for a double panel

$m - 2m - m$ for a triple panel

and the panel spacings (d) in the triple panel configuration are equal. Other combinations of panel masses for specific panel spacings are shown in Figure 43 for a double panel construction. The spacings given in this figure refer to the actual (rather than the nominal) dimensions of commonly used wooden studs. It should be noted that with an 8-inch wooden stud (actual dimension 7.5 inches), each panel is required to have a mass of 8.7 lbs/ft^2 to satisfy the 20 dB requirement. Alternatively, the panel masses could be 30 lbs/ft^2 and 5 lbs/ft^2 for the same spacing which, although less efficient in terms of total mass, may be more feasible using common building materials. Note that with a 7.5-inch spacing, the minimum mass for either of the panels is in the order of 4.5 lbs/ft^2.

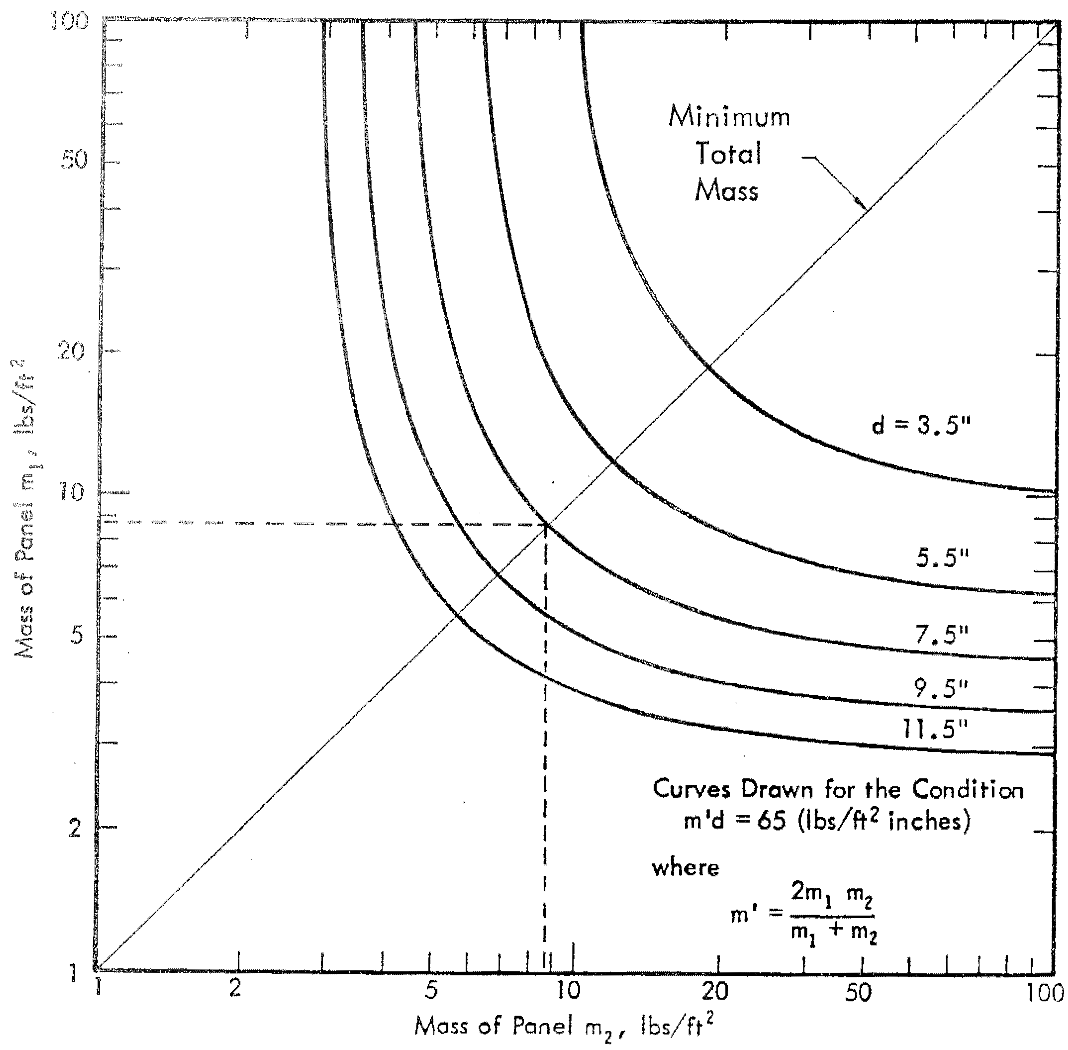


Figure 43. Requirements for the Masses m_1 and m_2 and Internal Spacing d for a Double Panel to Satisfy the 20 dB Requirement

At higher frequencies, it is necessary to maintain the value of ΔTL_M at 20 dB by correct choice of panels and support systems. If one of the two panels is mounted on point supports, then the value of the quantity ΔTL_M is given by:

$$\Delta TL_M = 20 \log (ef_c) - 61 \quad \text{dB} \tag{63}$$

where

e = the square root of the panel area associated with each point support

f_c = the critical frequency of the panel mounted on the point studs.

Again, it is assumed that the masses of the two panels are equal; otherwise, the more general expression given in Equation (35) must be used.

Inserting the condition that ΔTL_M is equal to 20 dB results in a requirement for the product ef_c, namely:

$$ef_c \geq 11{,}200 \text{ (ft/sec)} \tag{64}$$

If the point connections are located on a 2-foot square lattice, the critical frequency of the supported panel must be at least 5600 Hz for the construction to satisfy the 20 dB requirement.

3.1.2 Practical Realization of the 20 dB Requirement

The design of a double panel construction according to the requirements stated in Equations (62) and (64) will ensure that the transmission loss will exceed the mass law values by 20 dB at frequencies greater than 125 Hz. The cost of such a construction will be determined partly by the materials used. It is frequently convenient for both panels to be of the same material so as to minimize the number of techniques involved in the construction. In this case, for a given material, the material cost will be dependent on the mass or thickness of the panels, which should therefore be as light and thin as possible. The overall cost also is dependent on the floor area taken up by the construction, indicating that the overall thickness should be as small as possible. These two requirements are mutually incompatible with the requirements given in Equation (62). It is therefore worthwhile to study more closely the practical combinations of panel mass and separation that will satisfy the 20 dB requirement in order to determine the optimum configuration in terms of acoustic performance and cost.

For a given total mass, the optimum configuration for a double panel construction is obtained when the masses of the two panels are equal. Equation (62) shows that panels of high mass are required if a small panel separation is chosen. For a given material, however, an increase in mass is accompanied by a corresponding increase in panel thickness, which to some extent negates the usefulness of choosing a small separation. Continuing this argument, it can be shown that there is a minimum overall thickness with which the 20 dB requirement (or any general XdB requirement) can be met using a given material. This minimum thickness can be determined by expressing the overall thickness D for a double panel as:

$$D = d + \frac{2m}{\rho_m} \qquad (65)$$

where

m = mass per unit area of each of the two panels

ρ_m = density of the material of the panels

d = panel separation

Combining the requirement of Equation (62) with (65) results in the expression:

$$D = \frac{5.5}{m} + \frac{2m}{\rho_m} \quad \text{feet} \qquad (66)$$

where m is expressed in lbs/ft^2 and ρ_m is in lbs/ft^3. The minimum value of the overall construction thickness D is given by:

$$D_{min} = \frac{6.6}{\sqrt{\rho_m}} \quad \text{feet} \qquad (67)$$

where

$$m = 1.7\sqrt{\rho_m} \quad \text{lbs/ft}^2 \qquad (68)$$

and

$$d = 1/2\,D_{min} \tag{68a}$$

Since the definition of the 20 dB requirement is in terms of the calculated mass law over the entire frequency range 125 Hz to 4000 Hz, it is clear that the transmission loss of a structure just satisfying the requirement is implicity dependent on the mass of the structure. For a given total mass, therefore, both the transmission loss and the STC rating are completely defined. Moreover, the transmission loss curve will be parallel to the mass law line, as it will be in any bridged double panel construction. It is easily shown that for a transmission loss characteristic that follows the mass law, the numerical value of the STC rating is given by the expression:

$$STC = TL_M\ (500) + 4 \tag{69}$$

where $TL_M\ (500)$ = the mass law transmission loss at 500 Hz.

In the present case, the transmission loss of the construction is 20 dB in excess of the mass law. Therefore, the STC of the construction STC_c can be expressed as:

$$
\begin{aligned}
STC_c &= TL_M\ (500) + 24 \\
&= 20 \log (m) + 50 \qquad (70)
\end{aligned}
$$

where m is the mass (in lbs/ft^2) of each of the two panels in the construction. Combining (66) and (70) results in an expression relating the STC to the overall thickness for a construction meeting the 20 dB requirement. The only parameter in this relationship is the density ρ_m of the material of the panels.

For the case of gypsumboard panels, which have a density of approximately 48 lbs/ft^3, the relationship is plotted in Figure 44. The minimum overall thickness of a double wall with gypsumboard panels meeting the 20 dB requirement is slightly less than 11.5 inches. At this thickness, the STC rating for the construction is approximately 72. For all other combinations of panel mass and spacing – keeping the product constant – the overall thickness is greater than 11.5 inches. The minimum thickness of course will be less than 11.5 inches if the 20 dB requirement is changed to a requirement for only 15 dB or 10 dB greater than the mass law.

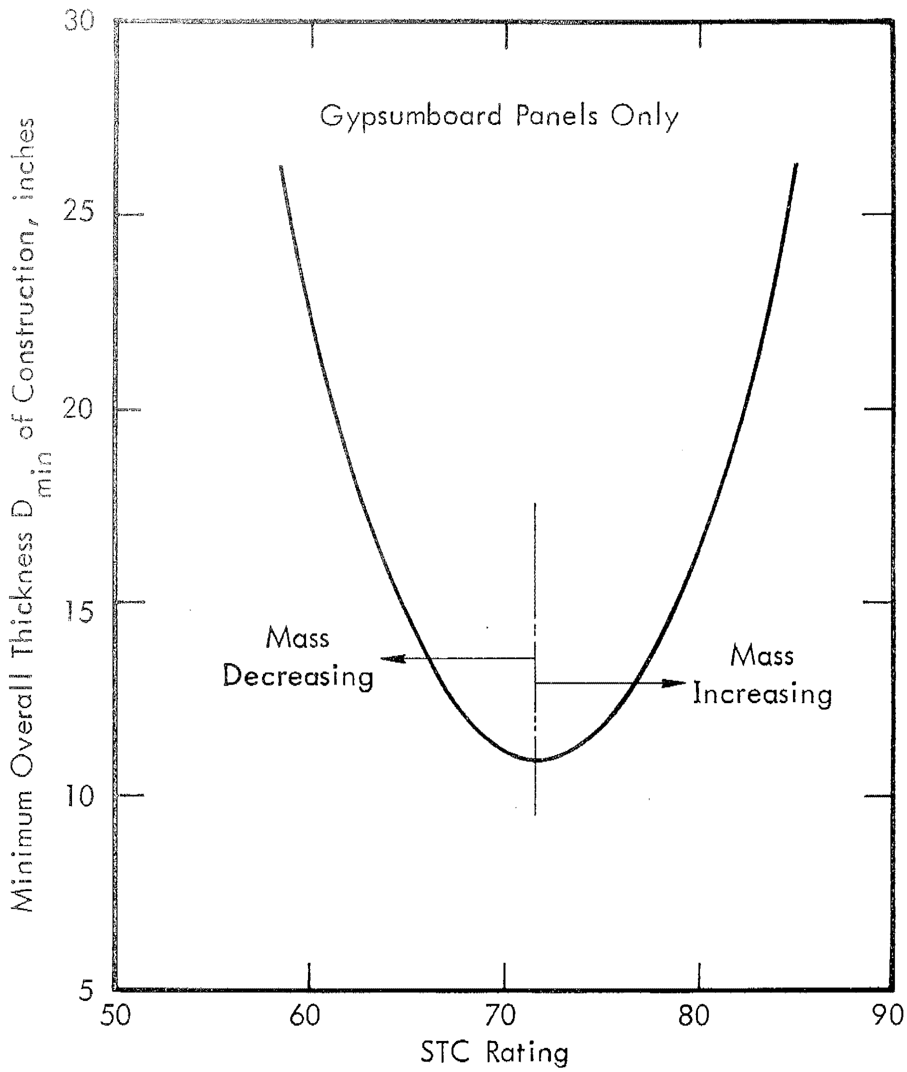


Figure 44. Minimum Overall Thickness as a Function of STC Rating for a Double Gypsumboard Panel Construction Satisfying the 20 dB Requirement

The minimum thickness for a double panel construction satisfying any general increment above the mass law can be determined from Figure 45, for the case where the two panels are of gypsumboard. If the maximum allowable thickness of the construction is set at 8 inches, for instance, then it is not possible to obtain a value of ΔTL_M greater than 14 dB.

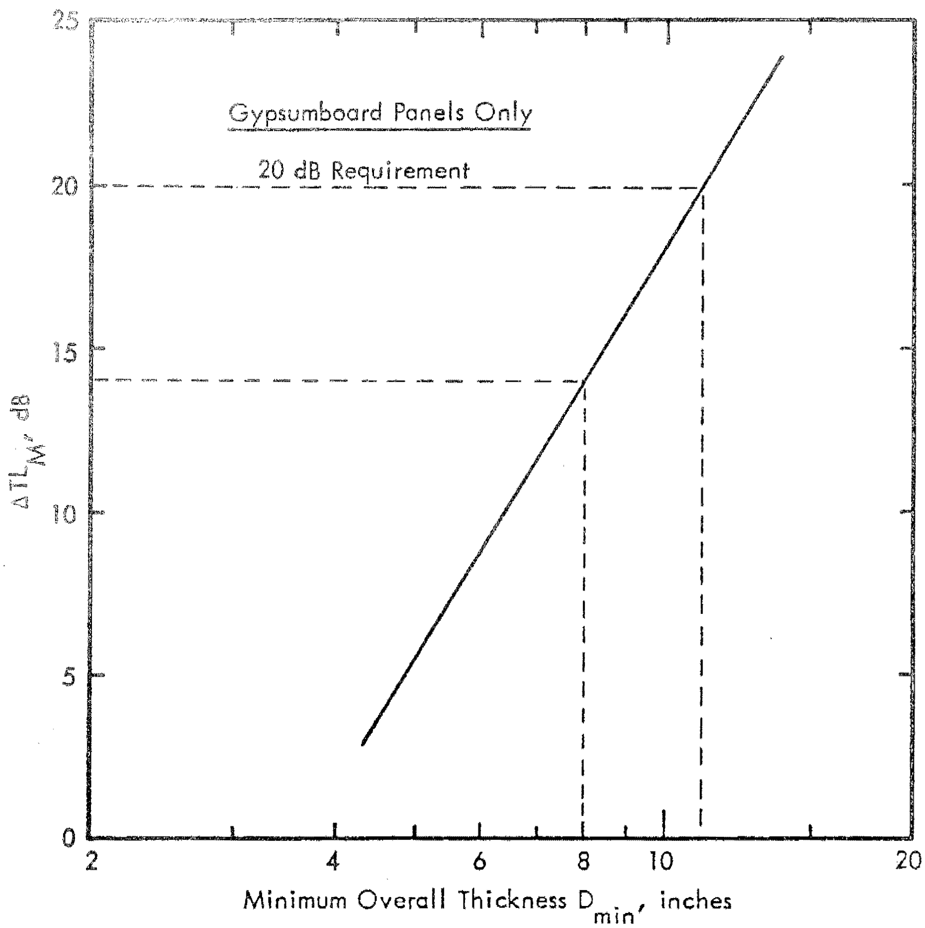


Figure 45. The Minimum Overall Thickness of a Double Gypsumboard Panel Construction Providing a Transmission Loss ΔTL_M dB in Excess of the Calculated Mass Law in the Frequency Range 125 Hz to 4000 Hz

It is possible that a thickness of 11.5 inches is too great for a practical wall construction, although it would be satisfactory for floor and roof-ceilings. The parameter involved in the determination of the minimum thickness is the material density; therefore, it is useful to study the relationship between these two quantities in the hope that the use of alternative materials may result in a more practical construction. The relationship between the overall thickness and the material density is plotted in Figure 46, with particular points on the curve corresponding to specific materials.

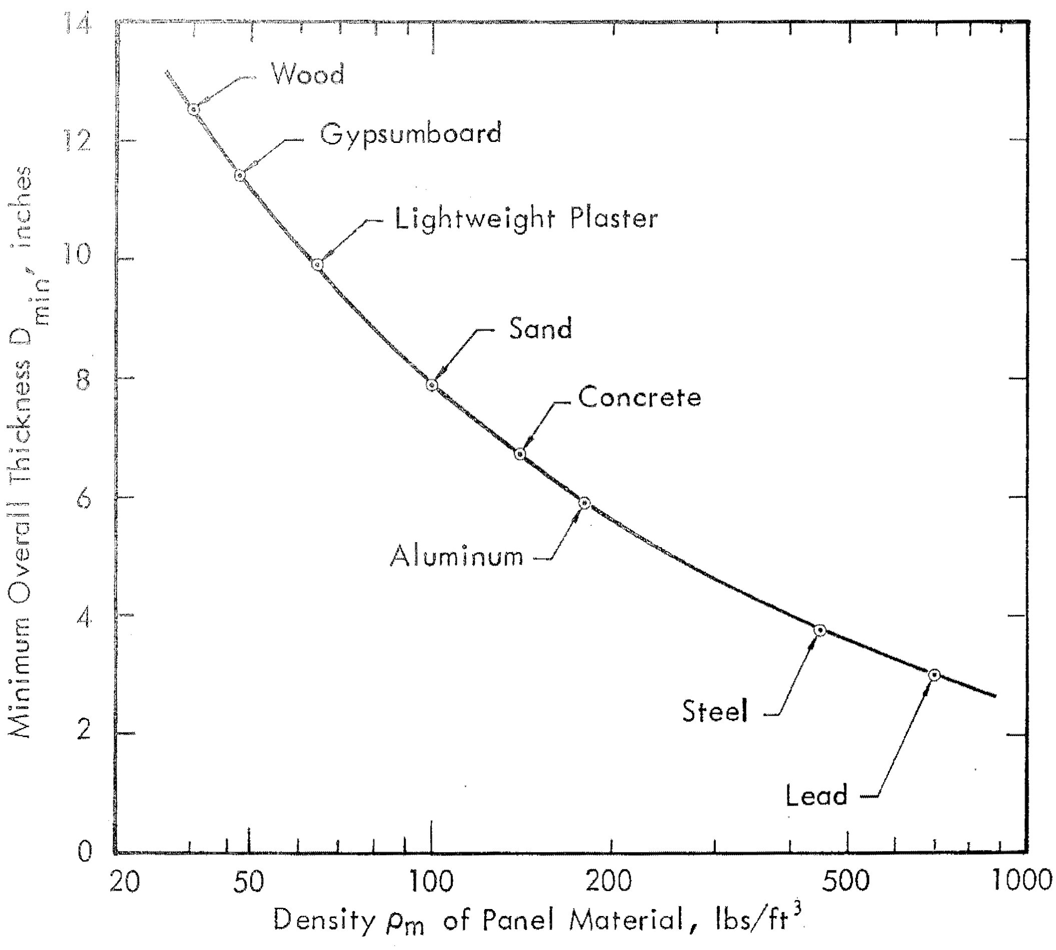


Figure 46. Minimum Overall Thickness D_{min} of a Double Panel Construction Satisfying the 20 dB Requirement as a Function of Material Density

The constructions of least total thickness are associated with the most expensive materials, namely, lead, steel and aluminum. Concrete is not particularly expensive, but is has a low value for the critical frequency in the thickness suitable for practical use. This means that any sound bridges between the panels would greatly reduce the transmission loss – see Section 2.3. Sand would be an ideal material to use due to its low cost and stiffness, but the rather severe problem of containing it in the form required reduces its usefulness. Lightweight plaster suffers from similar problems as concrete, namely, the low value for coincidence. For this material, the required panel thickness would be almost 2.5 inches, according to Figure 46 and Equation (68a). As a result, it appears that there are no low cost materials well qualified to provide the 20 dB acoustic requirement in a double wall construction of practical dimensions.

A similar calculation for the case of a triple wall construction shows that the minimum total thickness consistent with achieving the 20 dB requirement is given by:

$$D_{min} = \frac{7.5}{\sqrt{\rho_m}} \quad \text{feet}$$

where

$$m = 0.93 \sqrt{\rho_m} \quad \text{lbs/ft}^2$$

In other words, the minimum thickness and associated mass are greater than that for a double wall construction. Thus the triple wall does not offer any benefits in reducing the overall minimum thickness.

Approaching the problem from a different viewpoint, the best material that could be used is gypsumboard, based on cost/performance. As stated earlier, the overall thickness of a double wall construction that meets the 20 dB requirement at frequencies greater than 125 Hz is approximately 11.5 inches. The only way of reducing this thickness to a practical value is to relax the requirement on the lower frequency bound. For example, if the lower bound is allowed to be increased from 125 Hz to 200 Hz, the overall thickness of the construction is reduced by a factor of 1.6 to 7.1 inches, which is more reasonable – see Table 2.

TABLE 2

MINIMUM WALL THICKNESS FOR DOUBLE WALLS OF DIFFERENT MATERIALS REQUIRED TO MEET THE 20 dB REQUIREMENT AT DIFFERENT FREQUENCIES

Material	Density (lbs/ft^3)	Minimum Wall Thickness in Inches for 20 dB Requirement at and Above:		
		125 Hz	160 Hz	200 Hz
Timber	40	12.5	9.8	7.8
Gypsum Board	48	11.4	8.9	7.1
Lightweight Plaster	64	9.9	7.7	6.2
Sand	100	7.9	6.2	4.9
Concrete	140	6.7	5.2	4.2
Aluminum	180	5.9	4.6	3.7
Steel	450	3.7	2.9	2.3
Lead	700	3.0	2.3	1.9

Relaxing the frequency constraint in this manner does not affect the STC rating to any significant extent because the only reduction in transmission loss occurs at one or two of the lowest frequencies. Changing the lower bound from 125 Hz to 200 Hz results in a reduction of only one point in the rating. Further relaxation, however, reduces the rating by four points for every succeeding 1/3 octave increase in the lower bound frequency.

In concluding this section, it can be stated that the 20 dB requirement can be met with careful design considerations using both double and triple wall constructions. However, for constructions that will meet the approval of the building industry in terms of total thickness and weight, it is necessary to relax the constraints on the frequency range over which the 20 dB requirement is achieved. Since the transmission loss of such a construction is determined completely by the total mass, and since the mass cannot be small to comply with the minimum requirement for the product "md" with as small a separation as possible, the STC rating of a "20 dB" construction will invariably be high. For the gypsumboard construction, the STC rating is 72 at the minimum overall thickness of 11.5 inches. This is extremely high when compared to the rating of 55-60 recommended by FHA for Grade I installations. In general, it is not possible to obtain much lower STC ratings for 20 dB constructions without large panel separations which allow correspondingly lower panel masses. This is clearly demonstrated in Figure 47 which is a plot of the STC rating of a double wall constructed as a function of the panel separation (which, of course, is less than the overall thickness).

As a result, the practical realization of the 20 dB requirement is a construction that will find an extremely limited application in the building industry because of its size or weight. However, the principles involved in the design can be used to design more useful constructions to meet a specific acoustical requirement less than 20 dB in excess of the calculated mass law.

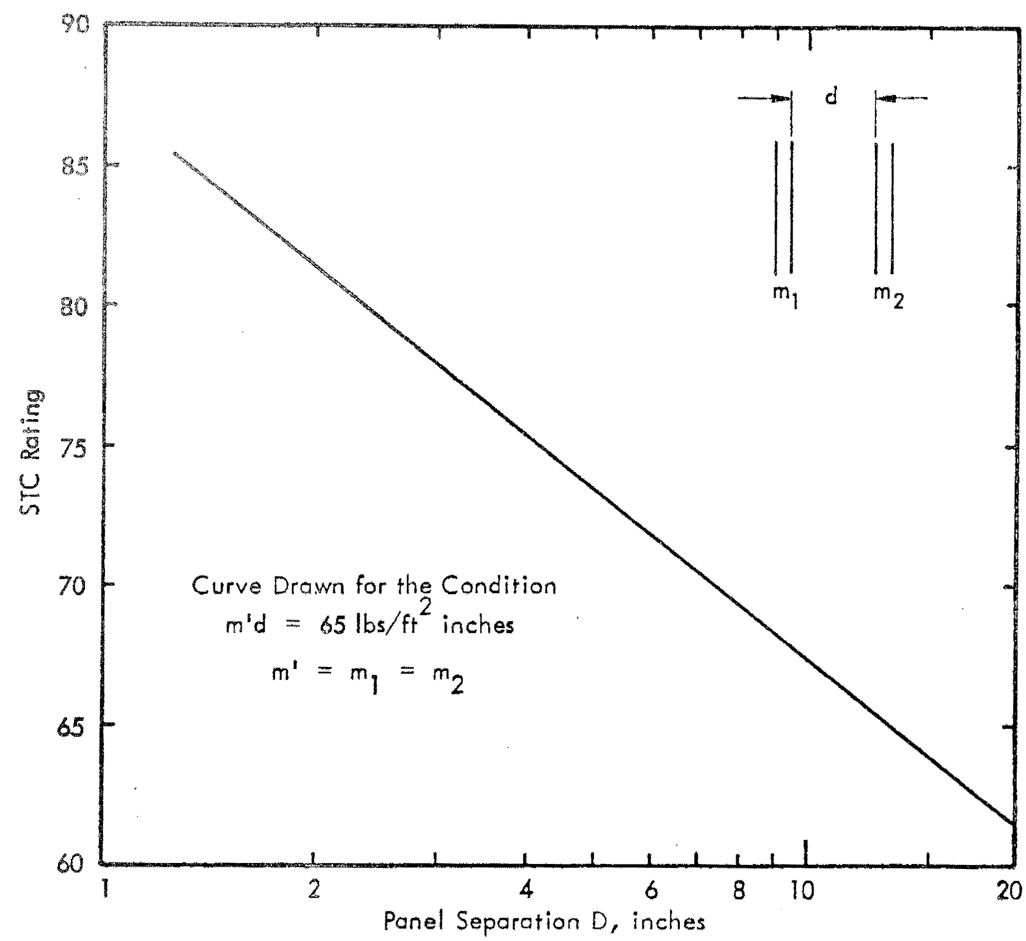


Figure 47. The STC Rating as a Function of Panel Spacing for a Double Panel Construction with Panels of Equal Mass Satisfying the 20 dB Requirement

3.2 ELEMENTS OF BUILDING CONSTRUCTIONS

Much of the preceding discussion on the principles of sound transmission loss and on the acoustical goal to be satisfied in this study has been directed primarily towards the acoustic performance of walls. However, the basic theoretical and practical principles are completely general; they can be applied to all types of building elements, and indeed to all types of structures where high values of sound attenuation are required. Of interest in this study are the various elements of building construction which include windows, doors, floor/ceilings and roof/ceilings, as well as walls. Each of these elements performs a specific function in the overall building system, and as such is subject to specific practical constraints in its construction. It is the purpose of this section to briefly review the functional constraints imposed on each of the other major elements and to examine techniques for obtaining optimum acoustical performance within these constraints.

3.2.1 Windows

The primary functions of windows, if ventilation is provided by alternative means, are to provide natural lighting and to provide the occupants of the dwelling with an external view. Both of these functions require that the window be constructed of a transparent material such as glass or acrylic. Typically, the glass installed in residential windows is either single strength (thickness 3/32-inch), double strength (thickness 1/8-inch) or occasionally 1/4-inch plate. The calculated transmission loss values for panels of 1/8-inch and 1/4-inch glass are shown in Figure 48.

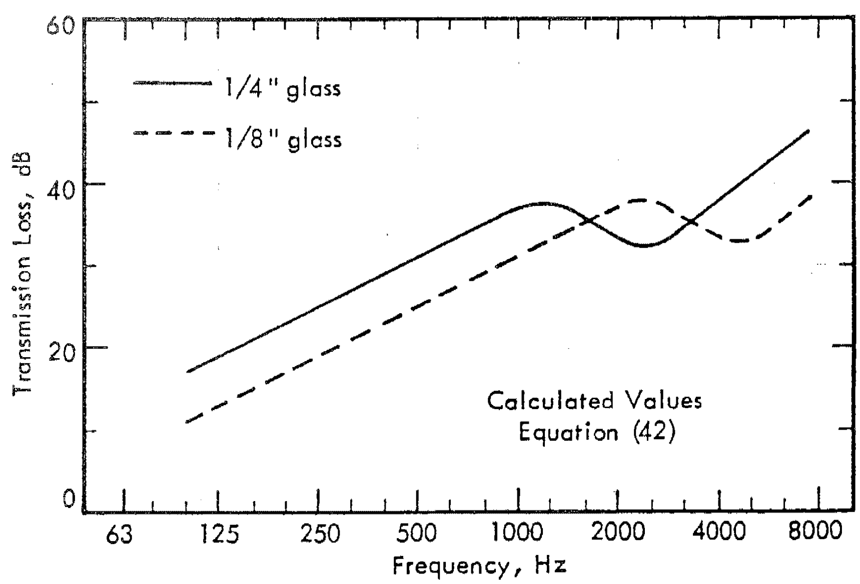


Figure 48. Calculated Values of Transmission Loss for 1/8-inch and 1/4-inch Sealed Glass Panels

As would be expected, the thicker panel provides the greatest transmission loss at low frequencies. At high frequencies, however, there is little to choose between the two. The effect of coincidence in the 1/4-inch panel is evident at the top end of the frequency range most important for speech communication. Any further increase in the thickness of the glass is undesirable, since the critical frequency is lowered to a value well within this important frequency range. As a result, the greatest thickness of glass that can be used in window assemblies is probably in the order of 1/4-inch.

If the window is operable, the transmission loss is normally less than that of the sealed version shown in Figure 48 due to leakage of sound between the moving parts and the frame. Typical values of transmission loss for a standard aluminum sliding glass window with 1/4-inch glass panels are shown in Figure 49. The reduction in transmission loss in the frequency range 1000 Hz to 2000 Hz is a result of sound leakage and not coincidence. The critical frequency of the glass panel in this case is 2400 Hz. The weatherstripping that is included in operable windows reduces the leakage of sound but its condition usually deteriorates fairly rapidly with use, thus limiting its usefulness.

A more effective and durable seal that can be applied to the perimeter of the moving section is shown in Figure 50. The seal consists of a metal channel containing a strip of fairly dense foam or soft neoprene. If the window is in constant use, the material in the channel should not contact the frame and should be of the foam variety to provide absorption in the channel thus formed. If the window is rarely opened, it is possible to obtain a better seal with neoprene that contacts the frame. The effect of such a seal on the transmission loss of a standard aluminum sliding glass window is shown in Figure 49. The improvement in performance over the unsealed window is evident over the entire frequency range and is in the order of 10 dB in the range 1000 Hz to 2000 Hz.

The results of Sections 2.2 and 2.3 indicate that a double window can be designed to provide higher values of transmission loss than a single window, provided that precautions are taken to reduce sound bridging between the glass panels. If the maximum practical thickness of the two panels is taken as 1/4-inch and the maximum possible separation as 8 inches, the lowest fundamental resonance will occur at a frequency (f_o) of 62 Hz. In the absence of sound bridges, the transmission loss will exceed the values calculated according to the mass law by 20 dB at a frequency of 195 Hz. Thus, it appears that a practical window system cannot be designed to satisfy the 20 dB requirement at frequencies as low as 125 Hz. It is possible to increase the separation of the glass panels if the wall is sufficiently thick or if one of the panels is allowed to protrude from the exterior wall, i.e., a bay window. However, since the reduction in the value of f_o is proportional to $1/\sqrt{d}$, a spacing of almost

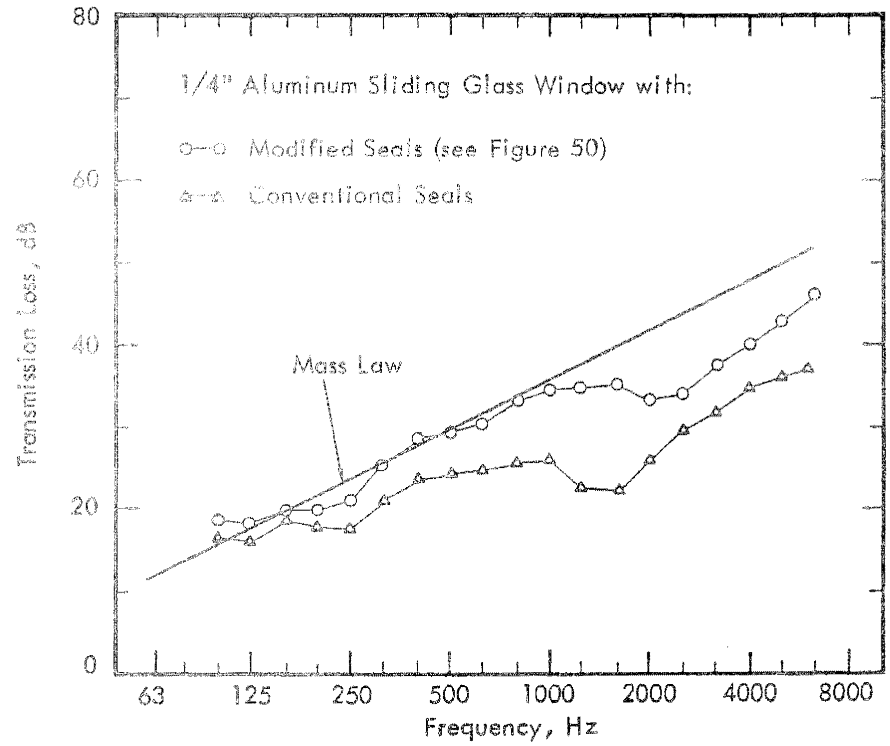


Figure 49. Measured Values of Transmission Loss of a 1/4-inch Aluminum Sliding Glass Window with Conventional and Modified Seals

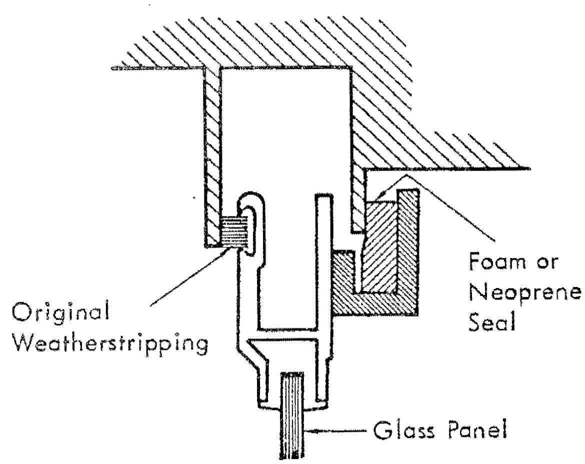


Figure 50. Diagram of a Modified Seal for Sliding Glass Windows

20 inches is required in conjunction with 1/4-inch glass panels to satisfy the 20 dB requirement at the low frequencies.

At higher frequencies, the transmission loss of a double window is determined by the sound bridging between the two glass panels, which in turn depends upon the method used to mount the glass panels and the type of wall in which they are mounted. If the wall is solid, then it is necessary to mount the glass panels in soft neoprene gaskets so as to provide partial isolation. This is not necessary if the panels are mounted in separate walls which are partially isolated from each other. The presence of sound bridges is one more reason for limiting the thickness of the glass in order for the critical frequency to remain high. It is, however, beneficial for the two panels to be of different thickness so that the critical frequencies are staggered — see Section 2.2.2.

The functional requirements of a window do not allow full coverage of acoustic absorption material in the airspace between the panels. As a result, the material must be placed at the internal perimeter of the window. The results of Section 2.2.5 indicate that perimeter absorption is not as effective as the full coverage in damping the cavity modes, so the maximum transmission loss cannot be obtained. This is true over the major part of the frequency range above the fundamental resonance of the construction. Naturally, higher values of transmission loss can be obtained by increasing the thickness of the perimeter absorption.

Since the lateral dimensions of a typical window are normally less than the height of the accompanying wall, the stiffness of the air in the window cavity can be reduced by arranging for the perimeter to be unsealed, that is, having the window cavity open directly into the wall cavity. In this manner, the fundamental resonant frequency can be reduced. It is important, however, to ensure that the fundamental resonance does not have the same frequency as the fundamental lateral cavity modes.

3.2.2 Doors

Since the primary function of a door is to provide a means of entry and exit to the dwelling, it has to be operable and must be light enough so that it can be used easily by young and old alike. Most doors presently are limited, by the availability of operating hardware such as handles and locks, to a maximum thickness of about 2 inches; however, there is no reason why this obstacle cannot be overcome in the future.

The majority of doors in common use today are either of the hollow core or solid core type, the former being restricted normally to internal use. The solid core door is typically 1-3/4 inches in thickness, constructed of compressed wood shavings and has a fairly low value for the critical frequency. The transmission loss of such a door with neoprene bulb seals is shown in Figure 51. At high frequencies, the transmission rises more slowly with frequency than would be expected due to leakage of sound through the seals. The acoustic performance shown in Figure 51 is probably the best that can be obtained from a solid core door in a practical installation. Most other types of seal configurations will result in lower values of transmission loss.

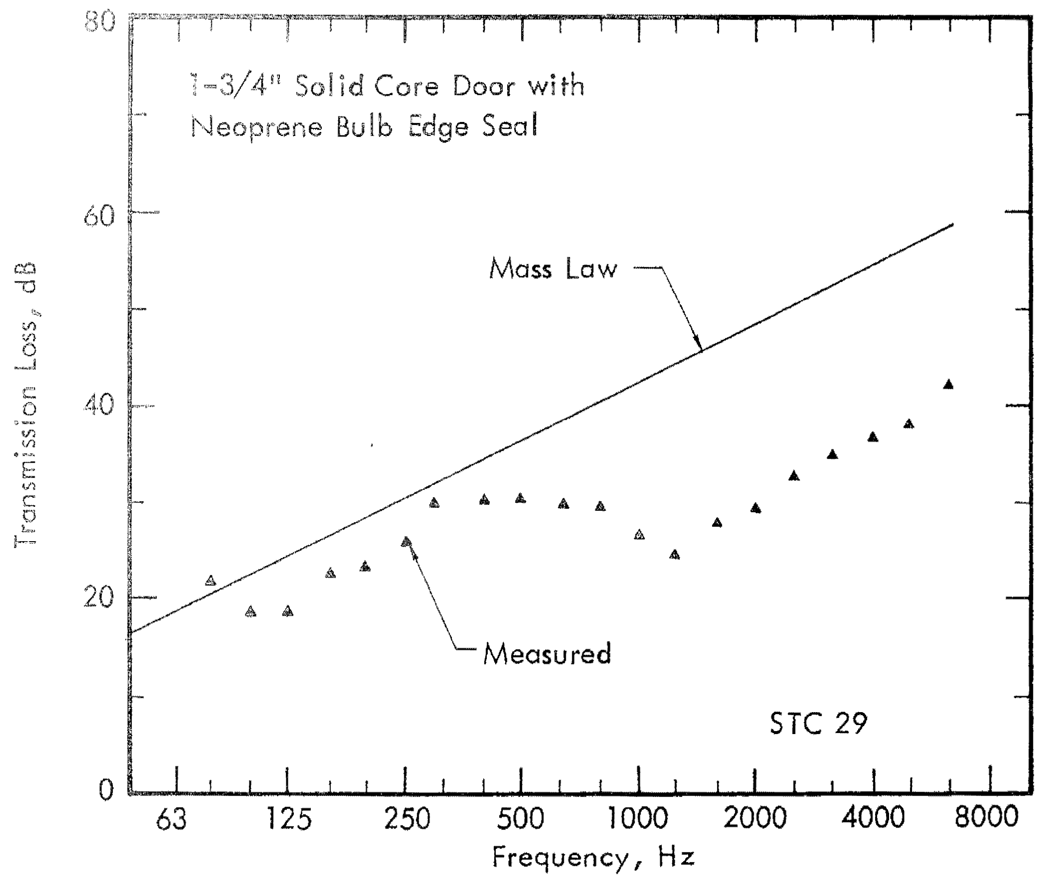


Figure 51. Measured Transmission Loss Values of a 1-3/4-inch Solid Core Door

There are two main methods by which the maximum transmission loss can be obtained from a structure, such as a door, where there are severe limitations on thickness and mass. The first is by the application of the double panel technique. The second is to use a sandwich type panel that has the properties of a double panel over a certain frequency range. This behavior can be obtained by using a massive though porous material, such as cemented wood shavings, onto which two facing layers are applied — one rigidly, one resiliently. The porous center layer successfully simulates a cavity with absorption and provides added mass. The transmission loss from this structure can be made to equal or exceed the calculated mass law over a major part of the frequency range of interest — see Section 3.3.

Since the area taken up by a door (or a window) is usually only a small percentage of the total wall area, it is not necessary for the acoustic performance of the door to equal that of the wall for optimum results. For example, if the door area is 10 percent of the wall area, the transmission loss of the door can be 5 or 6 dB less than that of the wall while still retaining a composite value essentially equal to that of the wall. However, for an STC 60 wall, this constraint requires a door providing an STC 55 rating which could be obtained only with a fairly cumbersome structure. One method of obtaining additional attenuation is to provide a short foyer with a 180-degree bend that is lined with an acoustical absorbent material similar to a lined duct. This addition would be capable of providing an additional 5 to 10 dB, particularly at the medium and high frequencies.

3.2.3 Floor and Roof/Ceiling Systems

The design principles described above for walls are also applicable to floor/ceiling and roof/ceiling constructions, except that different functional and loading requirements have to be considered. For example, the floor has to be rigid enough to withstand live and dead loads without too much deformation. In addition, the ceiling can be neither too massive nor too flexible or it will sag under its own weight.

It would appear that one of the advantages of a floor/ceiling system, from an acoustic point of view, is that the large allowable separation between the floor and ceiling (up to 18 inches or more) should allow high values of transmission loss to be obtained. Unfortunately, this is the case only at low frequencies. At higher frequencies, the necessity to provide closely spaced connectors between the ceiling and the floor (joists which are commonly 16 inches on center) introduces a substantial sound bridging that negates the effect of the large cavity. It is therefore difficult to achieve the 20 dB requirement with such systems unless a resiliently suspended or separately supported ceiling is used. This is excellent proof that high values of transmission loss are not necessarily obtained by incorporating large panel separations.

As with walls, it is desirable to have a massive flexible ceiling in a floor/ceiling system. However, the practical difficulties of installing such a ceiling preclude the use of some of the panels that are satisfactory for walls. An alternative method of achieving the required properties is to install the base panel, which may be flexible, to the ceiling joists and to subsequently apply 1/4 to 1/2-inch of sand pugging from above.

The previous discussion of design principles has been concerned primarily with the problem of constructions that are subject to excitation from airborne sound waves. In the case of floor/ceiling constructions, there also exists the problem of impact excitation such as would be obtained from footfalls, dropping objects, etc. This is a different type of excitation in that the area impacted is usually quite small and the forces involved quite large, when compared to airborne excitation. Impacts are also characterized by being of short duration rather than of a continuous nature.

The properties required of a floor/ceiling construction, as far as impact excitation is concerned, are similar to those required for airborne excitation. For example, the more massive the floor the greater in general will be the impact insulation. However, the resilience of the floor surface, which is of little or no importance in determining the airborne transmission loss, is extremely important in reducing the impact energy that is transmitted to the base floor. The transfer of sound or vibrational energy from the floor to the ceiling is again essentially the same as in a double wall with sound bridges. Consequently, many well designed double panel structures would exhibit properties similar to those required of floor/ceiling systems if a resilient layer was added to the impacted surface.

The impact insulation provided by a floor can be increased by adding a "floating floor." This consists of a fairly massive slab that is separated from the main floor by a resilient material such as rubber pads or rigid fiber glass. Although substantial increases in the insulation can be obtained by this method, the added slab must be fairly massive so as to keep the frequency at which the floating system resonates to as low a value as possible. However, substantial improvements in the impact noise rating of the basic floor/ceiling structure can be obtained by the addition of a carpet and under-pad. Figures 52 and 53 show the reduction in impact sound pressure level that can be obtained from a reinforced concrete floor and a typical wooden joist floor, respectively, by the addition of carpeting.

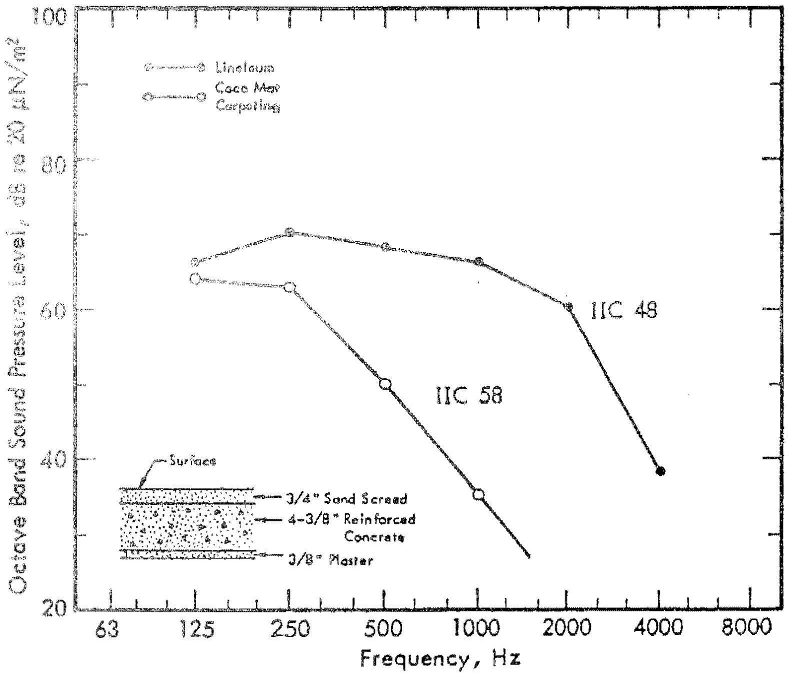


Figure 52. Impact Noise Levels for a Concrete Floor With and Without Carpet. (Data Normalized to an Absorption of 10 m^2 – Reference 14.)

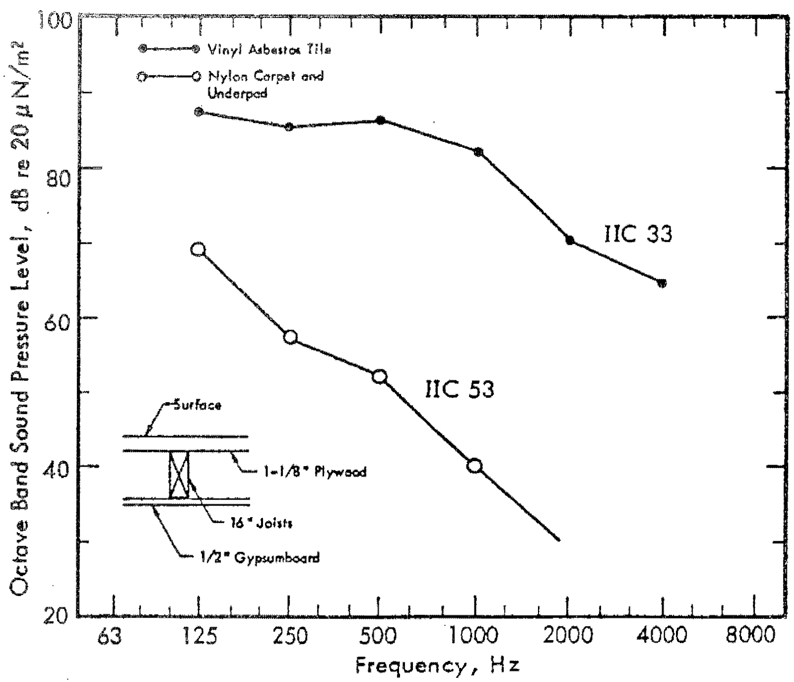


Figure 53. Impact Noise Levels for a Wood-Joist Floor With and Without Carpet. (Data Normalized to an Absorption of 10 m^2 – Reference 14.)

In the past, carpets have been considered more a luxury item than a part of the construction, particularly in low-cost housing. One reason that they have not been specified as part of the construction is that they have tended to deteriorate quickly in places with heavy traffic flow. Today, however, man-made fiber carpets with an appropriate under-pad are capable of supporting heavy traffic for 15 to 20 years without undue wear. In view of their remarkable properties at reducing impact noise both in the source and receiving rooms, it would seem appropriate to consider carpets as part of the building construction itself. In doing so, it is possible to reduce the complexity and hence the cost of floor/ceiling systems.

3.3 APPLICATION OF PRINCIPLES TO PROTOTYPE DESIGNS

The main objective of this study was to design and test building elements having higher values of transmission loss and a lower cost than that available from existing elements. Some of the principles which make the design of such improved building elements possible have been summarized in Section 2.4. These principles and associated design methods have been used to design: (1) a series of experimental prototypes with which the principles could be verified, and (2) a series of final prototypes which, with few modifications, could be considered as practical constructions. The designs and acoustic performance of these experimental and final prototypes are contained in this section.

3.3.1 Experimental Prototypes

The purpose of designing and testing a series of experimental prototypes was to put into practice the ideas and principles that had been enlarged upon or developed in the analytical and initial testing programs. Some of the principles which were considered to be worthy of further study had already been validated to a certain extent in tests conducted on what can be called "laboratory" constructions — constructions in which no attempt was made to consider practical constraints. However, it was necessary to combine some of the principles in a single construction to determine the values of transmission loss that could be obtained with optimum, though still partially idealized, designs. It was not intended that the experimental prototypes should be fully practical; but rather, they should be designed with "reasonable" constraints.

The main objectives of the experimental prototype test program can be summarized as follows:

- To verify the transmission loss theories and design procedures for semi-practical multiple panel constructions with sound bridges.

- To examine the feasibility of achieving the 20 dB requirement in a construction with reasonable constraints.

- To determine the maximum values of transmission loss that could be obtained in a construction with reasonable constraints.

- To determine the feasibility of using laminated and mass-loaded panels in multiple panel constructions, and to develop semi-practical methods for the configuration and construction of such panels.

- To apply the principles and design methods to all types of building elements including walls (internal, external, loadbearing and non-loadbearing), floor/ceilings, roof/ceilings, windows (sealed and operable) and doors.

- To determine the combinations of materials most suited to constructions designed according to the methods outlined in Section 2.4.

- To determine the increase in transmission loss that can be obtained by modifying existing construction types.

For a single panel to provide high values of transmission loss economically, the most desirable properties are as follows:

- High mass or density

- Low stiffness

- Low cost

An examination of the advantages and disadvantages of existing materials in this context – see Table 3 – shows that the most promising types are gypsumboard, hardboard, plywood and concrete, although not necessarily in this order. The remaining types of materials exhibit some desirable properties but in general are not at all comparable to the four mentioned above, unless some particular combination of acoustical and environmental criteria has to be satisfied.

One possible approach to the design of the experimental prototypes would be to attempt to satisfy the 20 dB requirement in every case. This was not the approach taken, however, for the following reasons. First, the discussion in Section 3.1 shows quite clearly that a construction satisfying the 20 dB requirement over the complete frequency range 125 Hz to 4000 Hz is either too thick

TABLE 3

A LIST OF THE ADVANTAGES AND DISADVANTAGES OF VARIOUS MATERIALS FOR USE IN HIGH TRANSMISSION LOSS CONSTRUCTIONS

Material Type	Advantages	Disadvantages
Metals	• High Mass • Low Stiffness in Typical Thicknesses	• Expensive • Poor Thermal Insulators • Possible Corrosion
Gypsumboard	• Variety of Masses and Critical Frequencies Available • Inexpensive • Good Fire Resistance	• Fragile in small Thicknesses
Hardboard	• Flexible – Good for Mass Loading • Inexpensive	• Poor Fire Resistance but can be Treated
Plastics	• Flexible – Good for Mass Loading	• Low Mass • Expensive • Poor Fire Resistance
Concrete	• High Mass • Can be Molded to any Shape • Inexpensive	• High Stiffness
Plywood	• Flexible in Thinner Types • Good for Mass Loading	• Poor Fire Resistance but can be Treated • More Expensive than Gypsumboard or Hardboard

or too expensive, and provides such inordinately high values of transmission loss that its applications are very limited. Second, it is impossible to achieve the 20 dB requirement over the complete frequency range with a practical window unit due to the limitations on glass thickness and spacing. Therefore, the combination of a wall and window cannot be made to meet the 20 dB requirement; in other words, the wall is over-designed for the window.

As a result of these constraints, only a limited number of prototypes were designed to satisfy the 20 dB requirement; these were termed Type I prototypes. The remainder (Type II prototypes) were designed to provide a transmission loss that was equal to or slightly better than that required by FHA for Grade I constructions. The majority of these building elements, with the exception of windows and doors, were designed to provide an STC rating in the range of 60 to 65. The window was designed to provide an STC rating of 55. For typical areas of glazing (say 20 percent of the wall area), the combination of such a window with a wall of STC 60 would result in an overall rating in the order of 58, which is fairly respectable. It should be mentioned, however, that the method of specifying the transmission loss characteristics of an exterior wall by its STC rating is not a good one because the rating is based on a typical internal noise environment and there is sometimes a great difference between the frequency spectra of the indoor and outdoor noise environment. Therefore, it is recommended that external walls be designed for a particular location and not be defined by an STC rating.

a. Designs and Results

The experimental prototypes were tested in the Transmission Loss Facility at Wyle Laboratories. This facility consists of two reverberation rooms of identical dimensions, each having a volume of 6400 cubic feet (181 cubic meters). One of the rooms (the source room) is constructed of damped steel panels and is mounted directly onto a concrete base. The other room (the receiving room) is constructed of gypsumboard and plywood laminations and is mounted on four air springs, one at each corner. Other than the indirect and isolated coupling through the concrete base, there are no connections between the two rooms. The overall transmission loss of the wall separating the two rooms is shown in Figure 54.

Since both source and receiving rooms are identical in shape and size, the natural modes in the two rooms are essentially the same and will tend to couple via the test panel. As a result, it is expected that lower values of transmission loss would be measured in this facility than in one having

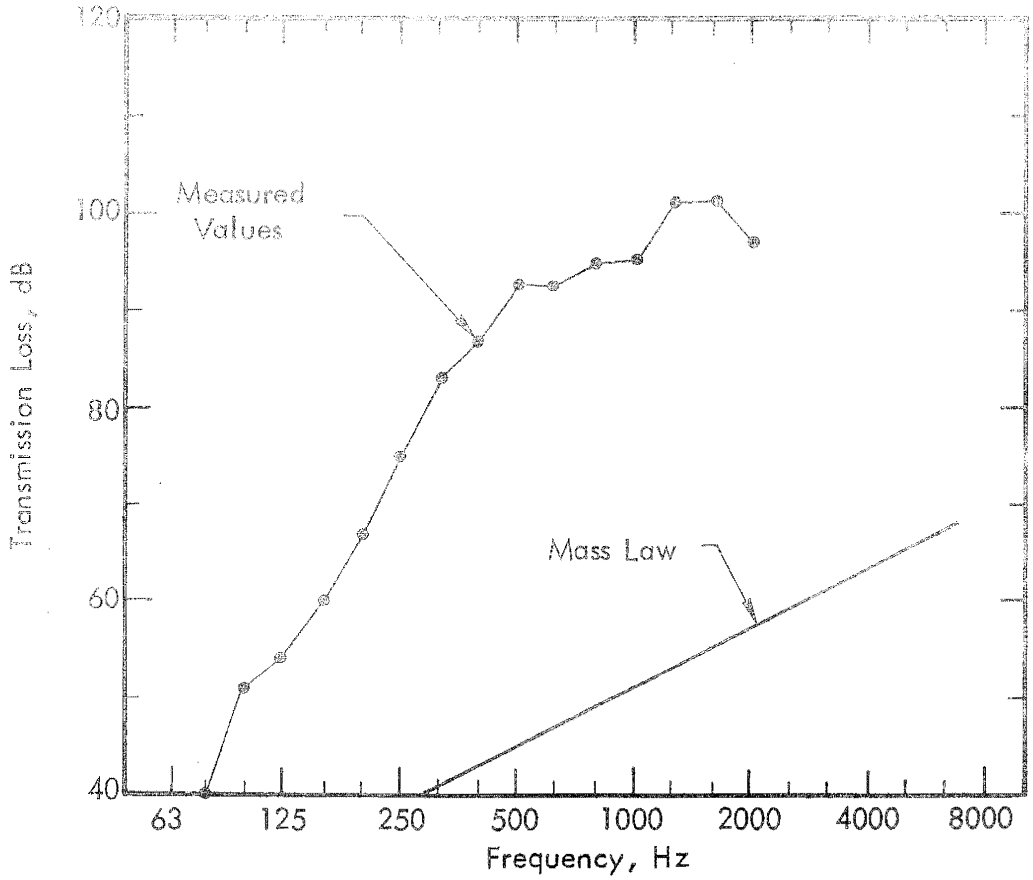


Figure 54. Transmission Loss of the Common Wall in the Wyle Transmission Loss Facility

dissimilar rooms, especially at the low frequencies. This is, in fact, what has been found – the familiar flattening of the transmission loss curve for a single panel at low frequencies is not observed from measurements in this facility, and the theoretical mass law is obeyed as shown in Figures 2 and 3. Thus the values of transmission loss and STC ratings given in this report are probably <u>lower</u> than those that would be measured in many other facilities.

Details on the construction of the experimental prototypes are to be found in the following pages, together with the measured values of transmission loss and brief comments on the overall acoustic performance. Included in the details for the wall constructions are the estimated in-place cost figures given in dollars per square foot of surface area. These costs do not include finishing and have been determined from the 1971-72 edition of the National Construction Estimator (Reference 16) as far as this is applicable. Because these constructions are experimental, the costs must be considered approximate.

Prototypes	Building Element
A – H	Walls
I – J	Floor/Ceilings
K – L	Roof/Ceilings
M	Doors
N – O	Windows

PROTOTYPE A – WALL

CONSTRUCTION DETAILS:

2" x 4" wooden studs, 16" on centers staggered, 8" on centers attached to 2" x 6" wooden plates at base and top. On one side, 5/8" gypsum wallboard (m_1) mounted on 1/4" x 1" x 1" double-sided adhesive backed PVC foam tape square 24" on center vertically. On the other side, two sheets of 1/2" gypsum wallboard (m_2) spot-laminated on a 12" square lattice mounted on 1/4" x 1" x 1" double-sided adhesive backed PVC foam tape 24" on center vertically. 2" fiber glass insulation hung between the studs.

PARAMETER VALUES:

M	$= 8.5$ lbs/ft^2		
m_1	$= 2.6$ lbs/ft^2;	m_2	$= 4.0$ lbs/ft^2
f_{c1}	$= 2500$ Hz;	f_{c2}	$= 3000$ Hz
D	$= 7.25$ inches;	d	$= 6.0$ inches
e	$= 1.6$ ft		

STC RATING: 57

COMMENTS:

This construction contains a conventional staggered wooden stud system and standard materials. However, it includes resilient point-mounting and a laminated panel on one of the sides. The STC rating of 57 is a considerable improvement over that of approximately 46 for the conventional staggered stud construction (see Prototype H).

APPROXIMATE COST: $1.45/ft^2

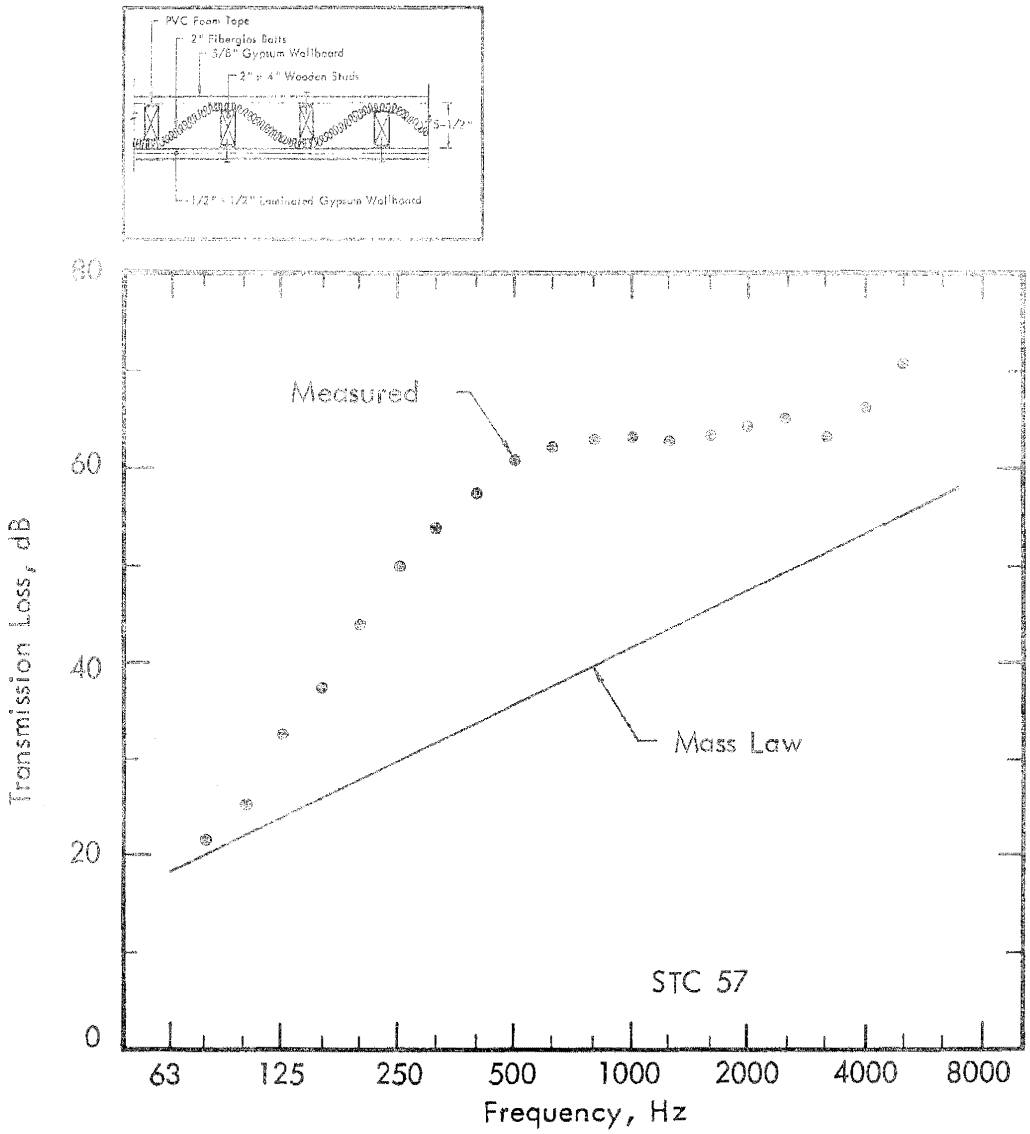


Figure 55. Transmission Loss Values for Prototype A

PROTOTYPE B – WALL

CONSTRUCTION DETAILS:

2" x 8" wooden studs, 24" on centers, attached to 2" x 8" wooden plates at base and top. On one side, 1/2" plywood mass-loaded to 4 lbs/ft^2 nailed to 1/4" x 1" x 1" plywood squares, 24" on centers vertically. On the other side, 1/4" tempered hardboard mass-loaded to 4 lbs/ft^2 mounted and screwed through 1/4" x 1" x 1" squares of double-sided adhesive backed PVC foam tape, 24" on centers vertically. Mass-loading in both cases achieved by stapling layers of asphalt roofing paper to the base panel. 2" fiber glass insulation batts hung between the studs.

PARAMETER VALUES:

M	$= 9.2\ lbs/ft^2$		
m_1	$= 4\ lbs/ft^2$;	m_2	$= 4\ lbs/ft^2$
f_{c1}	$= 1800$ Hz;	f_{c2}	$= 4000$ Hz
D	≈ 9 inches;	d	≈ 8 inches
e	$= 2$ ft		

STC RATING: 67 (with screws)

COMMENTS:

This construction was designed to test the concept of mass-loading and resilient point connections. The method of loading is therefore not necessarily practical for field constructions. The measured values of transmission loss exceed those predicted. This is probably due to inaccuracies in determining the critical frequency of the loaded panels. It will be noticed that the construction meets the 20 dB requirement at all frequencies greater than 200 Hz.

APPROXIMATE COST: $2.00/ft²

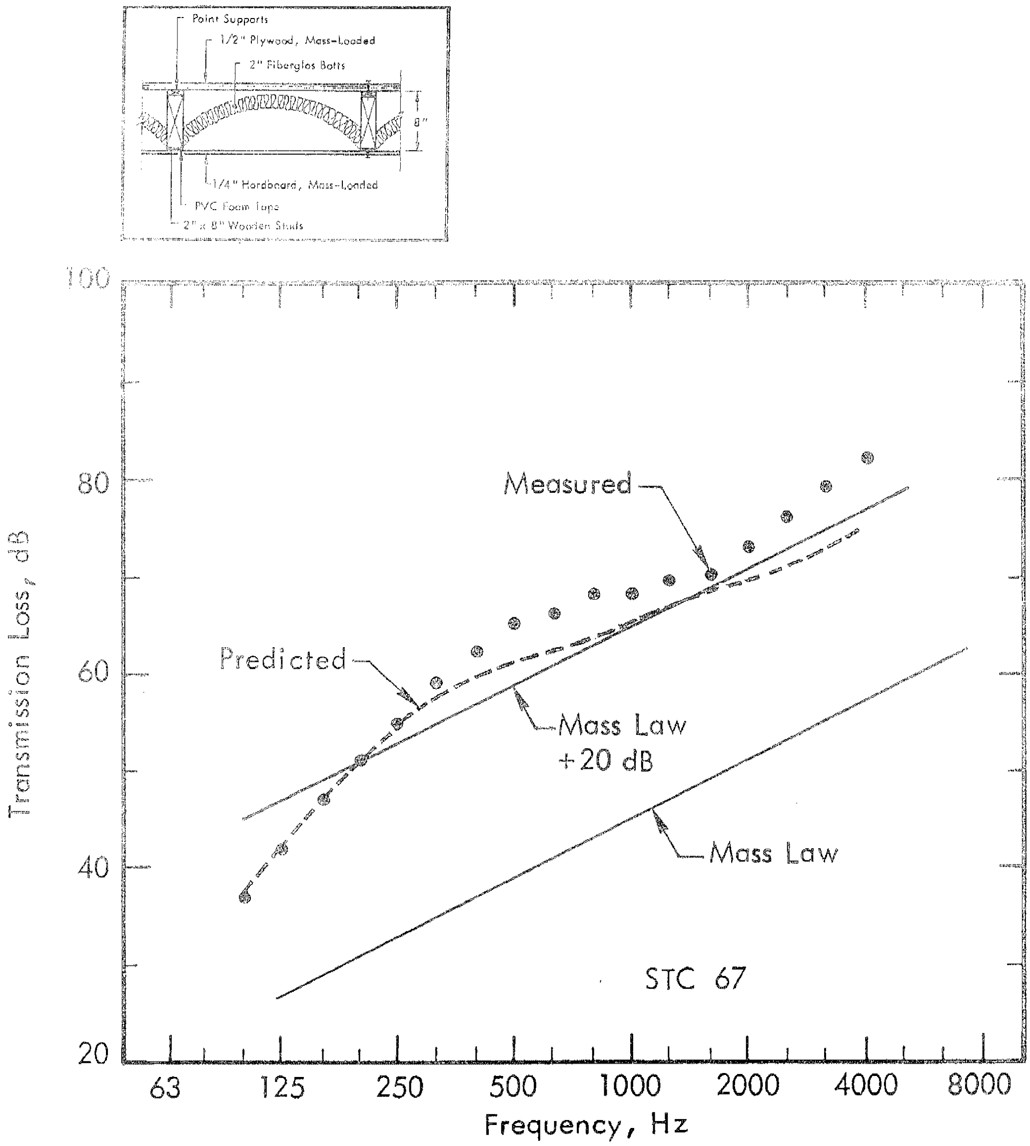


Figure 56. Transmission Loss Values for Prototype B

PROTOTYPE C – WALL

CONSTRUCTION DETAILS:

Two sets of 2" x 4" wooden studs, 24" on centers, attached to double 2" x 4" wooden plates at base and top spaced 1/2" apart. On the outer sides, mounted on 1/4" x 1" x 1" double-sided adhesive backed PVC foam tape squares, 24" on centers vertically, sheets of 1/2" and 3/8" gypsum wallboard spot-laminated. In the center, mounted on solid point supports, consisting of 1/4" x 2" x 1-1/2" plywood, 24" on centers vertically, sheets of 5/8", 1/2" and 5/8" gypsum wallboard spot-laminated on a 24" square lattice. 2" fiber glass insulation batts hung between the studs in each cavity.

PARAMETER VALUES:

$M = 16.7$ lbs/ft^2

$m_1 = m_3 = 3.6$ lbs/ft^2; $m_2 = 7.2$ lbs/ft^2

$f_{c1} = f_{c2} = f_{c3} \approx 2500$ Hz

$D = 13.5$ inches; $d_1 = d_2 = 5$ inches

$e = 2$ ft

STC RATING: 76

COMMENTS:

This triple panel construction is not well-suited for normal use due to its large overall thickness, although the acoustic performance – STC 76 – is high, which means that it could be of use in special conditions. The construction was designed to obtain the maximum transmission loss possible within "reasonable" design constraints. The transmission loss exceeds 20 dB greater than the calculated mass law in the frequency range above 125 Hz, and 30 dB greater than the mass law over the frequency range 315 Hz to 3150 Hz. It was necessary to correct the measured values of transmission loss at the low frequencies since they approached the facility limit.

APPROXIMATE COST: $2.36/ft^2

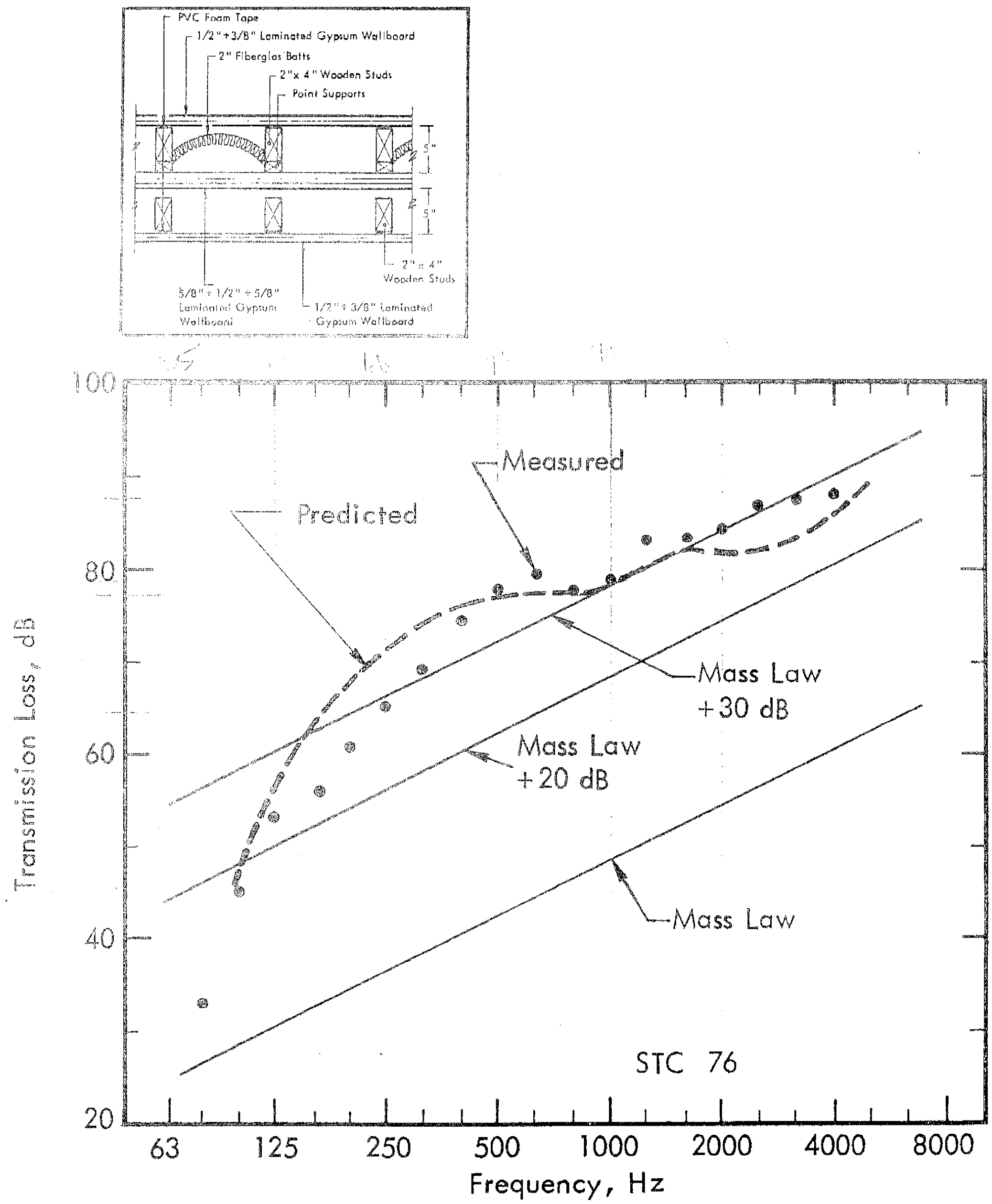


Figure 57. Transmission Loss Values for Prototype C

PROTOTYPE D – WALL

CONSTRUCTION DETAILS:

2" x 8" wooden studs, 24" on centers attached to 2" x 8" wooden plates at base and top. On one side, sheets of 1/2", 3/8", 1/2" and 3/8" gypsum wallboard, spot-laminated on a 24" square lattice, mounted on 1/4" double-sided adhesive backed PVC foam tape, 24" on centers vertically. On the other side, sheets of 5/8", 1/2" and 5/8" gypsum wallboard, spot-laminated on a 24" square lattice, mounted on 1/4" x 2" x 1-1/2" plywood points, 24" on centers vertically. 2" fiber glass insulation batts hung between the studs.

PARAMETER VALUES:

$M = 16.7$ lbs/ft^2

$m_1 = 7.0$ lbs/ft^2; $m_2 = 7.2$ lbs/ft^2

$f_{c1} \approx 3000$ Hz; $f_{c2} \approx 2500$ Hz

$D = 11.5$ inches; $d = 8$ inches

$e = 2$ ft

STC RATING: 69

COMMENTS:

This double panel construction has the same total mass as that of the triple panel in Prototype C. It is 2 inches less in overall thickness and exhibits an STC rating that is 7 points lower. The main reason for this difference is the lower values of transmission loss in the mid-frequency region. This supports the previous contention that triple panel constructions are superior to the double panel types (for similar mass and thickness) at medium and high frequencies (see Section 2.2). Again, this panel is suitable for use in special conditions. It is to be noted that the STC rating of 69 for an overall thickness of 11.5 inches does not quite meet the analytical criterion for the 20 dB requirement – see Section 3.1.2 – and this fact is verified by the measured results.

APPROXIMATE COST: $1.85/ft²

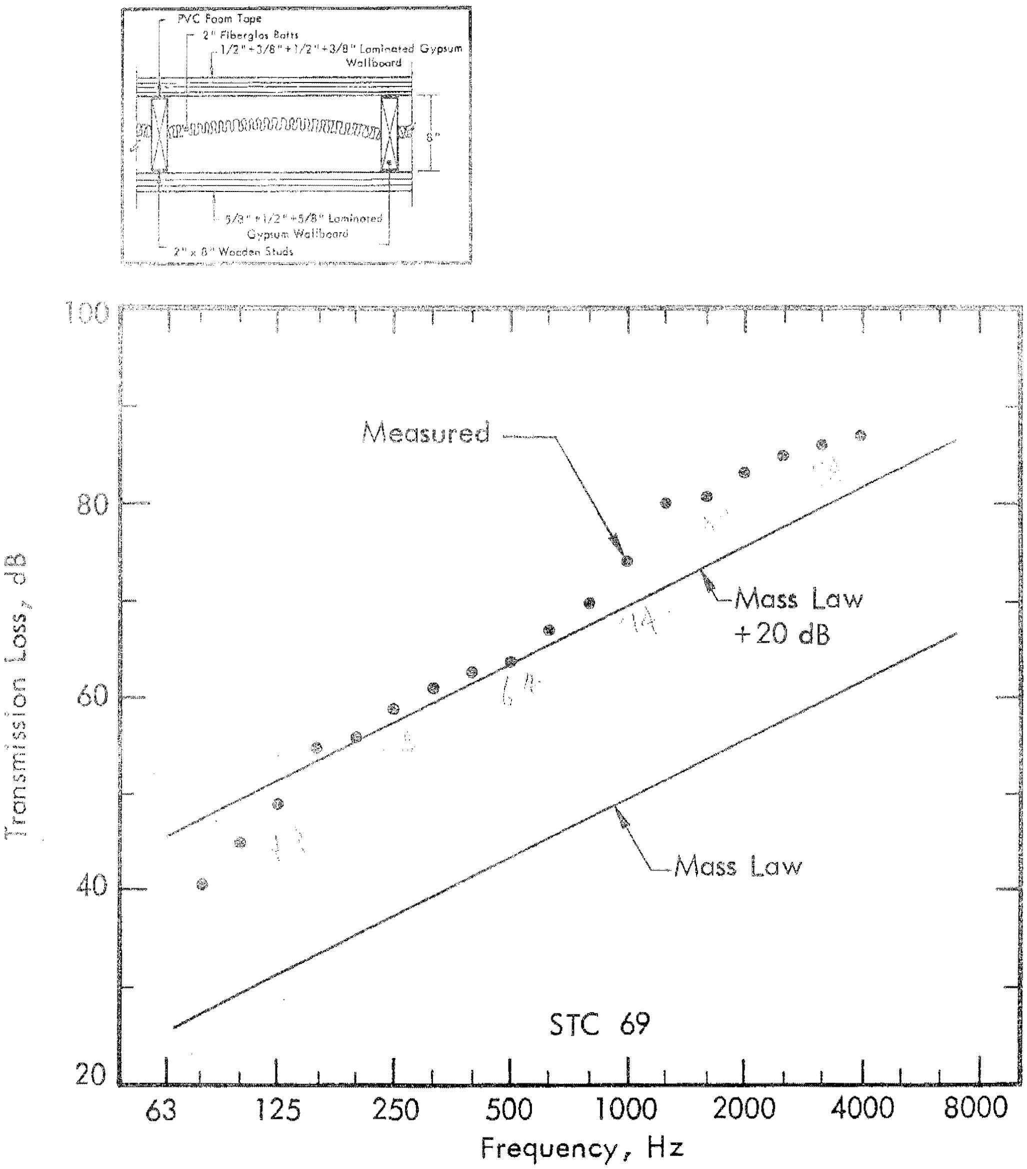


Figure 58. Transmission Loss Values for Prototype D

PROTOTYPE E – WALL

CONSTRUCTION DETAILS:

4" reinforced concrete panel, together with 1/2" plywood sheet mass-loaded to 4 lbs/ft^2 by means of loose sand contained in "egg carton" type containers. Plywood sheet mounted on point supports of dimensions 2" x 4", 24" on centers, with 1/4" double-sided adhesive backed PVC foam tape. 2" fiber glass insulation batts hung between the point studs.

PARAMETER VALUES:

M = 52 lbs/ft^2			
m_1	= 48 lbs/ft^2;	m_2	= 4 lbs/ft^2
f_{c1}	= 200 Hz;	f_{c2}	= 1800 Hz
D	= 10.5 inches;	d	= 6 inches
e	= 2 ft		

STC RATING: 72

COMMENTS:

The method of mass-loading used in this construction was included as an attempt to utilize the beneficial properties of loose sand, i.e., high mass and low stiffness. The measured values of transmission loss are affected by what appears to be resonances in the mass-loaded panel and a lack of low frequency absorption, although the STC is substantial.

APPROXIMATE COST: $2.00/ft^2

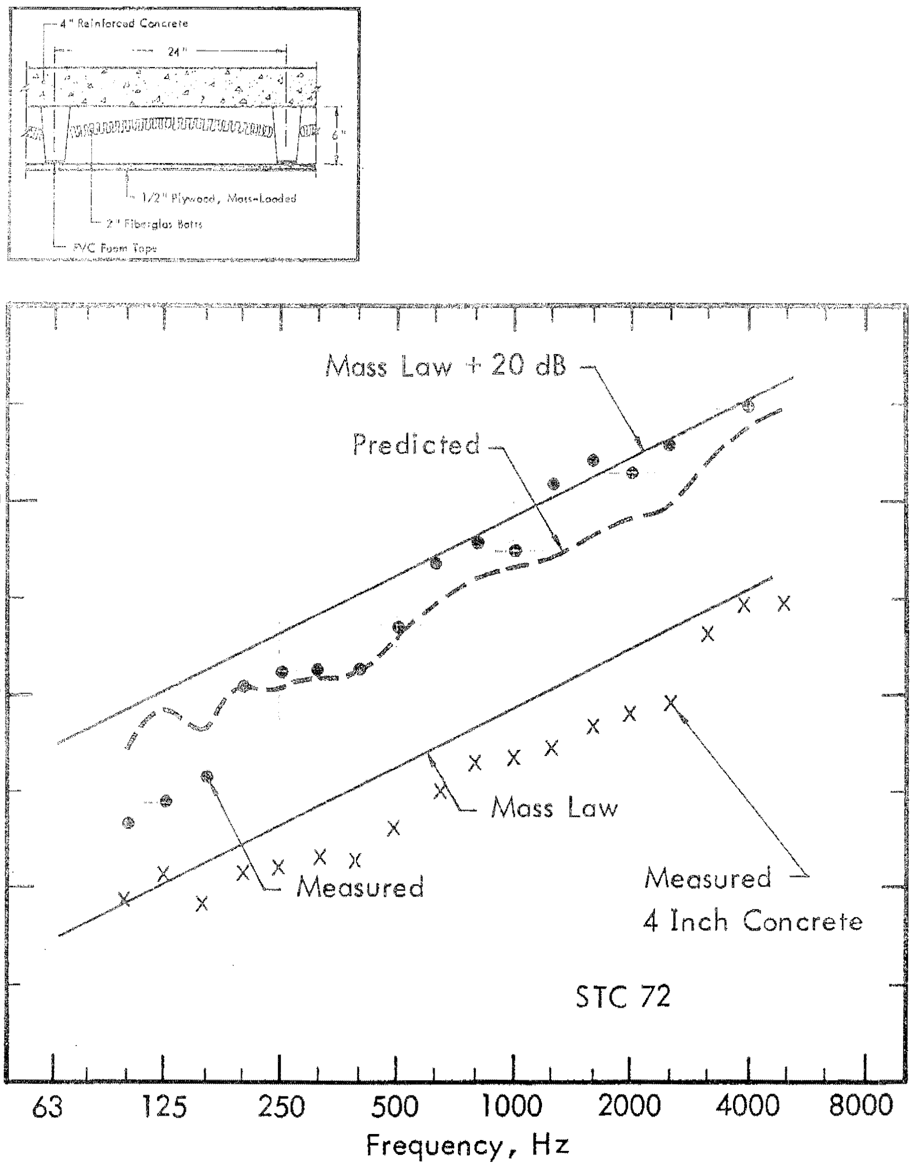


Figure 59. Transmission Loss Values for Prototype E

PROTOTYPE F – WALL

CONSTRUCTION DETAILS:

2" reinforced concrete panel (m_1) with 2" x 8" wooden studs, 24" on centers attached with nails to simulate concrete ribs. On the other side 1/2" plywood (m_2) mass-loaded to 4 lbs/ft^2 by stapling three layers of asphalt roofing paper (0.9 lbs/ft^2 each layer) attached by means of 1/4" x 1" x 1" double-sided adhesive backed PVC foam tape squares 24" on centers vertically. 2" fiber glass insulation batts hung between the studs.

PARAMETER VALUES:

M	=	28 lbs/ft^2			
m_1	=	22 lbs/ft^2;	m_2	=	4 lbs/ft^2
f_{c1}	=	400 Hz;	f_{c2}	=	1800 Hz
D	=	10.5 inches;	d	=	8 inches
e	=	2 feet			

STC RATING: 68

COMMENTS:

This construction is similar in basis to that of Prototype E with the exception that the method of mass-loading is different and that 2" concrete is utilized in place of 4" concrete. Comparing the measured results of transmission loss for the two prototypes shows that the low frequency performance approaches the predicted values more closely for this construction using 2" concrete, although the absolute values for the 4" concrete are comparable or higher. At high frequencies, the measured results for Prototype F exceed those predicted, probably as a result of the PVC foam isolators, the effect of which is not included in the prediction method. The measured results do not satisfy the 20 dB requirement, but at frequencies greater than 200 Hz they are 20 dB or more in excess of the values of transmission loss for the 2 inch concrete.

APPROXIMATE COST: \$1.74/ft^2

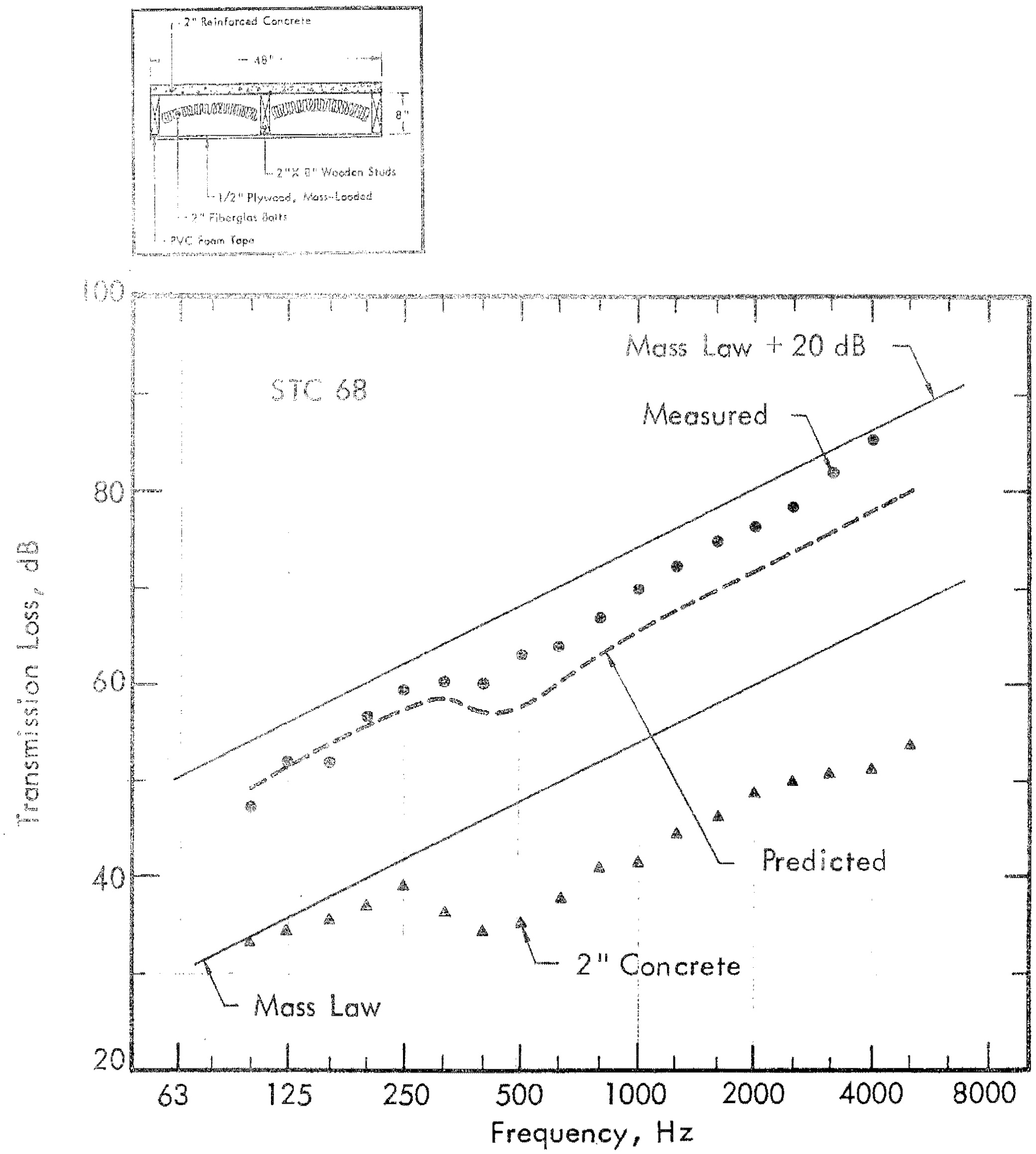


Figure 60. Transmission Loss Values for Prototype F

PROTOTYPE G – WALL

CONSTRUCTION DETAILS:

2" x 8" wooden studs, 24" on centers, attached to 2" x 8" wooden plates at base and top. On both sides, 1/8" fiber glass sheets loaded to 4 lbs/ft^2 with 1" x 1" squares of a mixture of sand and a commercially available vibration damping material (this being used simply to hold the sand in place) mounted on 1/4" x 1" x 1" squares of double-sided adhesive backed PVC foam tape 24" on centers vertically. 2" fiber glass insulation batts hung between the studs.

PARAMETER VALUES:

$M = 10\ lbs/ft^2$

$m_1 = m_2 = 4\ lbs/ft^2$

$f_{c1} = f_{c2} = 6000$ (with no mass-loading)

$D = 8.5$ inches; $d = 8$ inches

$e = 2$ feet

STC RATING: 60

COMMENTS:

A different type of mass-loading is utilized in this construction and appears to have been successful. The agreement between measured and calculated results is good over most of the frequency range. Since the critical frequencies of both panels are high, the effect of the isolators on the transmission loss is small; hence they are not required. For practical purposes, however, a cheaper base material is required.

APPROXIMATE COST: $\$3.55/ft^2$

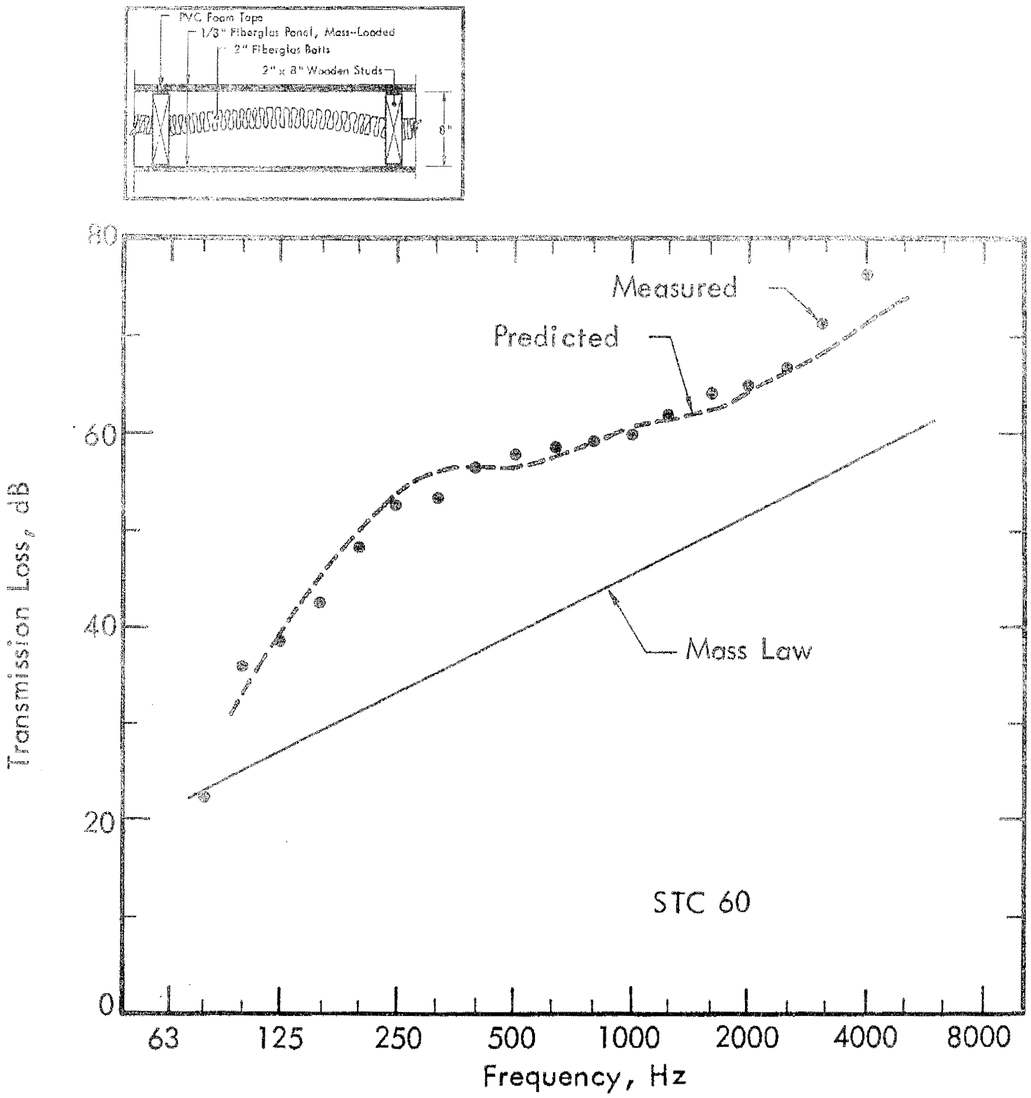


Figure 61. Transmission Loss Values for Prototype G

PROTOTYPE H – WALL

CONSTRUCTION DETAILS:

2" x 4" wooden studs, 32" on centers, staggered 16" on centers attached to 2" x 6" wooden plates at base and top. On both sides, 5/8" gypsum wallboard nailed at 24" on center to studs. 2" fiber glass insulation batts hung between studs.

PARAMETER VALUES:

$M = 6.5\ \text{lbs/ft}^2$

$m_1 = m_2 = 2.6\ \text{lbs/ft}^2$

$f_{c1} = f_{c2} = 2500$ Hz

$D = 6.75$ inches; $d = 5.5$ inches

STC RATING: 43

COMMENTS:

This staggered stud construction is fairly typical of a standard construction, with the exception that the studs are on 32" rather than 16" centers. The STC rating of 43 is low for the construction and is completely determined by the transmission loss at the critical frequency of 2500 Hz at which the maximum allowable deviation of 8 dB is taken. An increase of only a few dB in this frequency region raises the STC rating to its more usual value of 46.

APPROXIMATE COST: $\$1.25/\text{ft}^2$

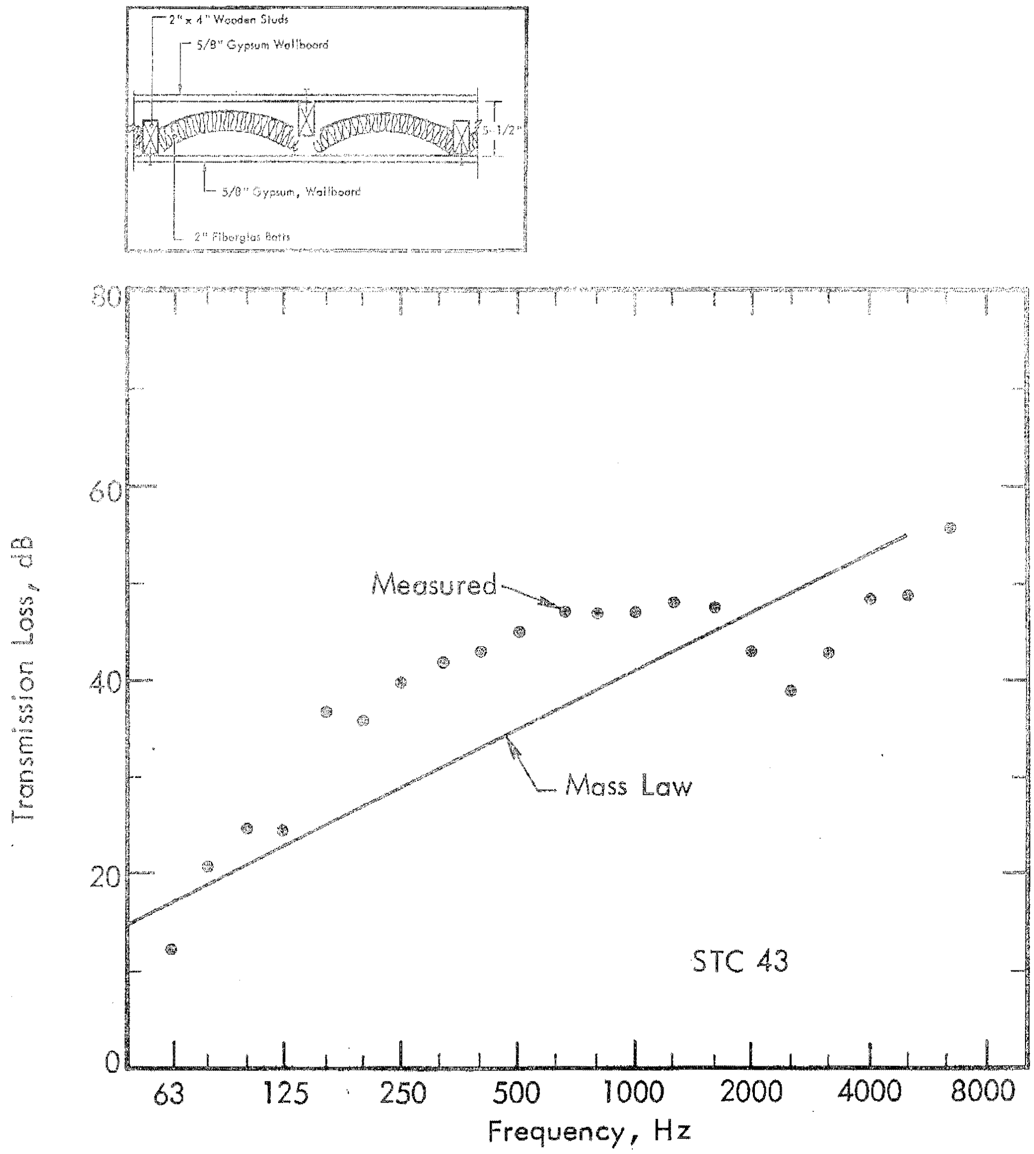


Figure 62. Transmission Loss Values for Prototype H

PROTOTYPE I – FLOOR/CEILING

CONSTRUCTION DETAILS:

2" x 10" wooden joists, 24" on centers, on one side of which is nailed 1/2" plywood. Spot laminated to the plywood (at 12" on centers) are sheets of 3/8" plywood and 5/8" gypsum wallboard which in turn are spot laminated at points 24" on centers. On the other side, sheets of 5/8" and 1/2" gypsum wallboard, similarly laminated, are mounted on 1/4" x 1" x 1" squares of double sided adhesive backed PVC foam tape. 2" fiber glass insulation batts are hung diagonally between the joists.

PARAMETER VALUES:

M	$= 12\ \text{lbs/ft}^2$		
m_1	$= 5.3\ \text{lbs/ft}^2$;	m_2	$= 4.6\ \text{lbs/ft}^2$
f_{c1}	$= 1400$ Hz;	f_{c2}	$= 2500$ Hz
D	$= 12.6$ inches;	d	$= 10$ inches
e	$= 2$ feet		

STC RATING: 62

IIC RATING: 49 (with vinyl tiles)

COMMENTS:

This floor/ceiling construction is of fairly conventional design with a few modifications such as laminated floor and ceiling panels and point isolaltion for the ceiling. In its tested form, it is anticipated that the ceiling suspension would not be adequate, but could be improved by methods discussed earlier. The STC rating is high but the IIC rating is disappointingly low, at least with the vinyl floor covering.

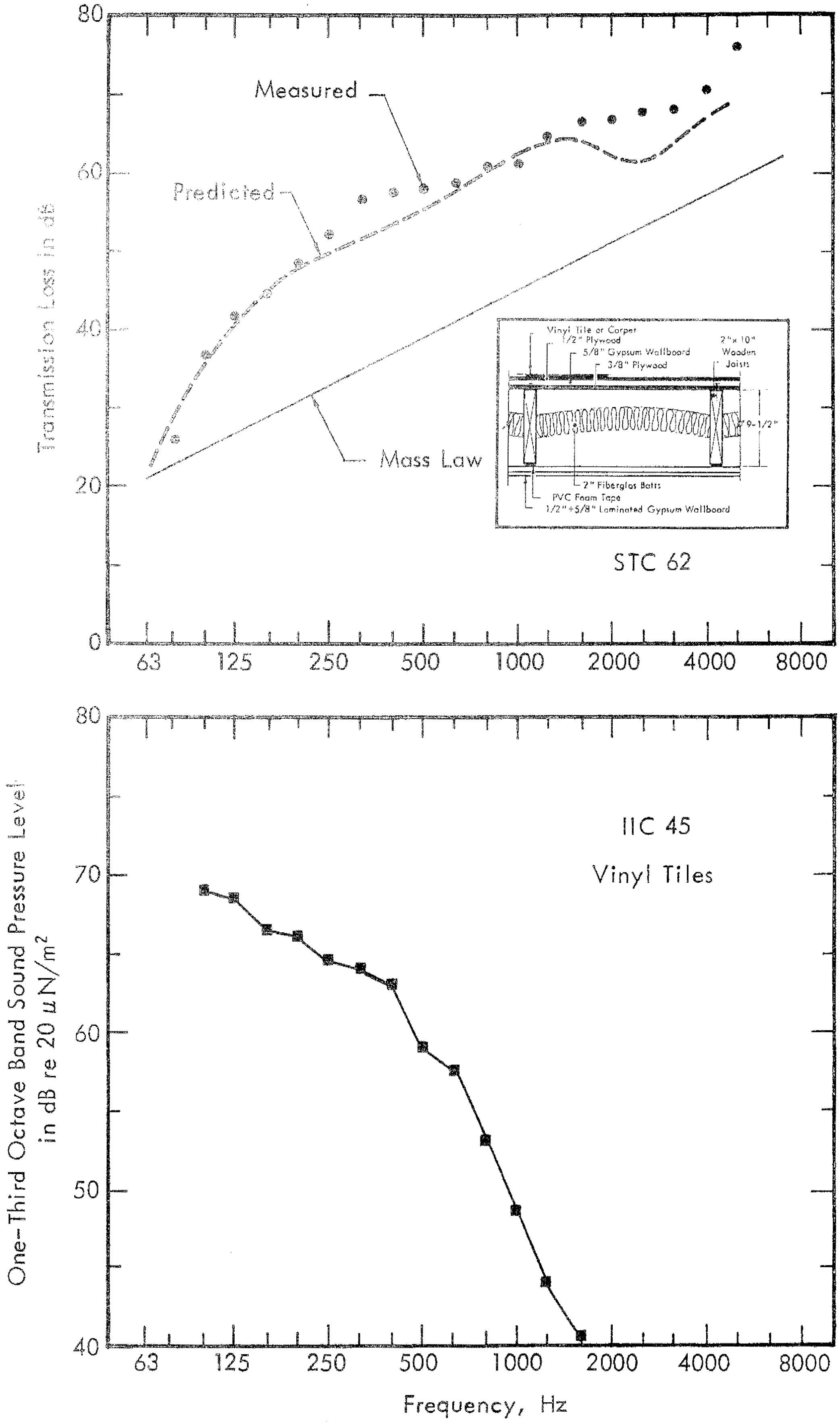


Figure 63. Transmission Loss and Impact Noise Level Values for Prototype I

PROTOTYPE J – FLOOR/CEILING

CONSTRUCTION DETAILS:

2" x 18" wooden joists, 24" on centers, acting as a simulated subfloor system, on one side of which is 2" reinforced concrete. On the other side, 1/4" hardboard mass loaded with asphalt roofing paper to approximately 4 lbs/ft^2 mounted on 1/4" x 1" x 1" squares of double sided adhesive backed PVC foam tape. 2" fiber glass insulation batts are hung diagonally between the joists.

PARAMETER VALUES:

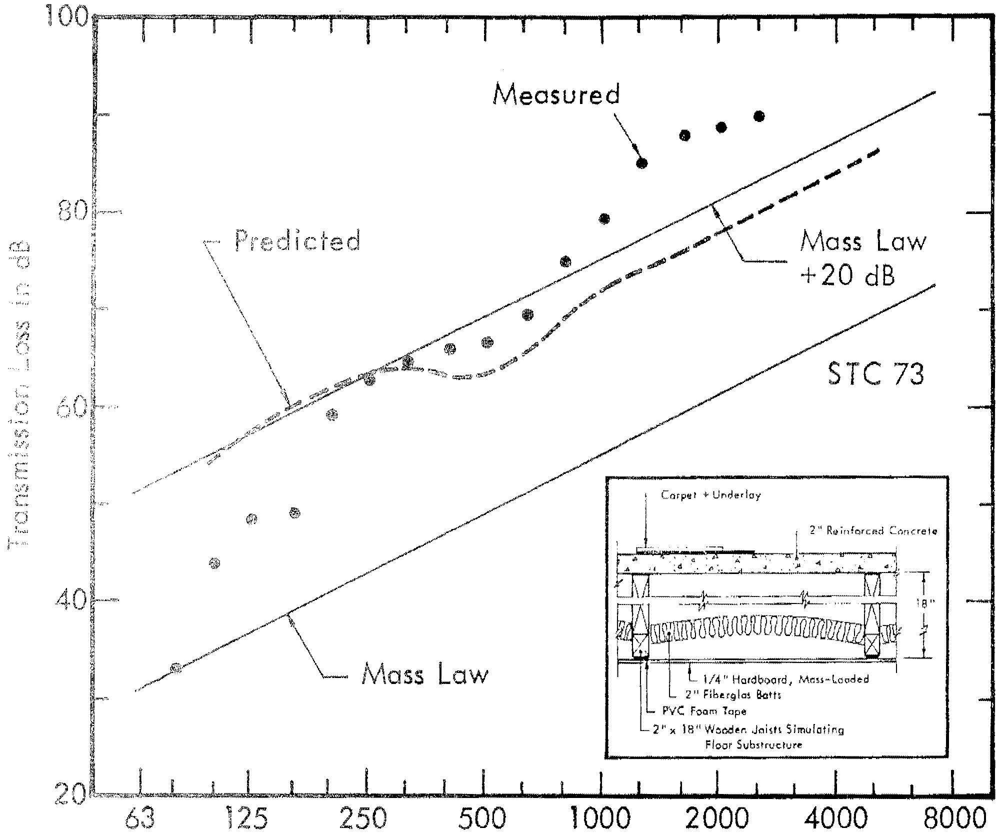
M	= 32 lbs/ft^2		
m_1	= 24 lbs/ft^2;	m_2	= 4 lbs/ft^2
f_{c1}	= 400 Hz;	f_{c2}	= 4000 Hz
D	= 20.25 inches;	d	= 18 inches
e	= 2 feet		

STC RATING: 73

IIC RATING: 59 (with vinyl on cork)
60 (with carpet)
73 (with carpet and foam pad)

COMMENTS:

The measured values of transmission loss exceed the predicted values at medium and high frequencies. The reason for the fairly large discrepancies at the high frequencies are not fully understood. At low frequencies, the measured values are close to the transmission loss of the facility, and so the necessary corrections (included in the graph) are probably inaccurate. This partly explains the negative discrepancies in this range. It is interesting to note that the introduction of a carpet alone does not significantly reduce the impact noise levels, but that a foam pad underneath the carpet does result in a substantial reduction.



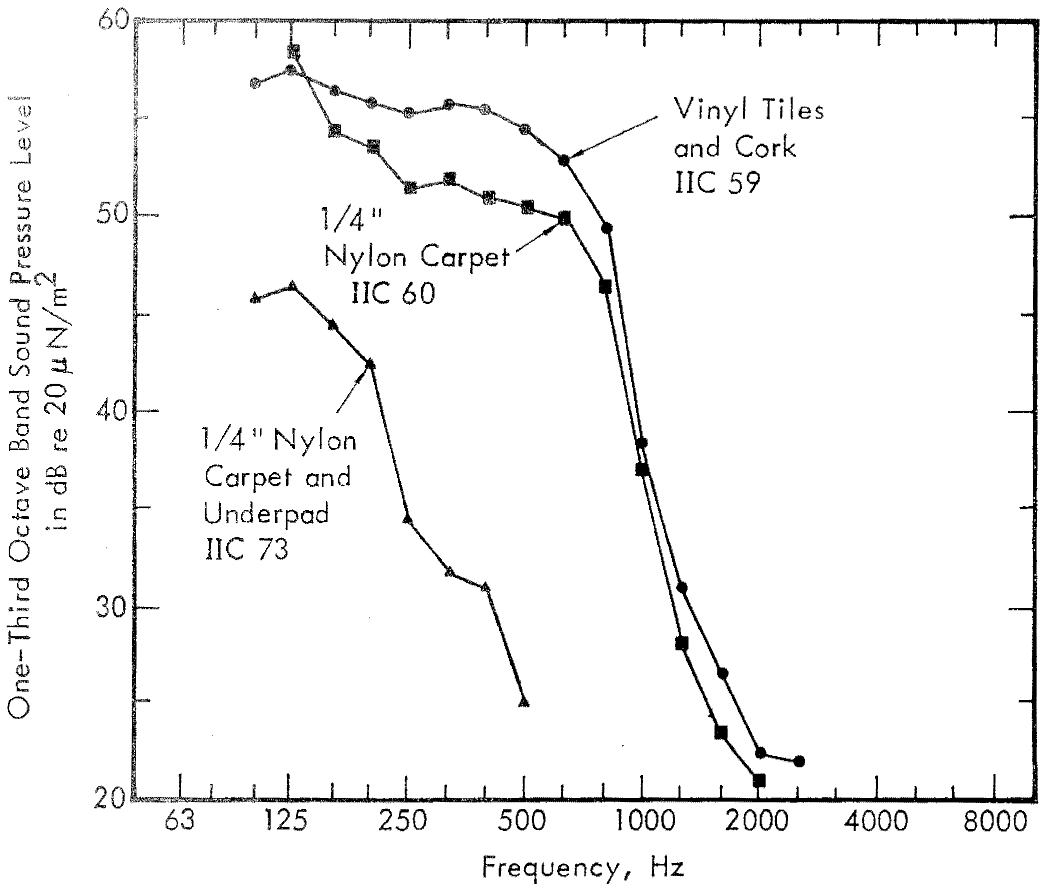


Figure 64. Transmission Loss and Impact Noise Level Values for Prototype J

PROTOTYPE K – ROOF/CEILING

CONSTRUCTION DETAILS:

2" x 10" wooden joists, 30" on centers, on one side of which is 2" reinforced concrete (m_1). On the other side, a lightweight steel channel is nailed perpendicularly to the main joist direction, to which is mounted 1/2" and 5/8" gypsum wallboard (m_2) spot-laminated at 24" on centers, by means of 1/4" x 1" x 1" squares of double-sided adhesive backed PVC foam tape, 24" on centers. 2" fiber glass insulation batts are hung diagonally between the joists.

PARAMETER VALUES:

M	$= 30\ lbs/ft^2$		
m_1	$= 24\ lbs/ft^2$;	m_2	$= 4.6\ lbs/ft^2$
f_{c1}	$= 400$ Hz;	f_{c2}	$= 2500$ Hz
D	$= 15$ inches;	d	$= 12$ inches
e	$= 2$ feet		

STC RATING: 69

COMMENTS:

The effect of coincidence in the 2" concrete roof in this construction is evident at 400 Hz. It results in more substantial reduction in transmission loss in this frequency region than was observed in the previous prototype (J) because the ceiling panel in this construction is less flexible. Again, the predicted results fall below those measured.. This is partly due to the resilient connections between the ceiling panel and the joists.

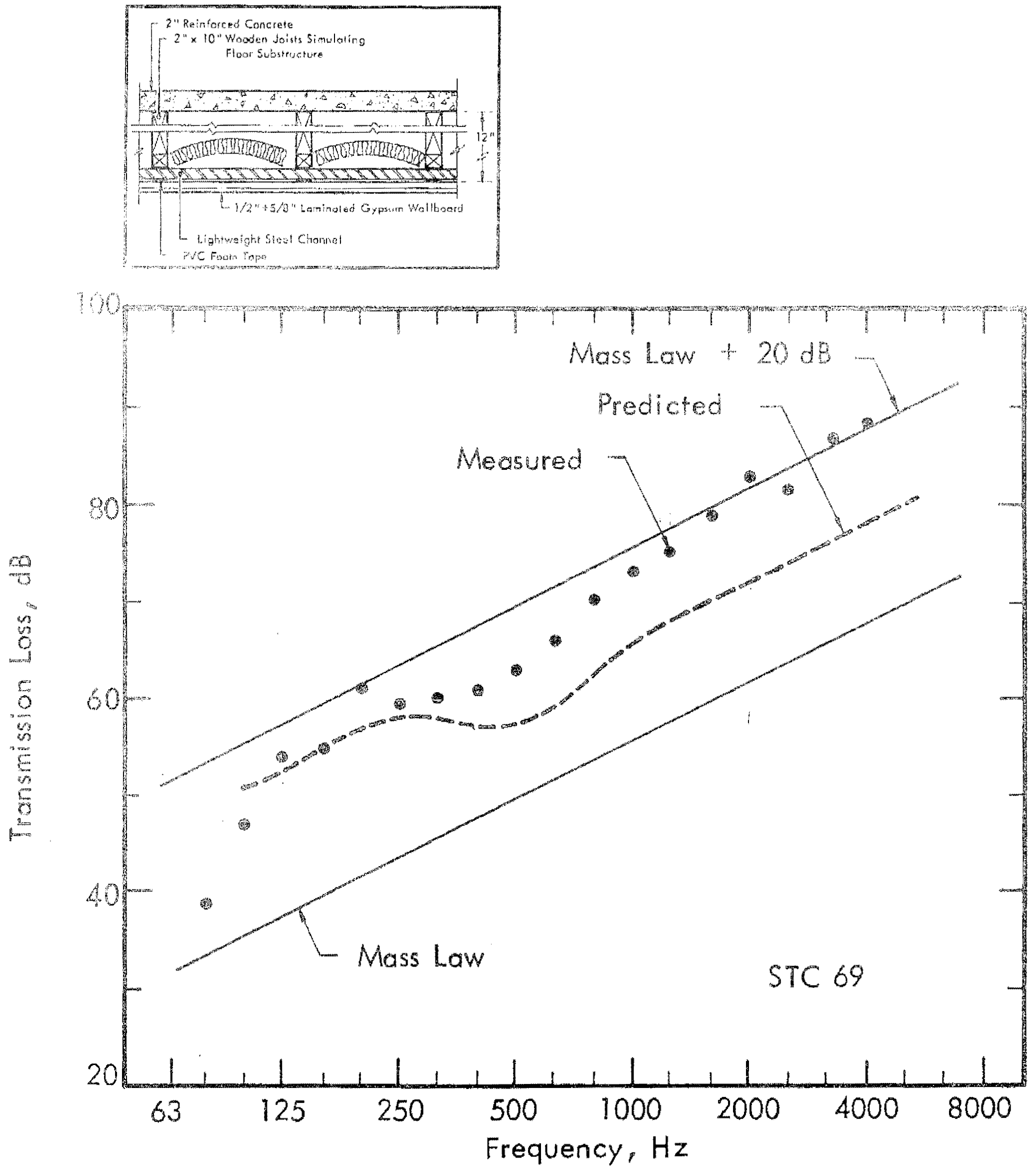


Figure 65. Transmission Loss Values for Prototype K

PROTOTYPE L – ROOF/CEILING

CONSTRUCTION DETAILS:

2" x 10" wooden studs, 24" on centers, on one of which is nailed 1/2" plywood mass-loaded to 4.2 lbs/ft^2 (m_1) with asphalt roofing paper. On the other side, two sheets of 5/8" gypsum wallboard (m_2) spot-laminated at points 24" on centers, mounted to the joists with 1/4" x 1" x 1" squares of double-sided adhesive backed PVC foam tape. 2" fiber glass batts were hung diagonally between the joists.

PARAMETER VALUES:

M	= 11.5 lbs/ft^2		
m_1	= 4.2 lbs/ft^2;	m_2	= 5.6 lbs/ft^2
f_{c1}	= 2000 Hz;	f_{c2}	= 2500 Hz
D	= 12 inches;	d	= 9.5 inches
e	= 2 feet		

STC RATING: 63

COMMENTS:

The agreement between the measured and approximate predicted results for this construction is good. It is interesting to note that the effect of coincidence at 2500 Hz for the gypsum wallboard is not evident indicating the value of the PVC isolators. In addition, the approximate straight line method for predicting the transmission loss is fairly accurate.

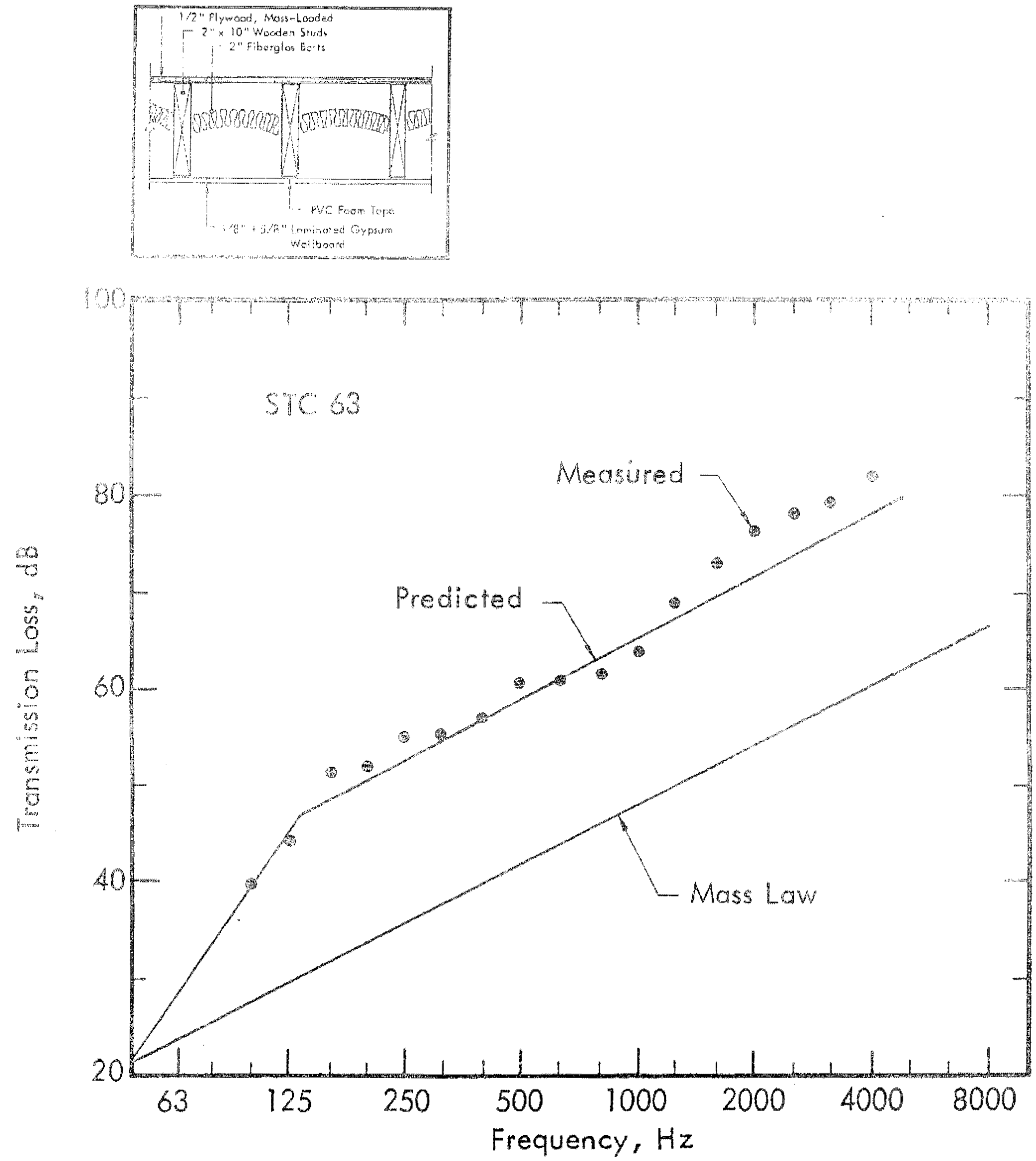


Figure 66. Transmission Loss Values for Prototype L

PROTOTYPE M – DOOR

CONSTRUCTION DETAILS:

2" Tectum (m_1) (cemented wood shavings), one side of which has bonded to it a layer of 5/8" gypsum wallboard (m_2) and 1/4" hardboard (m_3). On the other side, 1/8" hardboard (m_4) mounted on 1/8" x 1" x 1" squares of double sided adhesive backed PVC foam tape 12" on centers vertically and horizontally. The frame consisted of 2" x 2" lumber, to which the gypsum wallboard and the 1/8" hardboard were nailed.

PARAMETER VALUES:

M	= 8 lbs/ft^2		
m_1	= 3 lbs/ft^2;	m_2	= 2.6 lbs/ft^2
m_3	= 1.4 lbs/ft^2;	m_4	= 0.7 lbs/ft^2
f_{c1}	= (unknown)	f_{c2}	= 2500 Hz
f_{c3}	= 5000 Hz	f_{c4}	= 10,000 Hz
D	= 3 inches		
e	= 1 foot		

STC RATING: 43 (sealed)

COMMENTS:

Of major interest in this construction is the tectum which is a porous material and hence provides both mass and absorption. With the 1/8" hardboard spaced away from the tectum, a double panel characteristic is obtained without the need for large, empty cavities that are wasteful of space.

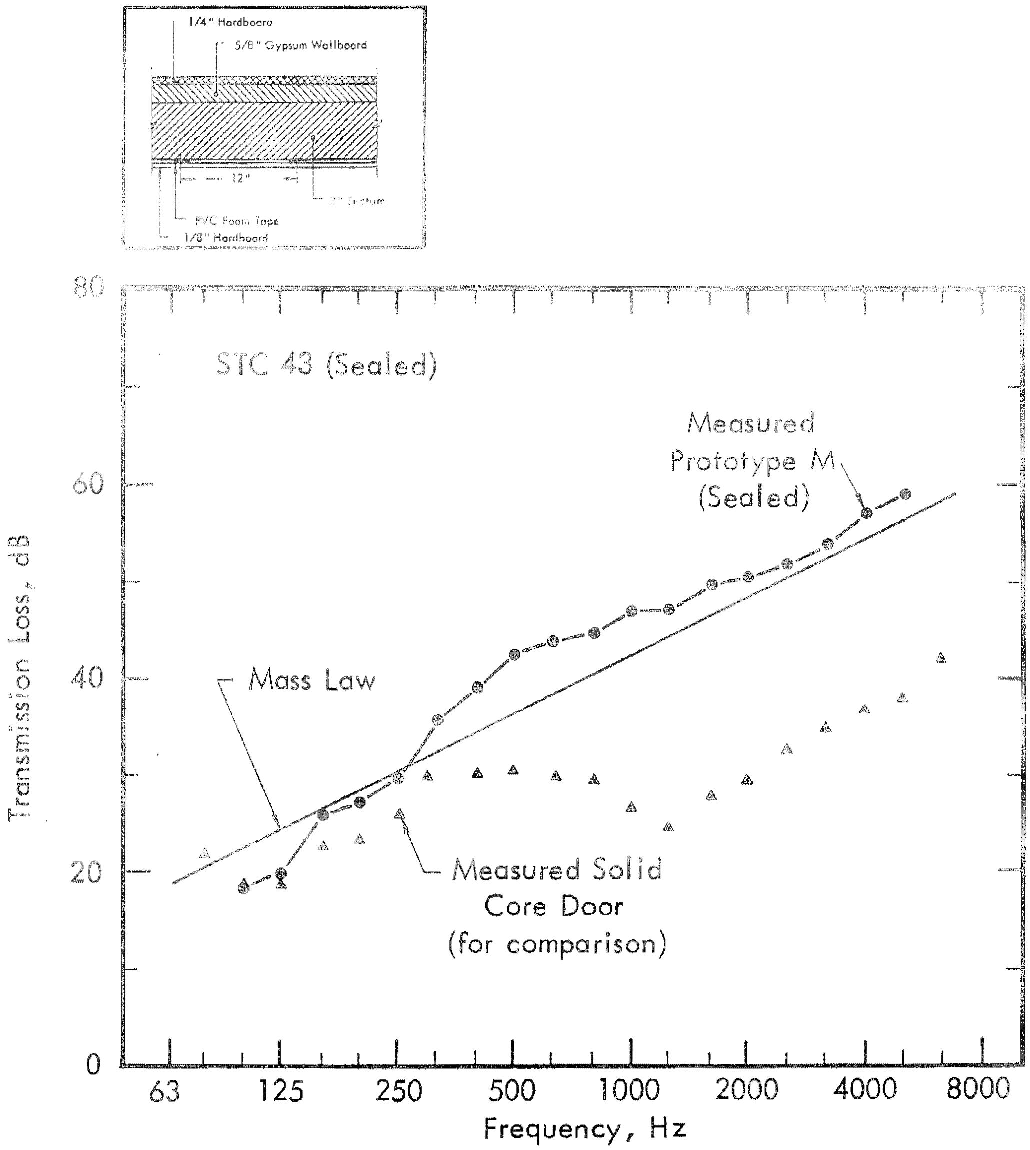


Figure 67. Transmission Loss Values for Prototype M

PROTOTYPE N – WINDOW (SEALED)

CONSTRUCTION DETAILS:

1/4" (m_1) and 3/16" (m_2) plate glass panels mounted 8" apart in two sides of an isolated, high transmission loss wall system (STC 69). The perimeter of the assembly was effectively sealed without introducing significant sound bridges and 2" fiber glass insulation board was placed around the perimeter.

PARAMETER VALUES:

M	= 5.7 lbs/ft^2		
m_1	= 3.3 lbs/ft^2;	m_2	= 2.4 lbs/ft^2
f_{c1}	= 2400 Hz;	f_{c2}	= 3200 Hz
D	= 8.4 inches;	d	= 8 inches

STC RATING: 54

COMMENTS:

The need for complex and costly perimeter gaskets is partially eliminated by placing the two glass panels in separate panels of a high transmission double panel construction. At high frequencies, greater than 300 Hz, the transmission loss is determined by the degree of isolation between the two panels of the wall and by the lack of a full layer of absorption in the airspace.

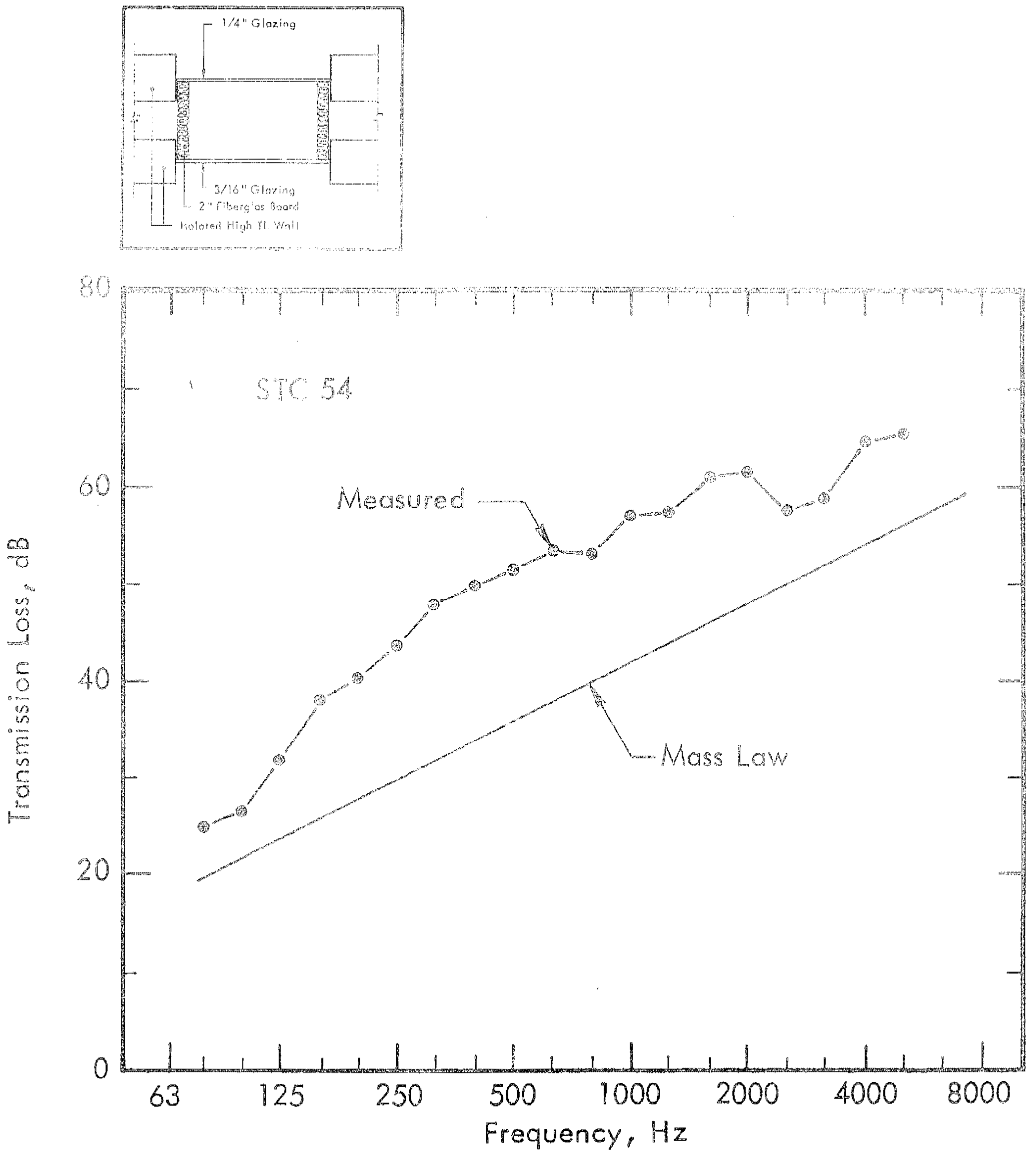


Figure 68. Transmission Loss Values for Prototype N

PROTOTYPE O – WINDOW (OPERABLE)

CONSTRUCTION DETAILS:

1/4" (m_1) and 3/16" (m_2) plate glass panels mounted in standard aluminum sliding window frames 8" apart in two sides of an isolated, high transmission loss wall system (STC 69). The perimeter of the assembly was effectively sealed without introducing significant sound bridges, and 2" fiber glass insulation board was placed around the perimeter. Metal channels containing neoprene seals were screwed to the perimeter of the movable section of each window.

PARAMETER VALUES:

M	= 5.7 lbs/ft^2		
m_1	= 3.3 lbs/ft^2;	m_2	= 2.4 lbs/ft^2
f_{c1}	= 2400 Hz;	f_{c2}	= 3200 Hz
D	= 8.4 inches	d	= 8 inches

STC RATING: 50

COMMENTS:

The effect of the neoprene edge seals is evident in the frequency region near 1500 Hz. The STC rating of 50 is just 4 points lower than for a sealed double window – see Prototype N.

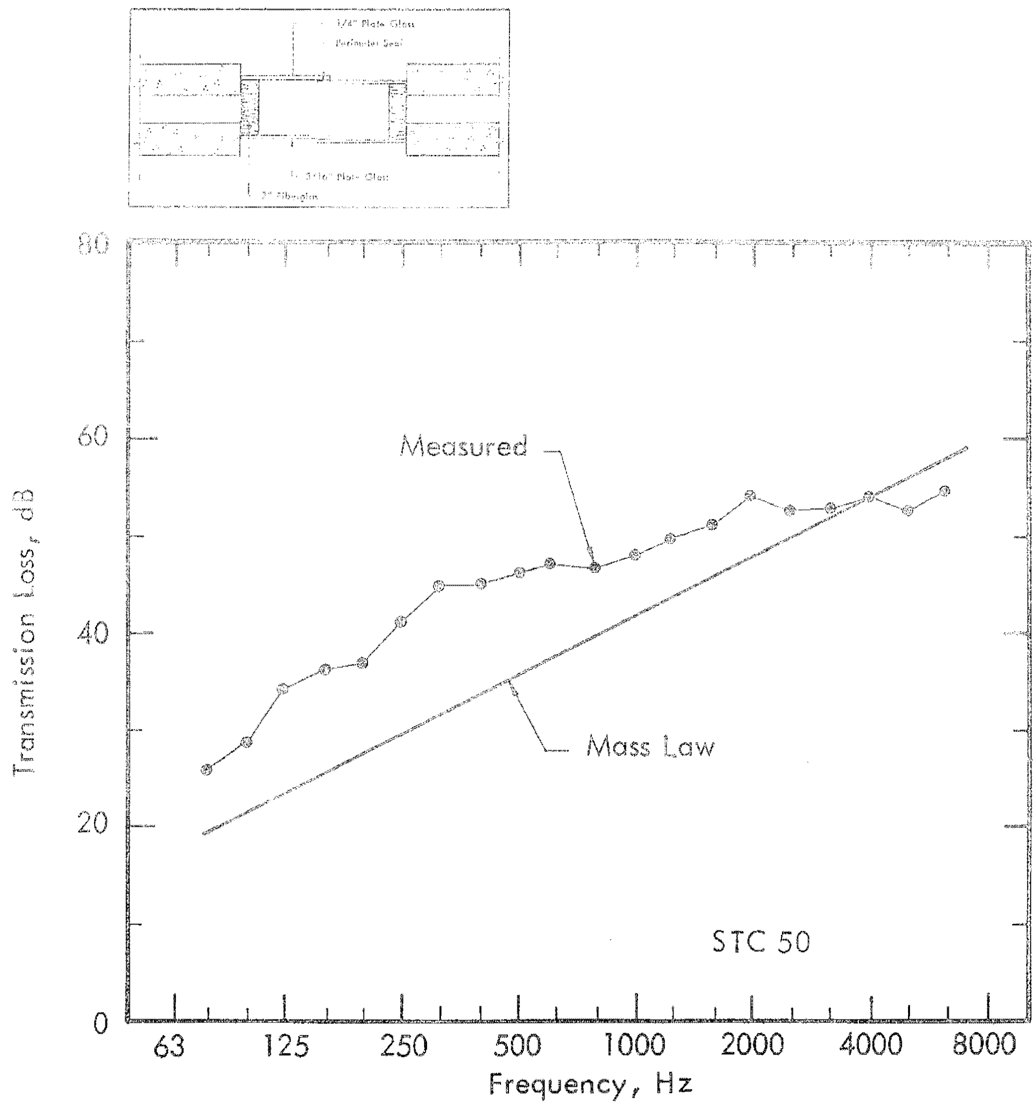


Figure 69. Transmission Loss Values for Prototype O

b. Summary of Experimental Prototype Results

In order to present the results in a simplified summary form, the performance of the various prototypes has been rated in terms of two single numbers, a combination of which indicates whether or not a particular construction achieved the goals presented in the contract. One of the classifications used is the familiar STC method. In nearly every case, however, the determining factor in the classification of the measured results for the prototypes using this method is the value at 125 Hz. Thus, the STC figure for these prototypes is purely a low frequency classification. In order to obtain a classification of the constructions in terms of the measured performance results at high frequencies, it was decided to use the SIL (Speech Interference Level) method. The SIL figure is the numerical average of the measured transmission loss values in the 500, 1000 and 2000 Hz octave bands. A combination of the two methods of classification enables a clear picture to be obtained for the overall performance of the prototype constructions.

The results of the prototype tests are condensed in Table 4 to illustrate the most important features. This table briefly describes the basic construction of the various prototypes; it includes the mass and the single-figure methods of classifying the performance. Additionally, there are three columns that relate to the goal of the contract. The fourth column shows the percentage (F) of the 16 measured frequencies at which the measured results attain or exceed the 20 dB requirement. The sixth column shows the difference in dB (ΔSTC_m) between the STC figure for the measured values of transmission loss and the STC figure for the calculated mass law line. The final column is similar, except that differences in the SIL figures are presented.

A study of the ΔSTC_m and ΔSIL_m columns presents a picture of the relationship existing between the low and high frequency results. It is revealing to compare the figures for the prototypes with those for the standard type of staggered stud wall (Prototype H). The STC rating of the latter is lower than the normal measured rating of approximately 46, primarily due to the large dip in transmission loss at the critical frequency of the panels. For the purpose of comparison, however, consistency is maintained by taking the STC rating of the standard construction as 43. Note that the modified staggered stud wall (Prototype A) has significantly greater performance than that of the standard, 14 dB in STC and 18 dB in SIL transmission loss.

TABLE 4

EXPERIMENTAL PROTOTYPE TEST RESULTS

Prototype	Total Mass (lbs/ft^2)	Total Thickness (inches)	Design Type	F(%)	STC	ΔSTC_m	SIL TL	ΔSIL_m
(a) Walls								
A. Modified gypsum-board staggered stud	8.5	8 - 1/2	II	38	57	17	63	21
B. Plywood/loaded hardboard double wall	9.2	8 - 3/4	II	94	67	24	74	29
C. Triple gypsum-board (laminated)	16.7	13 - 1/2	I	100	76	29	81	33
D. Double gypsum-board (laminated	16.7	11 - 1/2	I	94	69	22	74	26
E. 4" concrete/loaded plywood double wall	52	10 - 1/2	I	19	72	15	76	17
F. 2" concrete/loaded plywood double wall	26	10 - 1/2	I	0	68	16	70	16
G. Loaded fiber glass double wall	10	8 - 1/2	II	13	60	17	61	16
H. Standard staggered stud w/gypsum board	6.2	6 - 3/4	-	0	43	4	45	4
(b) Floor/Ceilings								
I. Modified wood joist	12	12 - 5/8	II	13	62	19	63	18
J. 2" concrete/loaded hardboard	32	20 - 1/4	I	50	73	20	79	24
(c) Roof/Ceilings								
K. 2" concrete/laminated gypsum-board	29.5	15 - 1/8	I	19	69	16	73	17
L. Loaded plywood/gypsumboard	11.4	11 - 1/8	II	38	63	18	67	19

The average values of ΔSTC_m and ΔSIL_m for the wall prototypes (excluding Prototype F) are 20 dB and 23 dB, respectively, to the nearest dB. This indicates that the contract goal of the 20 dB requirement, averaged over the complete frequency range, has been essentially achieved. In a similar manner, the results of the other major structural elements, roof/ceiling and floor/ceiling, give averages at about 19 and 20 dB, respectively. It should be emphasized, however, that these single-number figures of transmission loss represent only an approximate method for classifying the results.

The results of the tests on the Type II prototypes demonstrate that Type II performance (i.e., better than FHA Grade I) is generally obtained; in some cases, it is exceeded. The results of the tests conducted on constructions predicted to be of Type I (i.e., 20 dB better than mass law) are varied. Because of the low frequency anomaly* in the test results, which reduced the observed values of transmission loss at low frequencies, the values obtained in this frequency range do not meet the "20 dB requirement." At high frequencies, most of the Type I constructions containing concrete do not meet the requirement. The reason for this reduced performance relative to mass law is the presence of the coincidence and shearing effects in the concrete panels which reduce the single panel transmission loss to 5 to 10 dB below the mass law over most of the frequency range. In all cases, the performance of the prototypes containing concrete averaged 20 dB, or more, greater than the transmission loss of the concrete panel alone which provided most of the mass of the prototype. Despite this defect, the absolute values of STC and SIL transmission loss for the prototypes containing concrete are very good and should encourage utilization of these new designs in future construction.

The main conclusions to be drawn from the results of the experimental prototype tests can be summarized as follows:

* The transmission loss of the dividing wall between the source and receiving room deteriorated in the one-third octave bands centered on 100 Hz and 160 Hz by as much as 4 dB. The defect was subsequently investigated and corrected at the end of the experimental prototype tests.

- The methods of predicting the transmission loss of multiple panel constructions with sound bridges as detailed in Section 2.4 provide values that are in fair agreement with measured values. With the exception of some of the constructions containing concrete panels, the predicted results are normally conservative estimates of the measured performance. This is partly because the true effect of wall isolators is underestimated in the theoretical predictions.

- The concepts of spot-laminating and mass-loading single panels appear to be satisfactory methods of obtaining higher masses without significantly increasing the stiffness of the panels. More refined methods may be required for the fabrication of mass-loaded panels.

- The 20 dB requirement can be satisfied; in fact, an excess of 30 dB greater than the mass law at frequencies above 315 Hz was obtained with the triple panel of Prototype C. The 20 dB requirement was not quite satisfied in the double panel of Prototype D, perhaps due to the low frequency problem in the Transmission Loss Facility.

- The techniques of point-mounting and spot-laminating can be applied to existing constructions to provide a substantial increase in the acoustic performance.

- The results from the tests conducted on Prototype B indicate that it is possible to nail or screw through the point isolators without reducing the values of transmission loss by more than a few dB. This is an important result, as one of the main reasons that some of the experimental prototypes are not fully practical is to be found in the method of mounting the panels.

3.3.2 Practical Prototypes

The results gained from the experimental prototype tests provided valuable indications of the applicability of the theory to the design of building elements. To put the theory into use for the design of practical constructions, it was decided to select goals that included not only very high values of transmission loss but also moderate values at low cost. Three ranges of STC values were considered – namely, 40-50, 50-60 and 60-70 – for each of the building elements, as shown in the matrix of Table 5. The STC range 50-60 covers that required for FHA Grade I and Grade II constructions. A fourth category is included in Table 5 for constructions meeting the 20 dB requirement.

TABLE 5

MATRIX OF POSSIBLE BUILDING ELEMENTS
AND STC RATINGS

Building Element	STC Rating			
	40-50	50-60	60-70	20 dB
Interior Wall	(45)		---	---
Party Wall	---	(55)		(70)
Exterior Wall			(66) (67)	(64)
Floor/Ceiling	---		(66)	
Window		(55)	---	---
Door	(43)		---	---

It should be noted that some of the elements of the matrix presented in Table 5 have been deleted. These combinations of construction type and STC rating are considered to be of less interest and hence have been excluded from further study. For the majority of the remaining combinations, there exists the possibility of the building element being loadbearing or non-loadbearing and of either conventional or new construction, whether this be represented by the choice of new materials or by construction techniques. This, of course, leads to a very large number of combinations from which eight final constructions were selected. Those selected include at least one element from each type, with the exception of a roof/ceiling which was excluded because of its obvious similarity in many respects to both an exterior wall and a floor/ceiling design.

The approach to the selection was twofold. First, it was decided to include one or more systems that would meet the 20 dB requirement at frequencies in excess of 200 Hz rather than 125 Hz, so that the overall dimensions could be kept within reasonable limits. The obvious choices for this requirement were a party wall and an exterior wall. The party wall was designed to provide an STC rating of 70, which is 10 to 15 greater than that recommended by FHA for Grade 1 constructions. It would therefore provide substantially greater sound insulation between dwelling units than is presently available at comparable weight and cost. The exterior wall was designed to provide an STC of 65, which would be well suited to an airport environment.

Second, as cost is of major concern, it was decided to include a system that provided an STC value consistent with or exceeding FHA Grade I or II requirements at low cost. This was preferred over systems that provided higher transmission loss, even though the cost per STC value for these was comparable to or less than that for the one selected. Consequently, a party wall providing an STC rating of approximately 55 was included. In addition, an interior dwelling wall of simple construction having an STC rating of 45 was designed. This is a higher rating than normally associated with this type of wall and is obtained at a fairly low cost.

Also included in the selections for testing were two exterior walls designed for high external noise environment (STC 62 and 67 without meeting the 20 dB requirement) and a floor/ceiling design suited for low-rise buildings (STC 63). Finally, a window with an STC rating of 54 and a door of STC rating 43 were included to be tested in combination with two of the walls.

a. Material Considerations

The materials that were used in the prototype constructions were limited mainly to gypsumboard, concrete, hardboard and plywood. The thickness of these materials was chosen for the specific application. Each of these materials, of course, could have been replaced with any other material, provided the physical properties of the replacement were identical to those of the original. Thus the prototype constructions contained only a few of the many combinations of materials that could have been used.

It will be noticed that extensive use has been made of the laminating or mass-loading technique to increase the mass of a panel without substantially changing the stiffness. Since both methods achieve essentially similar results, it is of interest to discuss the rationale for the choice of one over another. Laminating is a method used to connect together two or three flexible panels of a given material, using discrete spots or points of adhesive. Since it would seem to be wasteful in time and money to laminate more than two or three such panels, it is generally not practical to increase the mass of the composite panel to more than two or three times the mass of each constituent panel. Mass-loading on the other hand, involves the addition of a series of discrete masses to a flexible base panel, such as hardboard, that may be of low mass and contribute nothing to the composite panel other than its flexibility. It is anticipated that this fabrication technique would be carried out in a factory. The material used to load the base panel would ideally be inexpensive – a good example is loose sand. The cost of mass-loading a panel would therefore not depend greatly on the additional mass required; consequently, increases in mass in the order of four or five times the original base panel could be obtained at a reasonable cost more efficiently than by using laminations.

It is difficult to estimate the relative cost of panels fabricated by these two techniques because of the unknown tooling expenses that would be involved. However, inspection of the cheaper building materials indicates that gypsumboard panels are extremely amenable to being laminated, whereas hardboard or plywood (which are less massive than gypsumboard in their more common thicknesses) would require mass-loaded configurations. The low cost of gypsumboard compared to other materials tends to indicate that laminated gypsumboard would be the cheaper of the two methods, provided only small increases in mass are required. For larger masses, mass-loading would probably be more cost/effective.

At this point, a word is in order concerning the designs and costs of the prototype constructions. Incorporated in these constructions are several techniques or materials that are not used in common building practice today. The methods of utilizing the techniques and the materials chosen are considered to be reasonably practical and cost/effective. Because they have not been extensively tried out in the practical confines of building sites, however, and since the designs have not been thoroughly reviewed by all the various types of engineers and tradesmen who may eventually be involved in their usage, it is premature to state that they are the best method in each case. Such a statement could be made only after several years of experience with application of the new concepts. It can be anticipated that many, if not all, of the techniques would undergo substantial changes before the final constructions actually appeared at the building site. The same is true for the estimated costs of the constructions. Without a full knowledge of the final details, these factors can be based only on assumption. Much work remains for industry to further develop means of fully utilizing and manufacturing the designs that are presented in this report.

One of the most important requirements that a building element must meet concerns its resistance to fire. Most building codes require the use of non-combustible materials for all but interior walls and partitions. The materials that constitute the proposed constructions are mainly gypsumboard, concrete and tempered hardboard, the first two of which are non-combustible. As far as hardboard is concerned, recent developments appear to have rendered the material non-combustible. The fire resistance properties of a building element depend not only on the materials used for the panels, but also on the method of support, i.e., the framing. Without conducting a fire test on each of the proposed constructions, it is difficult to state what the fire resistance properties will be. It appears that the state-of-the-art in this field does not allow accurate estimates to be made. In the case of non-loadbearing constructions, it is anticipated that the fire resistance requirements will be met. The only remaining question may be with loadbearing constructions with PVC foam isolators, or their equivalent, included in the method of fastening. However, since the panels are nailed through such isolators, a failure of the isolator should not affect the structural integrity of the construction. In conclusion, it is considered that the majority of the proposed constructions can be expected to provide adequate fire protection.

b. Design and Measured Results

Full descriptions of the eight practical prototype constructions are given in this section together with their acoustical performances. Included in the construction details are the estimated in-place cost figures given in dollars per square foot of surface area. These costs do not include finishing and have been determined using the 1971-72 edition of the National Construction Estimator (Reference 16) as far as this is applicable. In cases where the material or type of construction is uncommon to present building technology, attempts have been made with the assistance of an experienced architect to obtain a realistic estimate. Costs are based on the material and labor rates applicable in the Los Angeles area in 1971-72, which is fairly typical of the rates in other large cities across the nation. In the smaller cities, the costs may be somewhat lower.

The elements represented in the prototype constructions are as follows:

Prototype	Building Element
1	Interior Wall
2, 3	Party Wall
4, 5, 7	Exterior Wall
6	Window
8	Floor/Ceiling
9	Door

PROTOTYPE I – INTERNAL WALL

CONSTRUCTION DETAILS:

2" x 4" wooden studs, 24" on centers, attached to 2" x 4" wooden plates at base and top. On one side, 1/2" gypsum wallboard (m_1) nailed to studs. On the other side, 1/2" gypsum wallboard (m_2) nailed through 1/4" x 1" x 1" squares of PVC foam tape. 3-1/2" fiber glass batts hung between the studs.

ESTIMATED COST: \$1.00/ft^2

PARAMETER VALUES:

M	= 4.2 lbs/ft^2		
m_1	= 2.0 lbs/ft^2;	m_2	= 2.0 lbs/ft
f_{c_1}	= 3000 Hz,	f_{c_2}	= 3000 Hz
D	= 4-7/8 inches;	d	= 3-1/3 inches
e	= 2 feet		

STC RATING: 45

COMMENTS:

The agreement between calculated and measured results is good over the complete frequency range. The STC rating of 45 is good for an internal wall and approaches that for a standard staggered stud wall with 5/8-inch gypsum-board panels, which is both more massive and more costly (see Experimental Prototype H).

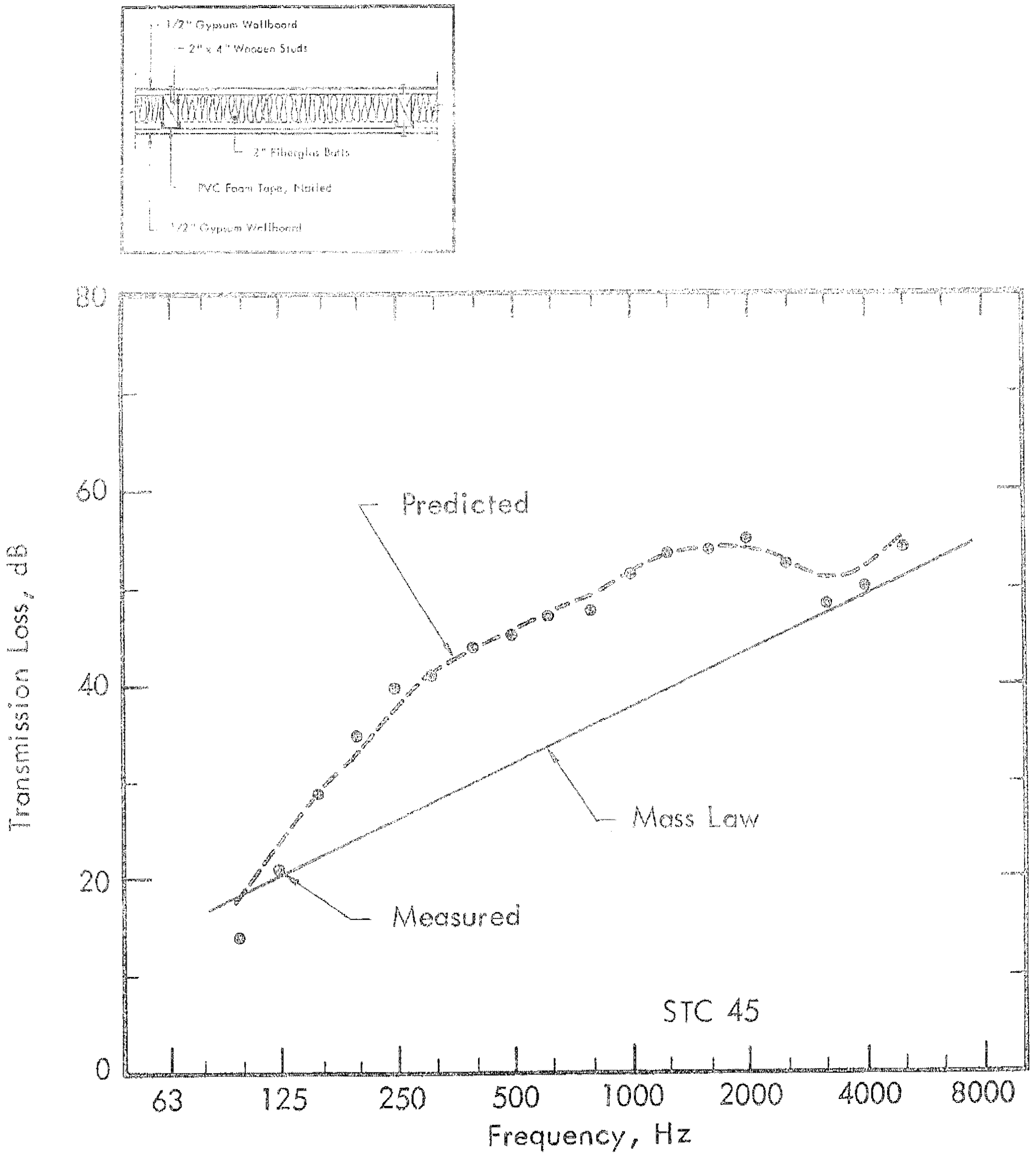


Figure 70. Transmission Loss Values for Prototype 1

PROTOTYPE 2 – PARTY WALL

CONSTRUCTION DETAILS:

2" x 6" wooden studs, 24" on centers, attached to 2" x 6" wooden plates at the base and top. On one side, 5/8" gypsum wallboard (m_1) nailed 24" on centers vertically. On the other side, two sheets of 3/8" gypsum wallboard (m_2) spot laminated 12" on centers nailed to studs through 1/4" x 1" x 1" squares of PVC foam 24" on centers. 3-1/2" fiber glass batts hung between the studs.

ESTIMATED COST: $1.21/ft^2$

PARAMETER VALUES:

M	$= 7 \text{ lbs/ft}^2$		
m_1	$= 2.6 \text{ lbs/ft}^2$;	m_2	$= 3.0 \text{ lbs/ft}^2$
f_{c_1}	$= 2500$ Hz;	f_{c_2}	≈ 4000 Hz
D	= 7-1/8 inches;	d	= 5-1/2 inches
e	= 2 feet		

STC RATING: 54

COMMENTS:

The agreement between calculated and measured results is again good, except at frequencies near the critical frequency. This construction is well suited for a party wall, both in terms of STC rating and cost.

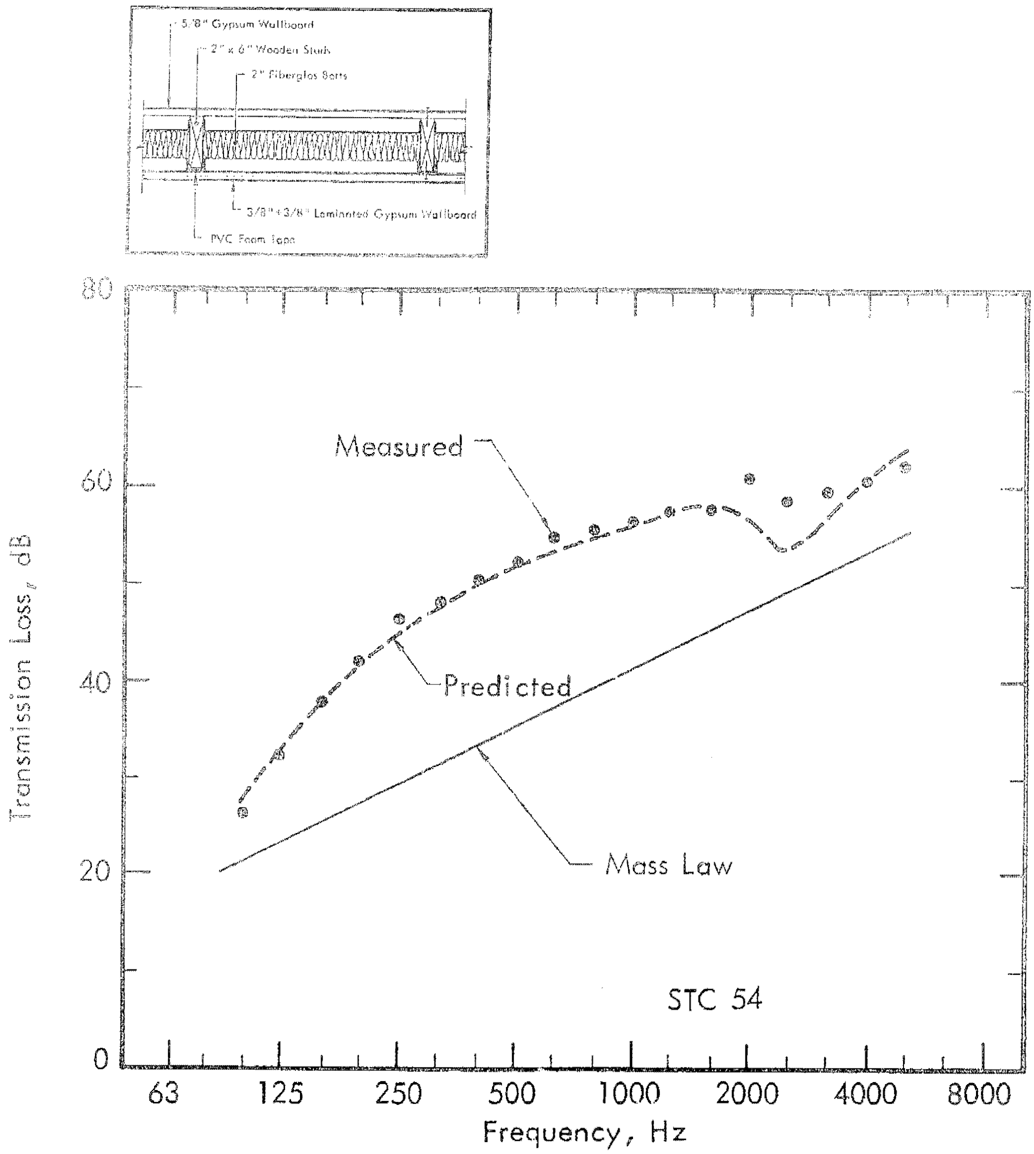


Figure 71. Transmission Loss Values for Prototype 2

PROTOTYPE 3 – PARTY WALL

CONSTRUCTION DETAILS:

2" reinforced concrete panel (m_1) on each side of which are sets of 2-1/2" steel studs, 24" on centers attached to 2-1/2" steel channels at base and top. On each side, two sheets of 1/4" gypsum wallboard (m_2) spot laminated, 12" on centers, screwed through 1/4" x 1" squares of PVC foam tape, at points 24" on centers vertically. 3-1/2 fiber glass batts hung between studs in each cavity.

ESTIMATED COST: \$2.18/ft^2

PARAMETER VALUES:

M	$= 27$ lbs/ft^2		
m_1	$= 22$ lbs/ft^2;	m_2	$= 2$ lbs/ft^2
f_{c_1}	≈ 630 Hz;	f_{c_2}	≈ 5000 Hz
D	$= 8$ inches;	d	$= 2$-1/2 inches
e	$= 2$ feet		

STC RATING: 72

COMMENTS:

This triple panel construction was designed to satisfy the 20 dB requirement at frequencies greater than 200 Hz. The high STC rating and low cost make it a useful construction for separating areas of high noise level to living or studying rooms.

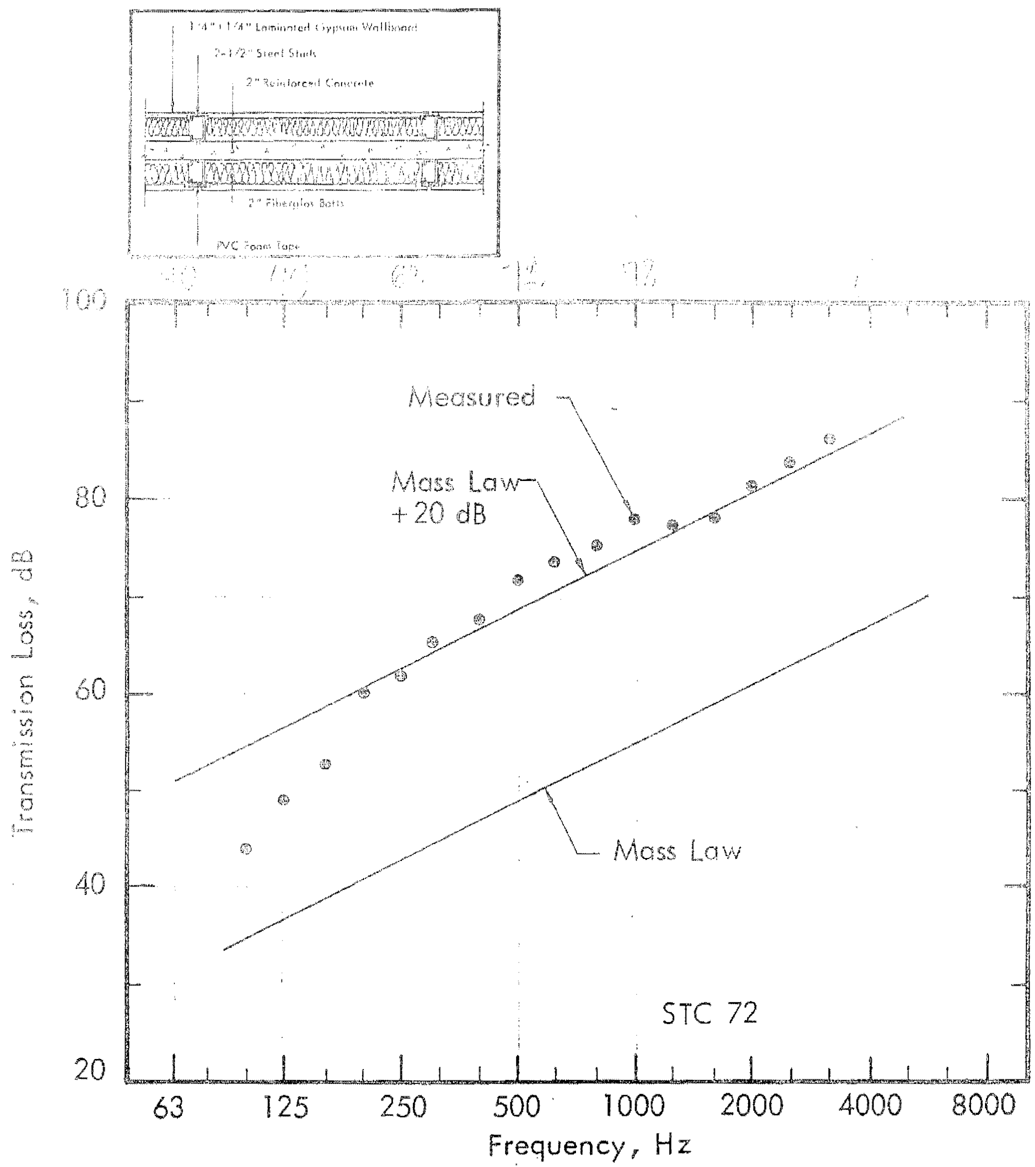


Figure 72. Transmission Loss Values for Prototype 3

PROTOTYPE 4 – EXTERNAL WALL

CONSTRUCTION DETAILS:

2" reinforced concrete panel (m_1) with 2-1/2" steel studs, 24" on centers, attached to 2-1/2" steel channels at base and top. On the other side, two sheets of 1/4" gypsum wallboard (m_2) spot laminated 12" on centers, screwed through 1/4" x 1" x 1" squares of PVC foam tape at points 24" on centers vertically. 3-1/2" fiber glass batts hung between the steel studs.

ESTIMATED COST: $\$1.34/ft^2$

PARAMETER VALUES:

M	$= 26$ lbs/ft^2		
m_1	$= 22$ lbs/ft^2;	m_2	$= 2$ lbs/ft
f_{c_1}	≈ 630 Hz;	f_{c_2}	≈ 5000 Hz
D	$= 5$ inches;	d	$= 2\text{-}1/2$ inches
e	$= 2$ feet		

STC RATING: 64

COMMENTS:

This construction provides a high STC rating at low cost and is extremely thin – only 5 inches overall. Applications include exterior and party walls. Of all the prototypes listed, it is probably the construction with the widest range of applications.

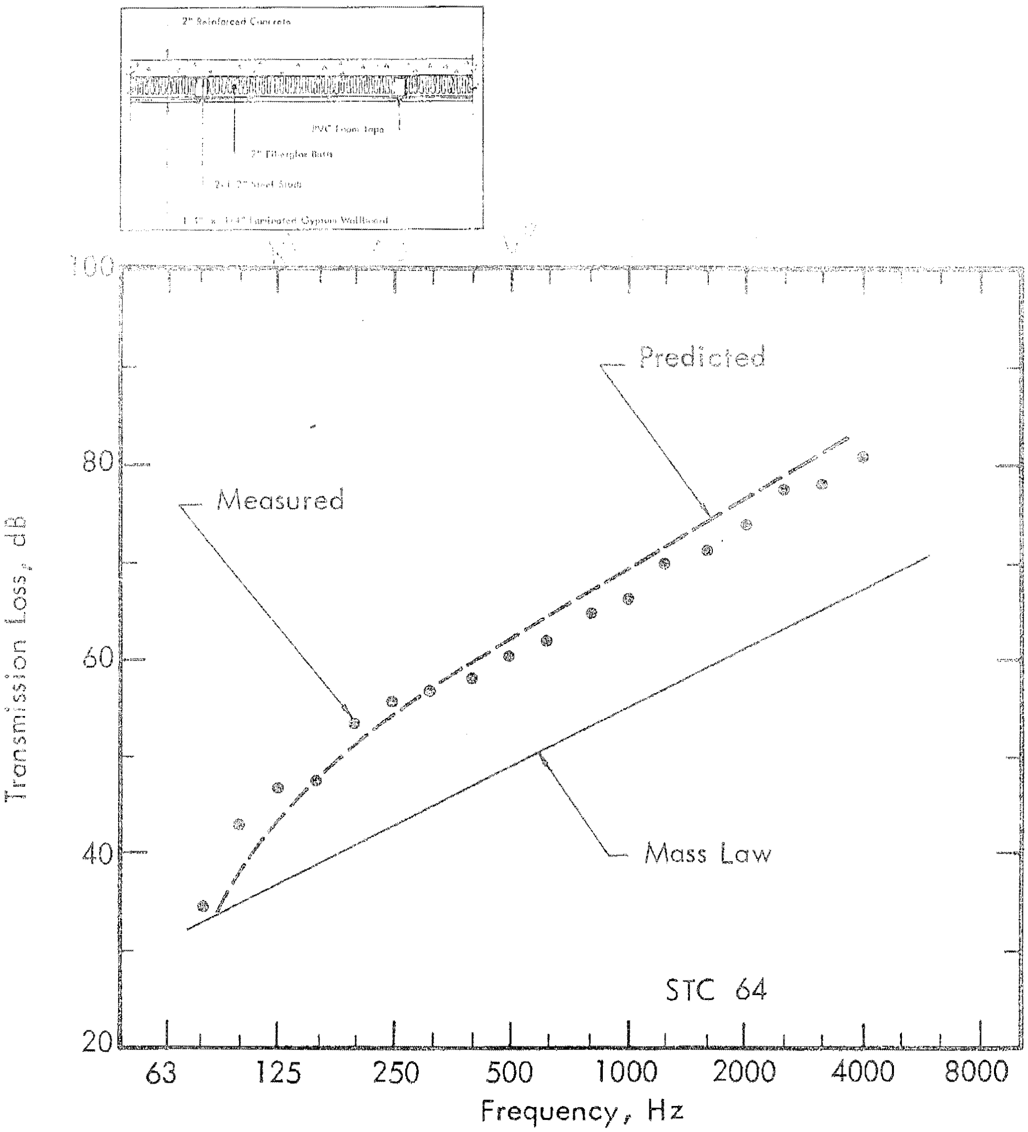


Figure 73. Transmission Loss Values for Prototype 4

PROTOTYPE 5 – EXTERIOR WALL

CONSTRUCTION DETAILS:

2" reinforced, modular concrete wall (m_1), 4' wide, with two sheets of 1/4" gypsum wallboard (m_2), spot laminated at points 12" on centers, nailed through 1/4" x 1" x 1" squares of PVC foam tape 24" on centers. 3-1/2" fiber glass batts hung in the cavity.

ESTIMATED COST: $\$1.59/ft^2$

PARAMETER VALUES:

M	$= 26\ lbs/ft^2$		
m_1	$= 22\ lbs/ft^2$;	m_2	$= 2\ lbs/ft$
f_{c_1}	≈ 630 Hz;	f_{c_2}	≈ 5000 Hz
D	= 8-3/4 inches;	d	= 6 inches
e	= 2 feet		

STC RATING: 63

COMMENTS:

The measured results generally are lower than those predicted at all but the highest frequencies due to coincidence effects in the 2-inch concrete – in the region of 500 to 630 Hz. Since the cavity perimeter in this case is bounded byconcrete ribs with high sound reflection coefficients, the low values of transmission loss may be due also to insufficient absorption in the cavity.

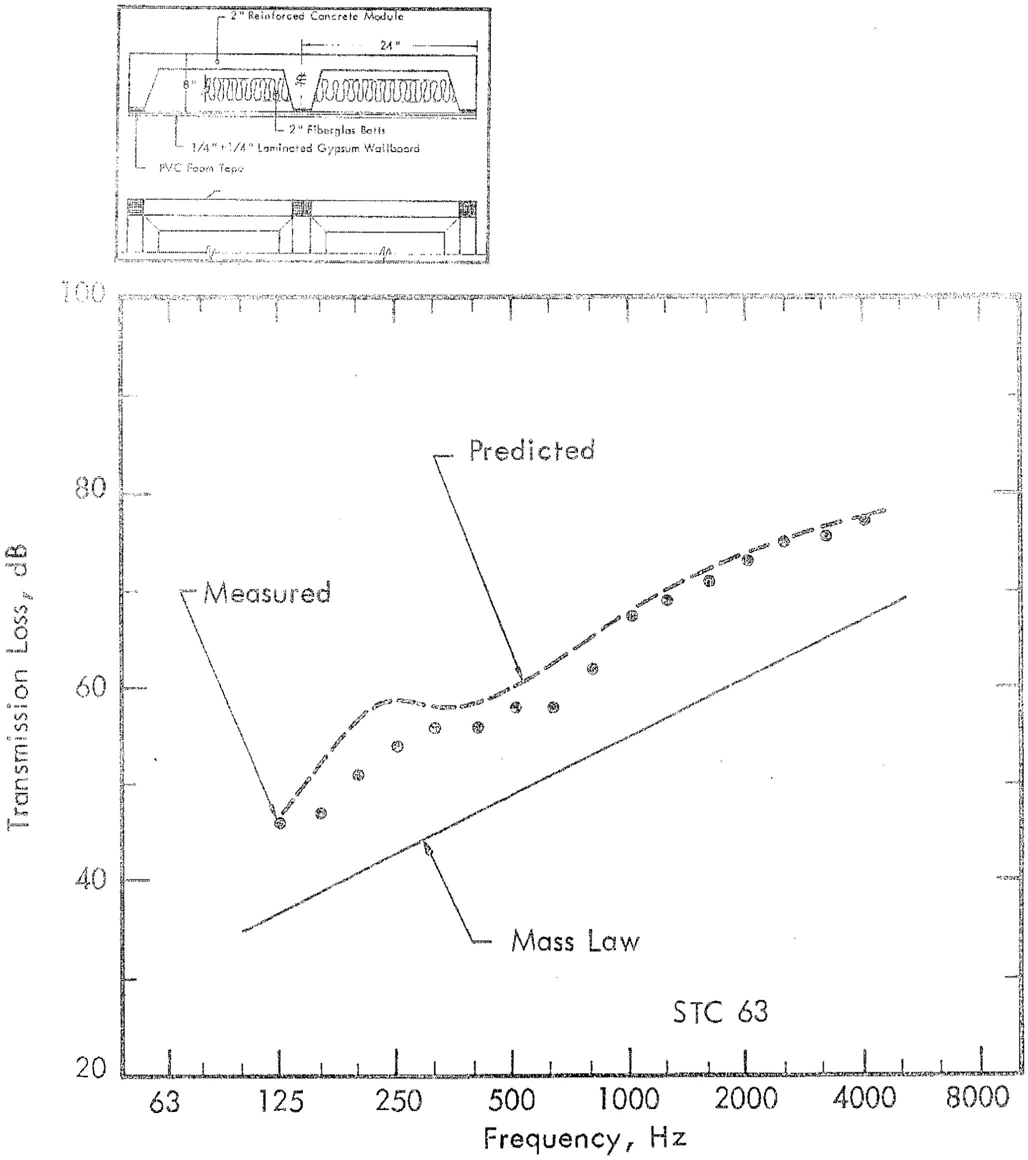


Figure 74. Transmission Loss Values for Prototype 5

PROTOTYPE 6 – WINDOW

CONSTRUCTION DETAILS:

3/16" (m_1) and 1/4" (m_2) plate glass panels mounted in metal channels 8" apart in two walls of an isolated, high transmission loss wall system (Prototype 5, STC 63). The perimeter of the assembly opened into the cavity of the wall which contained 3-1/2" fiber glass batts.

ESTIMATED COST:

Unknown – will depend largely on the cost of a practical type of frame.

PARAMETER VALUES:

M	= 5.7 lbs/ft^2		
m_1	= 2.4 lbs/ft^2	m_2	= 3.3 lbs/ft^2
f_{c1}	= 3200 Hz	f_{c2}	= 2400 Hz
D	= 8-7/16 inches	d	= 8 inches

STC RATING: 61 in combination with the wall of Prototype 5.

COMMENTS:

The STC of 61 for the combination of exterior wall and window is well suited for high external noise environments. Since the glass panels are located in partially isolated walls, there is no requirement for complex gaskets.

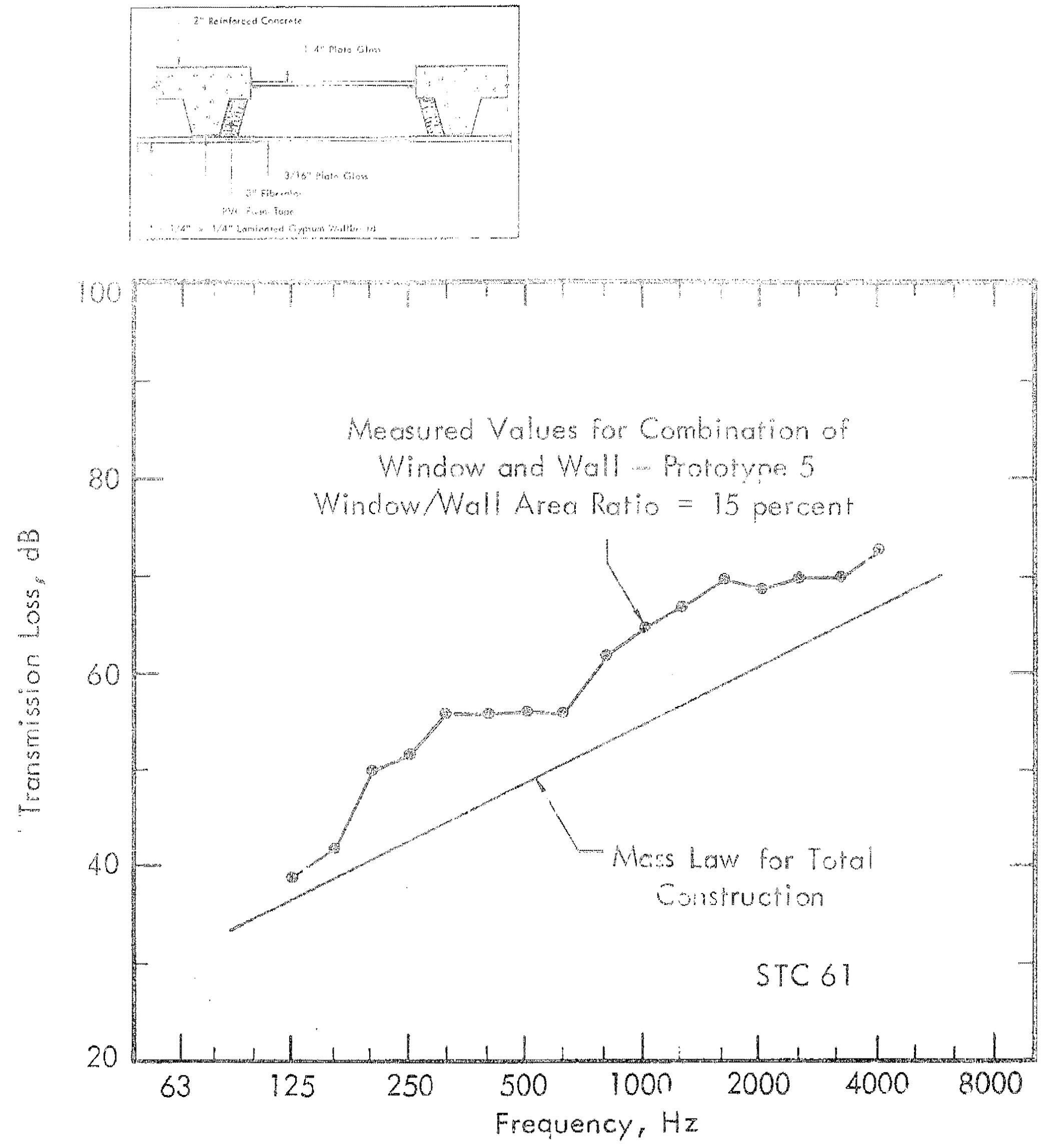


Figure 75. Transmission Loss Values for Prototype 6

PROTOTYPE 7 – EXTERNAL WALL

CONSTRUCTION DETAILS:

6" steel studs, 24" on centers, with 0.025" prefinished steel siding riveted on one side and sprayed with stucco (m_1) to a depth of 1". On the other side, 1/4" tempered hardboard mass loaded to 4 lbs/ft^2 nailed through 1/4" x 1" x 1" squares of PVC foam tape, at points 24" on centers vertically. The hardboard was loaded with loose sand contained in a plastic sheet containing a matrix of enclosed pockets. 3-1/2" fiber glass batts hung between the studs.

ESTIMATED COST: $2.25/ft^2

PARAMETER VALUES:

M	$= 15$ lbs/ft^2		
m_1	≈ 9 lbs/ft^2	m_2	$= 4$ lbs/ft^2
f_{c1}	≈ 630 Hz	f_{c2}	≈ 5000 Hz
D	$= 6\text{-}1/4$ inches	d	$= 5$ inches
e	$= 2$ feet		

STC RATING: 61

COMMENTS:

This construction was an attempt to achieve the 20 dB requirement at frequencies greater than 200 Hz. The main reason for its failure to do so is the effect of coincidence at 630 Hz. The transmission loss is, of course, well in excess of 20 dB greater than the measured values for the stucco alone, which provides most of the total mass.

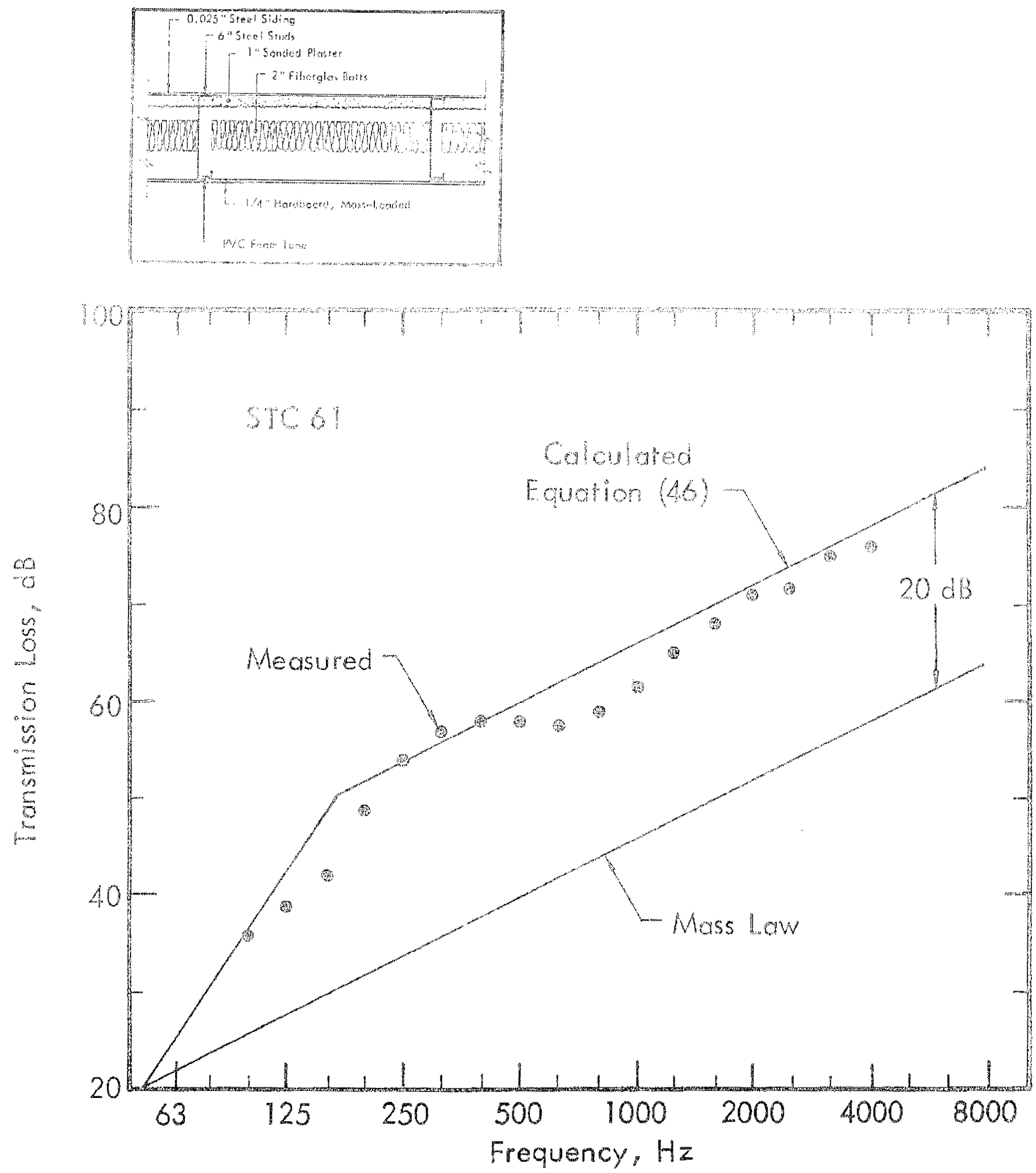


Figure 76. Transmission Loss Values for Prototype 7

PROTOTYPE 8 – FLOOR/CEILING

CONSTRUCTION DETAILS:

2" x 12" wooden floor joists with a floor (m_1) of 5/8" plywood (nailed) and resilient layer of 1/2" fiber glass insulation board on top of which is floated a floor of 1/2" plywood nailed to 7/8" x 7/8" wood stripping, 16" on centers, with loose sand in the cavity space formed. On the ceiling side, two sheets of 1/4" gypsum wallboard (m_2) 2' in width, spot laminated at points 12" on centers, such that during installation nails are driven through only one layer of the laminate. The nails were driven through 1/4" x 1" x 1" squares of PVC foam tape. 3-1/2" fiber glass batts hung diagonally between the joists.

ESTIMATED COST: $2.17/ft²

PARAMETER VALUES:

M	= 17 lbs/ft²		
m_1	≈ 11 lbs/ft²	m_2	= 2 lbs/ft²
f_{c1}	= (unknown)	f_{c2}	= 5000 Hz
D	= 14-1/2 inches	d	= 11-1/2 inches
e	= 1.6 feet		

STC RATING: 63

IIC RATING: 50 Base floor

64 Base floor with carpet and underpad

COMMENTS:

This construction again demonstrates the benefits of a carpet and underpad in reducing impact noise levels. The transmission loss values exceed 20 dB greater than the mass law at all frequencies above 250 Hz.

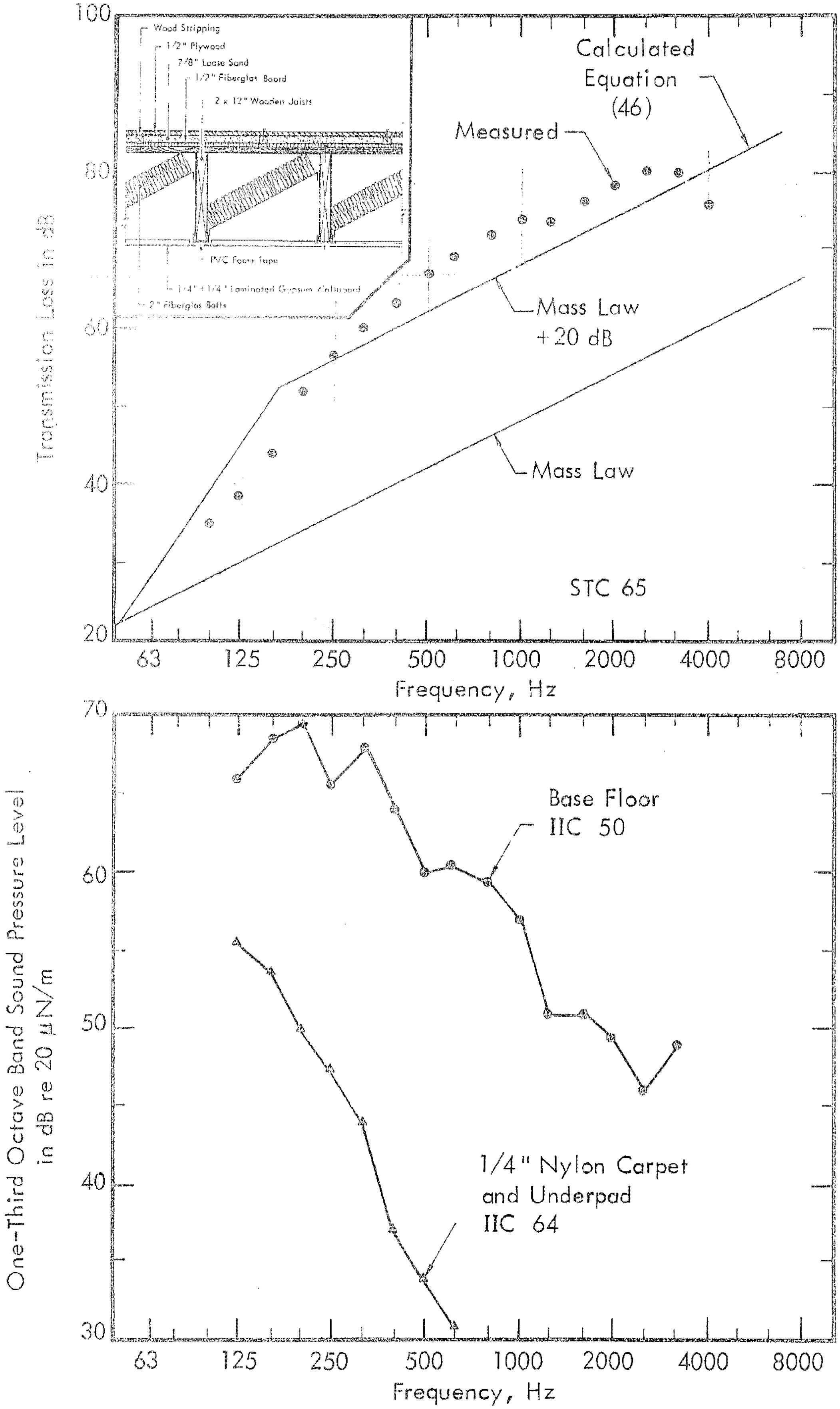


Figure 77. Transmission Loss and Impact Noise Level Values for Prototype 8

PROTOTYPE 9 – DOOR

CONSTRUCTION DETAILS:

Lamination of 1/4" tempered hardboard (m_1), 1/2" gypsum wallboard (m_2) and 1" cemented wood shavings (m_3) (Tectum) in a wooden perimeter frame, with 1/8" tempered hardboard (m_4) mounted on 1/4" x 1" x 1" squares of PVC foam tape. Compressed neoprene gaskets installed on the door frame.

ESTIMATED COST: (Unknown)

PARAMETER VALUES:

M	$= 6 \text{ lbs/ft}^2$		
m_1	$= 1.4 \text{ lbs/ft}^2$	m_2	$= 2 \text{ lbs/ft}^2$
m_3	$= 1.5 \text{ lbs/ft}^2$	m_4	$= 0.7 \text{ lbs/ft}^2$

STC RATING: 46

COMMENTS:

This construction provides an STC rating greater than that of the experimental Prototype M which implies that either that the seals were more efficient or that the construction method was superior. The rating of 46 is good for a single door, and could be effectively increased by the addition of a foyer. As such the door would be well suited for external application.

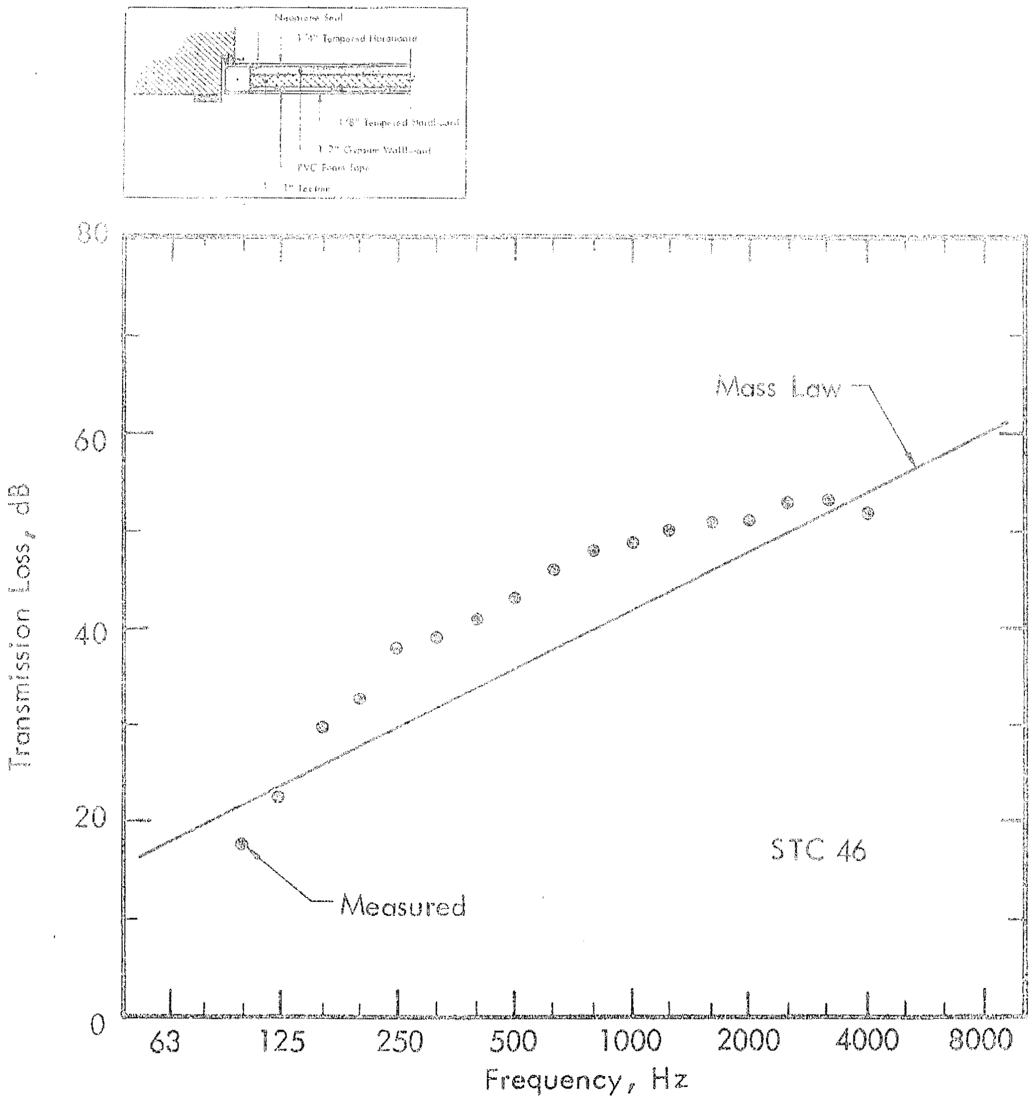


Figure 78. Transmission Loss Values for Prototype 9

c. Summary of Practical Prototype Results

Measured and predicted results of transmission loss for the practical prototypes are presented in Table 6 in terms of the STC rating and the transmission loss in the speech interference range of frequencies. The first point to be noticed is the generally good agreement between the measured and predicted values. Prototype 3, a triple panel construction, as designed successfully meets the 20 dB requirement at all frequencies in the range 200 Hz to 4000 Hz, with an overall thickness of only 8 inches. The other wall designed to meet the 20 dB requirement, Prototype 7, failed to do so because of the effect of coincidence in the concrete panel. From this and previous results on double panel structures, it appears that the 20 dB requirement cannot be satisfied if one of the panels is of concrete, even though the overall transmission loss is more than 20 dB in excess of the transmission loss of the concrete panel.

More interesting, however, are Prototypes 2 and 4. Prototype 2 is a load-bearing party wall of extremely simple design with an STC rating of 54 and a mass of only 7 lbs/ft^2. Prototype 4 could be either a party or exterior wall, providing an STC rating of 64 with an overall thickness of only 5 inches. In both cases the costs are low.

TABLE 6

SUMMARY OF MEASURED AND PREDICTED VALUES OF TRANSMISSION LOSS FOR THE PRACTICAL PROTOTYPES

Prototype	Mass (lbs/ft^2)	Overall Thickness (Inches)	Estimated Cost \$/ft^2	STC		SIL – TL*	
				Estimated	Measured	Estimated	Measured
1. Interior Wall	4.2	4 - 7/8	1.00	45	45	50	50
2. Party Wall	7.0	7 - 1/8	1.21	55	54	54	56
3. Party Wall	27	8	2.18	70	72	75	77
4. Exterior Wall	25	5	1.34	66	64	70	67
5. Exterior Wall	26	8 - 3/4.	1.59	67	63	67	66
6. Window in Exterior Wall #5	5.7	8 - 7/16	-	-	61	-	63
7. External Wall	15	13 - 1/2	2.25	64	61	66	63
8. Floor/Ceiling	17	14 - 1/2	2.17	66	63	68	73
9. Door	7	3	-	43	46	-	48

*Transmission loss of construction in the frequency range most important for speech interference, i.e., the octave bands centered on 500, 1000 and 2000 Hz.

Prototype 1 is an excellent interior wall configuration with a mass of only 4.2 lbs/ft^2 and an STC rating of 45, which is similar to that for a common staggered stud wall with 5/8-inch gypsumboard – see Prototype H.

The wall and window combination of Prototype 6 provides an STC rating of 61 which is only 2 points less than that of the wall alone. Note that the effect of placing the two glass panels in the two partially isolated walls results in optimum performance of the window unit without the need for resilient gaskets. The door of Prototype 9 gave an STC rating of 46 with the addition of good quality vinyl bulb seals.

Finally, the floor/ceiling configuration, Prototype 8, with standard wooden joists and a floor loaded with sand, provides an Impact Insulation Class (IIC) of 50 with no covering. The addition of an indoor/outdoor type carpet with an integral rubber under-pad improves the IIC rating to a value of 64, emphasizing once again the value of including the carpet as part of the structure.

To see how these practical prototypes compare with existing constructions (see Table 7), the estimated costs have been plotted against the STC rating in Figure 79 for both types. The method for estimating the costs was the same for both types of constructions. The general trend is clear; the cost/effectiveness of the prototypes is superior to that of existing constructions and improves relatively as the STC increases. In particular, it appears that STC ratings in the range 60-70 can be obtained at a significant reduction in cost from those structures in common use today.

An alternative method of comparing the prototype constructions with existing types is to plot the STC rating against the total mass of the construction – see Figure 80. Again, the data for existing constructions has been taken from the HUD Noise Control Guide (Reference 14). Three deductions can be made from Figure 80, namely:

- It is possible with the new methods to obtain STC ratings suitable for internal walls – see Prototype 1 – with a significant reduction in mass from that of existing constructions.
- High values of the STC rating – STC 60-70 – can be obtained without excessive surface mass and with reasonable overall wall thickness.
- The STC rating of the practical constructions increases at a rate approximately equal to 6 points for a doubling of the mass. The rating thus follows the slope of the mass law, but is 10 to 12 points greater than the STC rating according to the mass of a structure.

TABLE 7

DESCRIPTION OF STANDARD CONSTRUCTIONS
INCLUDED IN FIGURE 79

No.	Description	Mass* (lbs/ft²)	STC**	$/ft²
a	9" thick brick wall with 1/2" plaster both sides.	100	52	2.52
b	Double wall of 4-1/2" brick leaves separated by 2" air cavity – no ties. 1/2" plaster on exposed surfaces.	100	54	2.72
c	Hollow cinder blocks 4" x 8" x 16" with 5/8" sanded gypsum plaster both sides.	36	46	1.33
d	6" thick concrete wall with 1/2" plaster both sides.	80	53	1.97
e	5/8" gypsumboard and 1/2" sound-deadening board on both sides of 2" x 4" wood studs, 16 inches on center, two separate 2" x 4" wood plates, floor and ceiling, spaced 2" apart.	10	50	1.62
f	5/8" gypsumboard on both sides of staggered 2" x 4" wood studs, 16 inches on center. One layer 2-1/2" foil-backed fiber glass in cavity.	6.2	43	1.25
g	5/8" gypsumboard on both sides of common 2" x 4" wood studs, 16 inches on center.	7.2	35	0.87
h	1/2" wood fiberboard and 1/2" sanded gypsum plaster on both sides of common 2" x 4" wood studs, 16 inches on center.	12.6	42	1.48
i	3/8" gypsum lath and 1/2" sanded plaster on both sides of 2" x 4" wood studs, 16 inches on center.	15	46	1.12
j	Double wall with 4-1/2" thick brick leaves, 6" cavity (no ties) with 1/2" plaster on 1" wood wool slabs mortared to each wall.	120	62	2.80
k	Double wall, 3-5/8" metal channel studs 24" o.c. with two layers of 5/8" gypsum wallboard laminated. 1-1/2" mineral fiber felt in cavity.	11.5	55	1.80

*Inclusive of studs.

**Laboratory data from Reference 4 with the exception of construction f which is a Wyle measurement.

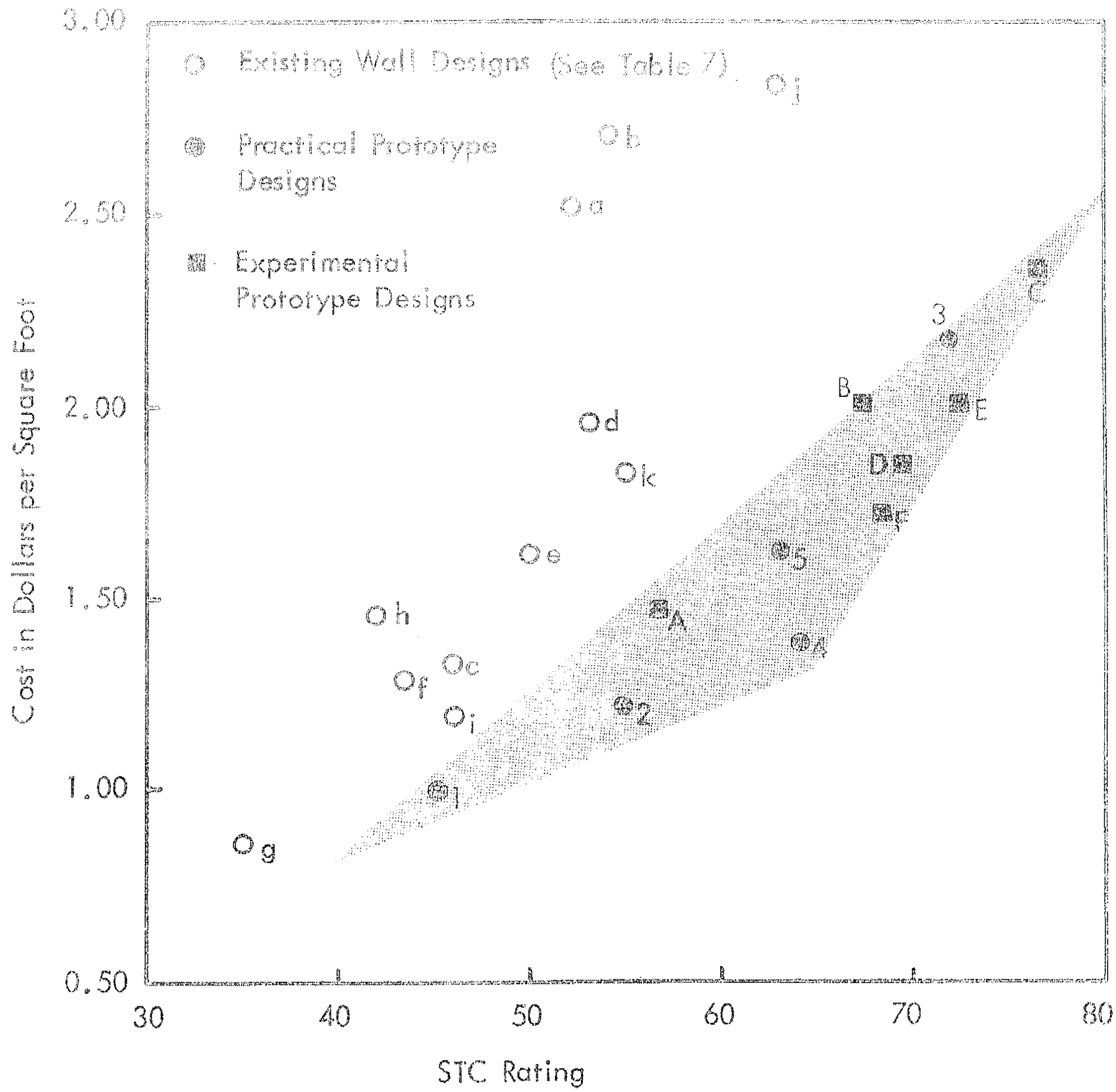


Figure 79. Cost versus STC Rating for Existing and New Wall Designs

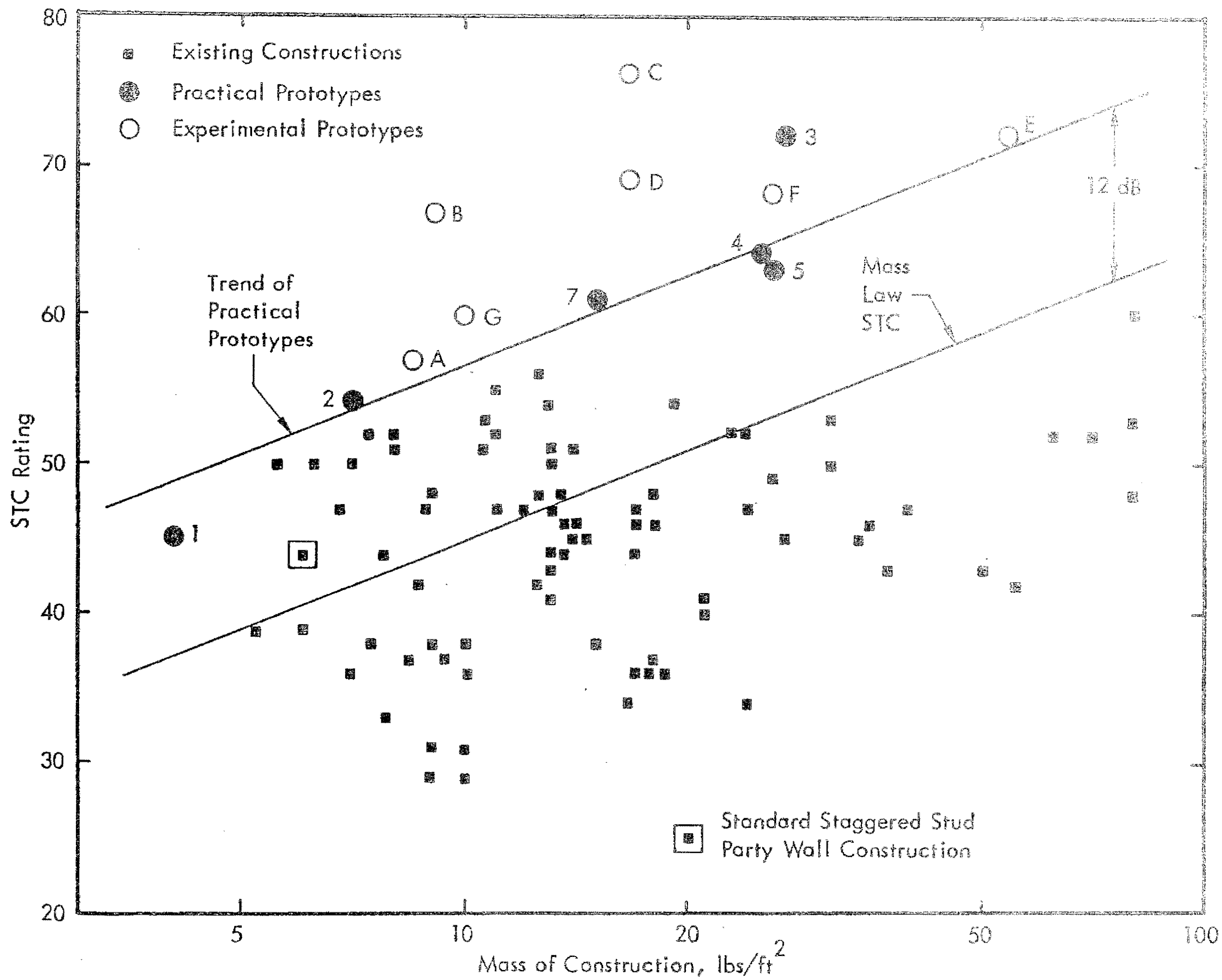


Figure 80. The STC Rating as a Function of the Mass for Existing and Prototype Wall Constructions

4.0 EXTERNAL STRUCTURES

Increasing the transmission loss of the exterior walls is only one method of reducing noise levels in residences. A barrier around a building or at specific locations around a building can also reduce internal noise levels; of greater importance, however, it may also reduce the levels in the immediate outdoor areas around the building, thus improving the local outdoor noise environment. The results of a recent study (Reference 17) on the feasibility of soundproofing homes near airports, gave an indication that if the local external noise levels exceed a certain value – approximately 80 dB (SIL) in this case – no amount of acoustical treatment to the building could make it satisfactory for living because the external levels are too high. The possibility of using external barriers thus required further investigation.

4.1 SHIELDING BY BARRIERS

A review of the published literature shows that the insertion loss of barriers – the difference in dB between noise levels before and after the introduction of the barrier – has been treated both experimentally and theoretically (References 18, 19, and 20). Figure 81 (Reference 18) shows experimental data taken on a semi-infinite screen in free space.

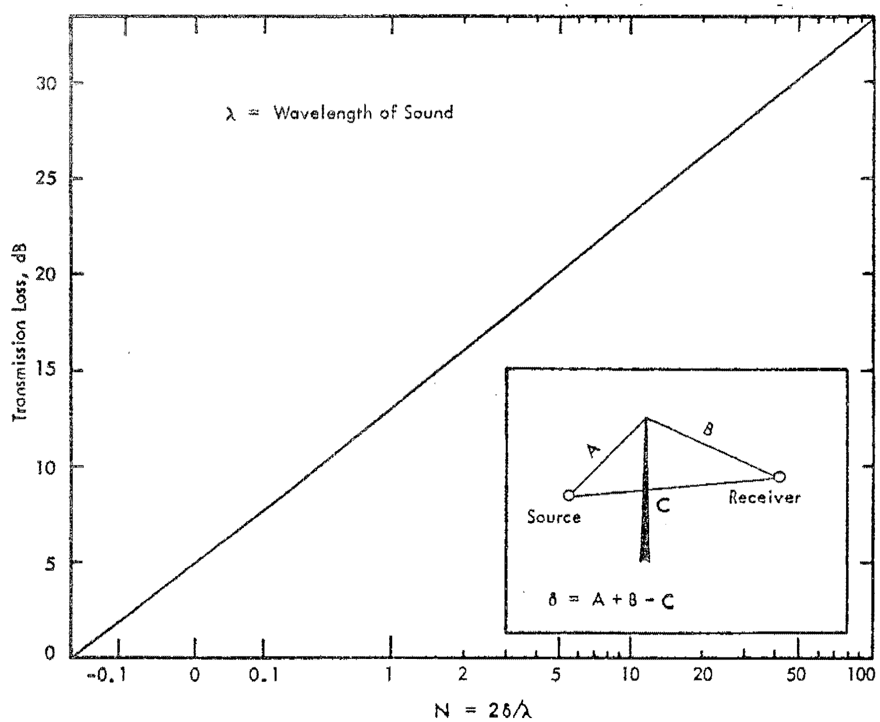


Figure 81. Experimental Curve of Insertion Loss by a Semi-Infinite Screen in Free Space as a Function of the Parameter N (Reference 18)

The horizontal scale is logarithmic in the region of the nondimensional distance parameter $N > 1$, but is altered to allow a straight line to pass through zero to negative numbers of N. The condition for $N = 0$ exists when the source, receiver and top of the barrier lie on a straight line. The theoretical values of insertion loss given in Figure 81 are for the condition where the source and receiver are situated in free space. It is to be expected that the values will differ somewhat if reflections from the ground plane are taken into account. The curve of insertion loss with frequency then exhibits maxima and minima due to the effects of interference between the direct and reflected paths. In addition, if a barrier is situated close to the wall of a building, reflections from this wall will reduce the effective insertion loss of the barrier.

A measurement program was conducted to evaluate the acoustic performance of barriers located close to large reflecting surfaces. The measurements were taken using a 1:6 scale model of a barrier with a rigid reflecting ground plane. In some cases, the vertical barrier was modified to include a 45 or 90-degree overhang. The effect of back reflections from a second barrier (i.e., house wall) was also studied. An electrostatic speaker was used with a reverse horn flaring down to a 1-inch opening to approximate a point source of sound. The measurements were taken using one-third octave bands of random noise centered on the frequencies given in Table 8.

TABLE 8

OCTAVE BAND CENTER FREQUENCIES –
FULL AND MODEL SCALE

Model Scale One-Third Octave Band Center Frequency (Hz)	Approximate Full Scale One-Third Octave Band Center Frequency (Hz)
2,500	400
4,000	630
6,300	1,000
10,000	1,600
16,000	2,500
25,000	4,000

The height of the receiving microphone above the ground corresponded to 3.5 feet in the full scale dimensions. This value remained constant throughout the series of measurements. Figure 82 is a diagram of a typical measurement configuration showing the locations of the barrier (with overhang) and the rear reflecting surface.

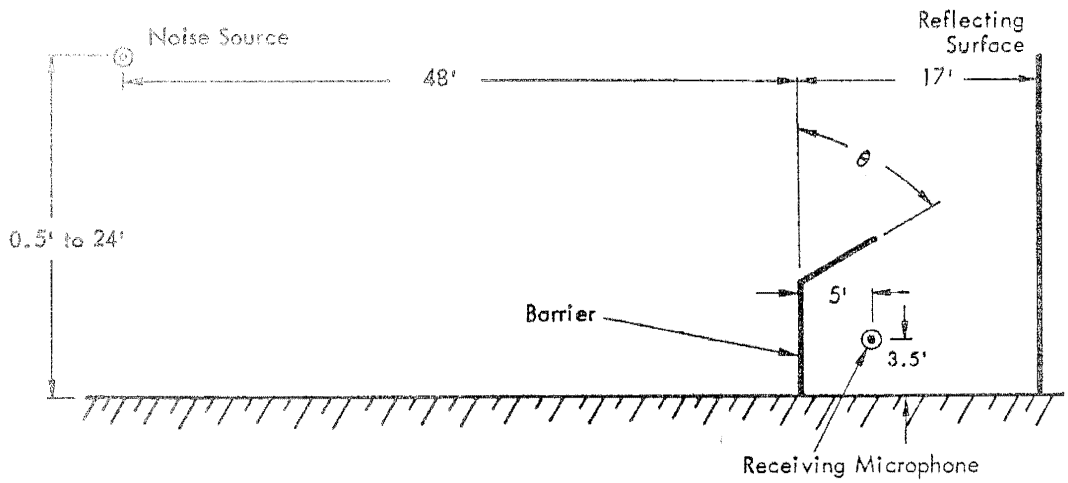


Figure 82. Configuration for Barrier Measurements – Full Scale Dimensions

Table 9 shows the full scale dimensions of the configurations that were tested. The receiving microphone was used to survey the area between the barrier and the reflecting surface to determine the variation in noise level. For a given configuration, typical variations at various receiver locations were in the order of ±2 dB. This amount of variation was observed for conditions with and without the rear reflector. A standard receiver location was then chosen 5 feet in full scale to the rear of the barrier.

The results of the measurements are shown in Figures 83 through 89. In each case, the data is presented to show the insertion loss provided by the barrier with and without the rear reflecting surfaces.

TABLE 9

EQUIVALENT FULL SCALE DIMENSIONS OF
SOURCE-RECEIVER-BARRIER CONFIGURATIONS TESTED

Configuration Number	Height in Feet				Overhang	
	Source	Receiver	Front Barrier	Rear Barrier	Angle θ	Length Feet
1	.5	3.5	6	-	-	-
2	.5	3.5	6	24	-	-
3	8	3.5	6	-	-	-
4	8	3.5	6	24	-	-
5	8	3.5	8	-	-	-
6	8	3.5	8	8	-	-
7	8	3.5	-	8	-	-
8	.5	3.5	8	-	45°	6
9	.5	3.5	8	24	45°	6
10	8	3.5	8	-	45°	6
11	8	3.5	8	8	45°	6
12	8	3.5	8	24	45°	6
13	24	3.5	8	-	45°	6
14	24	3.5	8	24	45°	6
15	8	3.5	8	-	90°	6
16	8	3.5	8	8	90°	6
17	8	3.5	8	24	90°	6

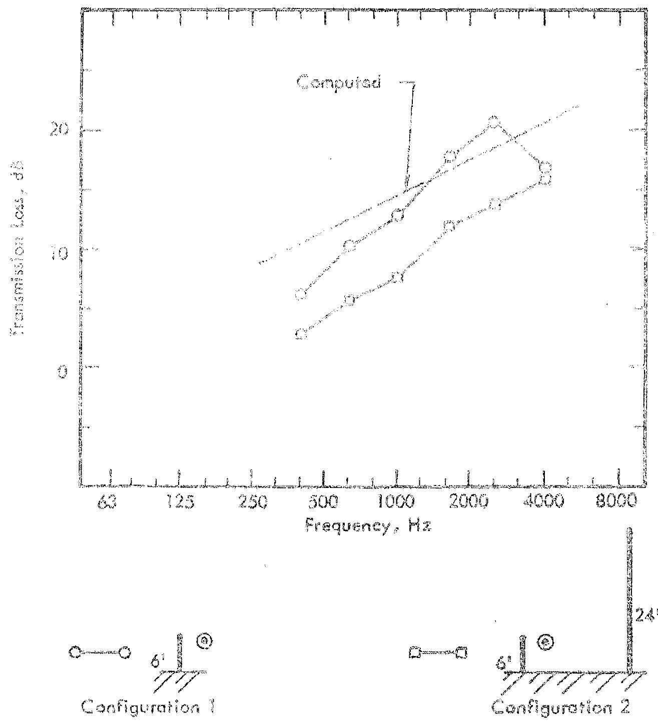
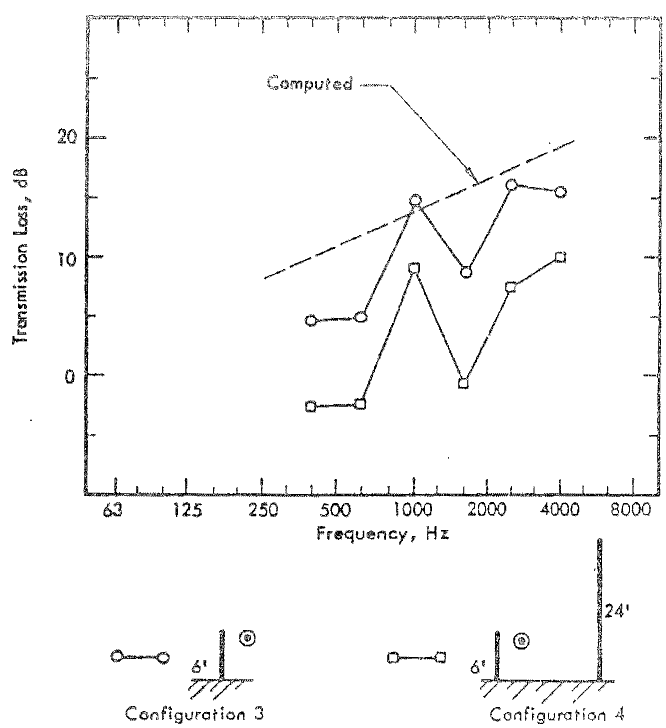


Figure 83.

Sound Attenuation by Barrier Configurations 1 and 2. Source Height = 0.5 feet

Figure 84.

Attenuation by Barrier Configurations 3 and 4. Source Height = 8 feet



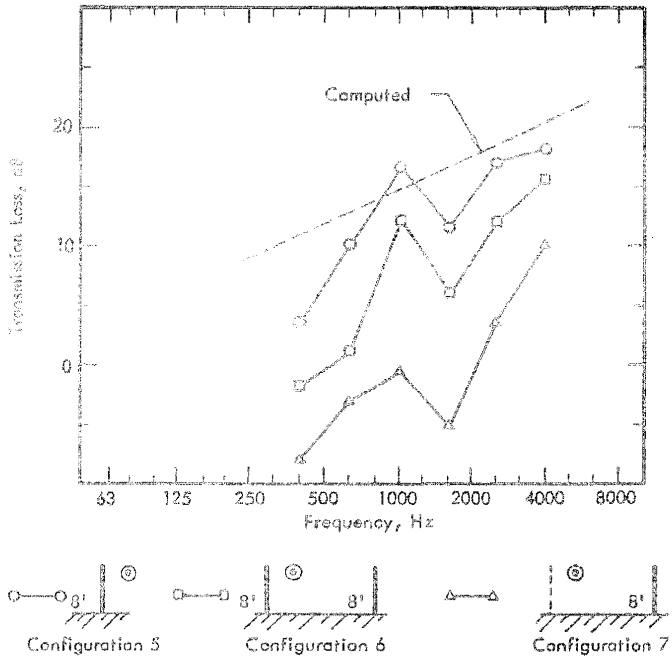
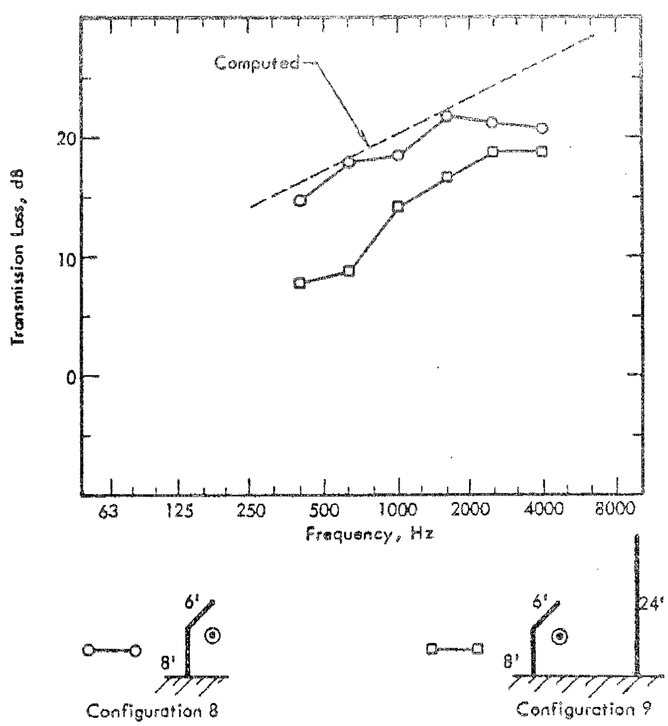


Figure 85.

Sound Attenuation by Configurations 5, 6 and 7. Source Height = 8 feet

Figure 86.

Sound Attenuation by Configurations 8 and 9. Source Height = 0.5 feet



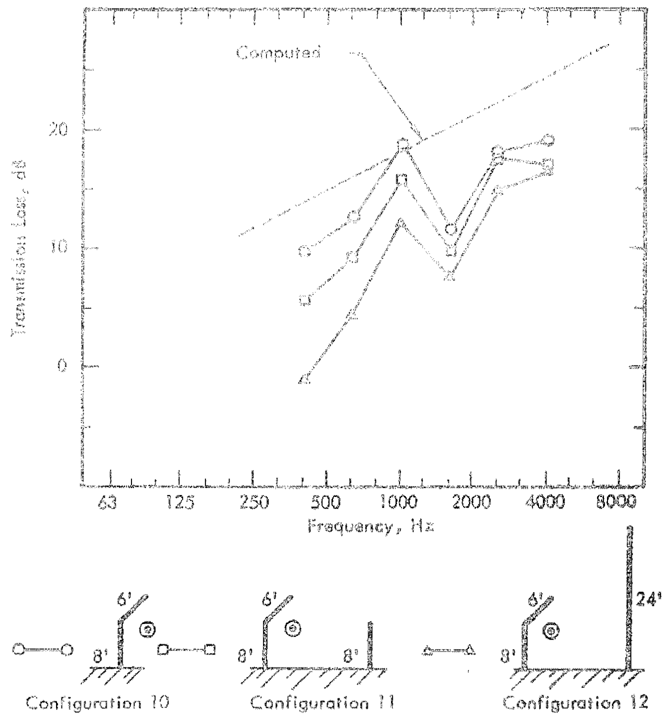


Figure 87.

Sound Attenuation by Configurations 10, 11 and 12. Source Height = 8 feet

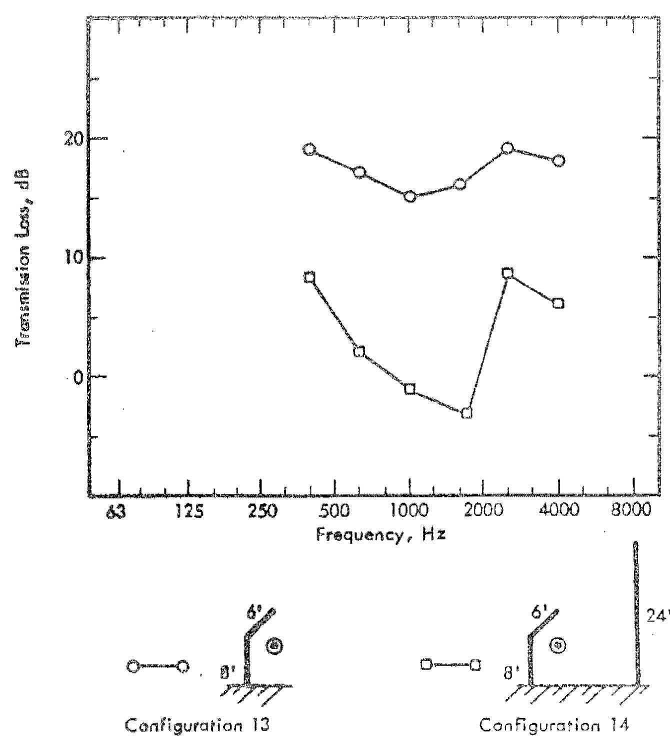


Figure 88.

Sound Attenuation by Configurations 13 and 14. Source Height = 24 feet

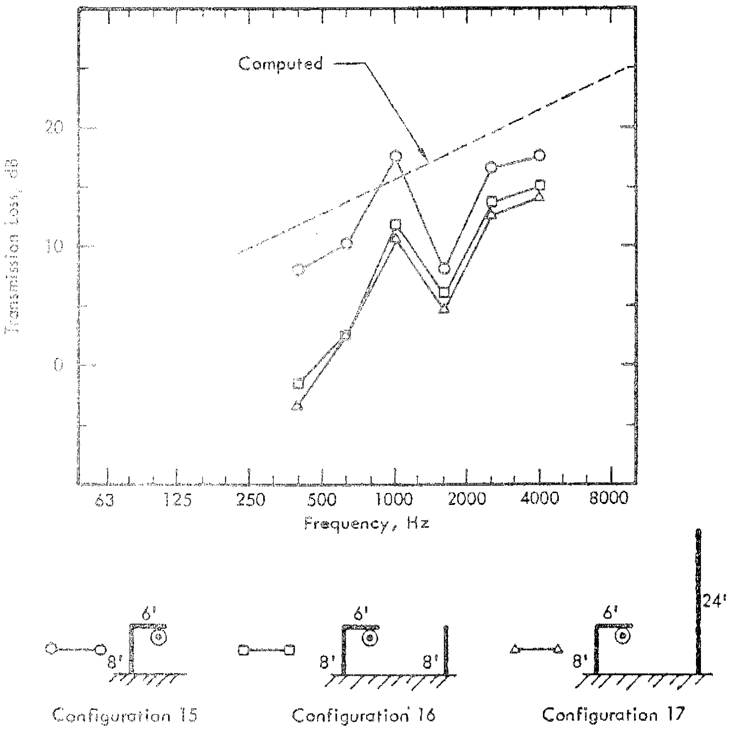


Figure 89.

Sound Attenuation by Configurations 15, 16 and 17. Source Height = 8 feet

The following conclusions can be drawn from the results:

- The calculated values of insertion loss for the barrier are similar to the measured values for each configuration except at frequencies affected by interference between the direct and reflected paths. These discrepancies are caused by the presence of the ground plane which is not considered in the simple theory. The ground plane introduces maxima and minima in the insertion loss at frequencies where the reflections are out-of-phase and in-phase, respectively. The magnitude of the effect increases as the height of the source above the ground increases.

- The presence of the rear reflector reduces the insertion loss provided by the barrier alone by 2 to 8 dB.

- The insertion loss decreases as the height of the rear reflecting surfaces increases. There will, of course, be a limiting height above which no further reduction is obtained. In the case of single story dwellings, the maximum height of the reflecting wall is approximately 10 feet, so the data for 8-foot reflecting surfaces is applicable. For high-rise buildings with balconies, the insertion loss is small unless the length of the balcony is considerably greater than its height. At low frequencies, the effect of a rear reflector was negative in some cases so that the noise level increased rather than decreased as a result of introducing the barrier.

- The insertion loss for all configurations decreases markedly as the height of source above the ground increases. As a result, a barrier affords little protection from the noise of passing aircraft.

- With the source 8 feet above the ground and 4 feet (full scale) from the barrier, computed and measured values of the insertion loss for configurations #10 and #15 (see Table 9) are both very similar to the computed values for a barrier of height 14 feet. Thus, there appears to be little justification for the use of an inclined barrier or overhang such as illustrated in Figure 87.

In summary, a barrier located near a building can provide a significant reduction in external noise levels, provided that the source is close to the ground. In all cases, the reduction will be less than that obtained without the rear reflecting surface. However, the effect of reflections from this surface can be reduced by the application of an outdoor absorption material such as cemented wood shavings. Thus, it is possible to improve the outdoor noise environment and in so doing perhaps increase the satisfaction that can be obtained by improved noise reduction provided by the building structure.

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5.0 CONCLUSIONS AND RECOMMENDATIONS

The principles and techniques that pertain to the design of building elements providing high values of transmission loss have been presented. Not all the techniques are new; some are developments of existing methods, and some have been used quite extensively in the past. These techniques have been validated by means of a series of laboratory tests conducted on experimental and practical prototype constructions. The cost/effectiveness of the practical constructions has been compared to that for existing constructions in common use today.

The principle conclusions from this study are as follows:

- The transmission loss characteristics of single panels and multiple panels with sound bridges can be determined accurately by means of a set of simple expressions — see Section 2.4.

- The design expressions given in Section 2.4 can be applied directly to the optimum design of building elements providing high values of transmission loss.

- With careful design, the 20 dB requirement can be achieved in a practical multiple panel construction; however this is at the expense of high mass or great thickness. Consequently, constructions meeting the requirement are limited in use to high noise level areas.

- From the standpoint of transmission loss performance, cost and total mass, the practical prototype constructions developed in this program are superior to constructions that are in common use today.

Perhaps one of the major outputs of this program however is a fuller understanding of the process of sound transmission through structures. It is always possible to refine this knowledge, but, since the real world of building design requires advances in technology which can provide adequate and improved sound insulation between dwellings at a reasonable cost, at this time it is probably more important to assess the performance of the improved constructions under field conditions.

As a result, it is recommended that some of the constructions described in this report should be incorporated in a building demonstration program so that their acoustical characteristics can be compared to those of existing constructions. At the same time, the structural and fire resistance properties of the new constructions should be examined, and modifications made if necessary.

Some of the constructions described and tested in this program make use of materials or material combinations that are not commercially available at the present time. Particular cases in point include mass-loaded and laminated panels. The methods of utilizing these two techniques in the constructions tested are considered to be realistic and cost/effective, but because they have not been tried out in field installations, it is premature to state that these are the best methods. The physical properties required of the component materials have been examined in the main body of the report and can be considered as performance requirements for future designs. It remains for industry to develop new materials and material configurations so that the performance requirements can be met at low cost.

Finally, the simple expressions that have been developed to describe the transmission loss characteristics of building structures are extremely amenable for inclusion in a computer program that could be used to design constructions to specific performance requirements. For example, the input of parameters such as maximum allowable mass, overall thickness, required STC rating or preferred materials could be sufficient for such a program to define alternative structures. Alternatively, the reverse procedure could also be adopted, and the STC rating or required mass determined given certain material constraints. A versatile computer program such as this might prove invaluable to HUD as an aid to designers and builders in the design of all types of constructions, from high-rise apartments down to single family residences. Moreover, it need not necessarily be a complex program requiring sophisticated computer facilities.

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APPENDIX A

DETERMINATION OF THE TRANSMISSION IMPEDANCE OF A SINGLE PANEL

Consider an infinite panel situated in the plane $z = 0$ with the coordinates of any point designated by (x, y). The equation for bending waves on the panel, including the effects of shear and rotary inertia, can be written as follows (Reference A 1):

$$\left(\nabla^2 - \frac{\rho_m}{\mu}\frac{\partial^2}{\partial t^2}\right)\left(B\nabla^2 - \frac{\rho_m h^3}{12}\frac{\partial^2}{\partial t^2}\right)\xi(x,y) + \rho_m h \frac{\partial^2}{\partial t^2}\xi(x,y) = \left(1 - \frac{B}{\mu h}\nabla^2 + \frac{\rho_m h^2}{12\mu}\frac{\partial^2}{\partial t^2}\right)\Delta p(x,y,0) \tag{A1}$$

where

∇^2 = the Laplacian operator $\dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2}$

ρ_m = density of panel material

h = panel thickness

μ = shear modulus of panel material

B = bending stiffness of panel

Δp = sound pressure differential across the panel

ξ = panel displacement

It will be assumed that the panel is subject to excitation by an incident sinusoidal plane acoustic wave of the form:

$$p(x,y,z) = p_o\, F(x,y,z) \quad \exp(j\omega t) \tag{A2}$$

where

$$F(x,y,z) = \exp\left[-jkx \sin\theta \cos\phi - jky \sin\theta \sin\phi - jkz \cos\theta\right]$$

k = wave number = ω/c

c = velocity of sound in air

θ, ϕ = angles of elevation and azimuth respectively

As a result of this driving force, the velocity of the panel will be of the form:

$$u(x,y) = u_o \quad F(x,y,0) \qquad \exp(j\omega t) \tag{A3}$$

Similarly, the acoustic pressure differential existing between the surfaces of the panel will be of the form:

$$\Delta p(x,y,0) = \Delta p_o \quad F(x,y,0) \qquad \exp(j\omega t) \tag{A4}$$

and the panel velocity can be written as:

$$u(x,y) = j\omega\,\xi(x,y) \tag{A5}$$

Inserting Equations (A3), (A4) and (A5) into (A1) and performing the operations with the operator ∇^2 results in the expression:

$$\left\{ B k^4 \sin^4\theta - \left(\frac{\rho_m h^3}{12} + \frac{B\rho_m}{\mu}\right) \omega^2 k^2 \sin^2\theta + \frac{\rho_m^2 h^3}{12\mu}\,\omega^4 - \rho_m h\,\omega^2 \right\} u_o = j\omega \left\{ 1 + \frac{B k^2 \sin^2\theta}{\mu h} - \frac{\rho_m h^2 \omega^2}{12\,\mu} \right\} \Delta p_o \tag{A6}$$

The specific transmission impedance Z of the panel is defined (see Section 2.1) as the ratio of acoustic pressure differential between the faces to the normal panel velocity, i.e.:

$$Z = \frac{\Delta p_o}{u_o}$$

Rearranging the terms in Equation (A6) thus gives an expression for the impedance Z as:

$$Z = \frac{j\left\{\left[\rho_m h + \left(\frac{\rho_m h^3}{12} + \frac{B\rho_m}{\mu}\right)\frac{\omega^2}{c^2}\sin^2\theta\right]\omega - \left[\frac{B}{c^4}\sin^4\theta + \frac{\rho_m^2 h^3}{12\mu}\right]\omega^3\right\}}{\left\{1 + \frac{B\omega^2\sin^2\theta}{\mu c^2 h} - \frac{\rho_m h^2\omega^2}{12\mu}\right\}} \tag{A7}$$

where

$$B = \frac{Eh^3}{12(1-\sigma^2)}$$

$2(1+\nu)$

E = Young's Modulus for the panel material

σ = Poisson's Ratio

If the thickness h of the panel is much smaller than a wavelength, then:

$$\omega h << 1$$

and Equation (A7) can be approximated by the expression:

$$Z \approx j\left\{\omega\rho_m h - \frac{B\omega^3}{c^4}\sin^4\theta\right\} \tag{A8}$$

which is the familiar expression for the transmission impedance of a thin panel.

Returning to the more general expression of Equation (A7), the denominator is dominated by the first two terms except at very low values of θ where a minimum is exhibited. However, at low values of θ the second term is very small. Therefore, the denominator can be approximated by neglecting the third term. In the numerator, the second term in the right-hand bracket is much less in value than the first; again, except at low angles of incidence. However, low angles of incidence are of major importance only at frequencies below coincidence; at these frequencies, the right-hand bracket can be ignored in comparison to the mass term in the left-hand bracket. As a result, it is possible to neglect the second term in the right-hand bracket. With these approximations, it is possible to express Equation (A7) to a good approximation for the general case as:

$$Z \approx j\omega\rho_m h - j\left\{\frac{\dfrac{B\omega^3 \sin^4\theta}{c^4}}{1 + \dfrac{B\omega^2\sin^2\theta}{\mu c^2 h}}\right\} \tag{A9}$$

$$\approx j\omega\rho_m h + \frac{Z_B Z_S}{Z_B + Z_S} \tag{A10}$$

where $Z_B = -j\dfrac{B\omega^3\sin^4\theta}{c^4}$ is the bending wave impedance

and $Z_S = -j\dfrac{\mu h\omega\sin^2\theta}{c^2}$ can be shown to be the shear wave impedance.

Although this result is approximate, it is useful since it provides a qualitative insight into the mechanism of sound transmission through thick panels. As presented in Equation (A9), the impedance consists of a mass term in series with the parallel combination of bending and shearing wave impedances. The ratio of the bending to shearing wave impedances is maximum for grazing incidence and is given as:

$$\frac{Z_B}{Z_S} = \frac{\omega^2 h^2}{6c^2(1-\sigma)}$$

$$= \frac{6.6}{1-\sigma}\left(\frac{h}{\lambda}\right)^2 \qquad \text{(A11)}$$

Thus, for panels in the frequency range where the thickness is much smaller than a wavelength, the bending impedance is smaller than the shearing impedance, Since the two are effectively in parallel to one another, the bending impedance predominates. This will occur for all panels at low frequencies and for thin panels at high frequencies. Under these conditions, the panel impedance will be as given in Equation (A8). Conversely, in the frequency range where the thickness is much greater than the wavelength, the shearing impedance will predominate.

Examination of Equations (A10) and (A11) shows that for the parallel combination of bending and shear impedances to be within 10 percent – approximately 1 dB in terms of the transmission loss at frequencies above coincidence – of the value of the bending impedance alone, the condition

$$\lambda_B > \left(\frac{7.7}{1-\sigma}\right) h \qquad \text{(A12)}$$

must be satisfied, where λ_B is the wavelength of bending waves on the panel. Thus, for concrete ($\sigma \approx 0.15$), shearing effects will become evident at frequencies where the bending wavelength becomes less than the quantity 9h. The condition given in Equation (A 12) can be restated in terms of a limiting frequency f_L, above which shearing waves predominate and below which bending waves predominate. This limiting frequency is given by the expression:

$$f_L = \frac{c^2(1-\sigma)^2}{59h^2 f_c}$$

This value for the limiting frequency agrees well with measured results for concrete panels – see Figure 6. At frequencies greater than f_L, the transmission impedance of the panel will be:

$$Z \approx j\omega\rho_m h - j\,\frac{\mu h \omega \sin^2\theta}{c^2}$$

$$= j\omega\rho_m h \left[1 - \left(\frac{c_s}{c}\right)^2 \sin^2\theta\right] \qquad \text{(A13)}$$

where $c_s = (\mu/\rho_m)^{1/2}$ is the velocity of shear waves on the panel. The expression given in Equation (A13) indicates that the panel impedance will be zero for a single angle of incidence θ_s given by:

$$\theta_s = \arcsin\left(\frac{c}{c_s}\right) \qquad \text{(A14)}$$

If $c_s < c$ then θ_s is imaginary and the impedance will be nonzero for all angles of incidence. Also, the condition $c_s < c$ implies that the change from bending to shearing waves occurs at a frequency less than the critical frequency; hence coincidence cannot occur. This is therefore the optimum condition. If $c_s > c$, not only will coincidence occur, but a zero will be evident at an angle θ_s given by Equation (A14), so that the transmission loss for thick panels at frequencies greater than the critical frequency does not increase with frequency as rapidly as that for a thin panel.

With the use of the expressions derived in this Appendix it is possible to extend the validity of the simple theory of transmission loss – as represented by Equation (A 8) – to higher frequencies where the panel thickness is comparable to the structureborne wavelength. There are however additional wave types – such as Rayleigh waves where the velocities of the two faces of the panel are not the same – not considered in the above treatment that may limit the validity of the expressions when the panel thickness greatly exceeds the wavelength (Reference A 2).

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APPENDIX B

THE TRANSMISSION LOSS OF A FINITE SINGLE PANEL SUBJECT TO REVERBERANT SOUND FIELD EXCITATION

The normal method of deriving an expression for the transmission coefficient τ_θ of a single panel is to consider a plane wave incident to the panel at a given angle, whereupon using the concept of impedance, the expression given in Equation (1) can be obtained. To determine the transmission coefficient for excitation by a rever-verant sound field, it is assumed that all angles of incidence are equally probable and that the average value of the coefficient is given by integrating τ_θ multiplied by an appropriate weighting factor over all angles in the range 0 to $\pi/2$. When the transmission loss is obtained by inserting the result of the integration into Equation (2), it is found that the result is usually about 3 dB lower than the measured values. The agreement between the calculated and measured results can be improved by arbitrarily limiting the integration range from 0 to θ_ℓ ($\theta_\ell < \pi/2$) where θ_ℓ is chosen simply so that the agreement is good. It is found that different laboratories require different values of θ_ℓ for the calculated results to agree with those measured in the laboratory. The values of θ_ℓ used by various workers ranges from 78° up to 85°. The explanation that is usually given to justify this empirical correction is that the sound field in a reverberation chamber is not totally diffuse and that little sound energy is incident to the panel at grazing angles of incidence. However, there appears to be no experimental justification for this assumption.

The problem of the angle of incidence occurs again when considering the transmission loss of a double panel. At low frequencies in a double panel, the masses of the two panels combine with the stiffness of the air trapped in the cavity to produce a resonance. For a plane sound wave incident at an angle θ, the frequency f_θ at which this resonance occurs is given by the expression:

$$f_\theta = \frac{c^2}{2\pi \cos \theta} \sqrt{\frac{\rho c^2}{md}} \qquad \text{(B1)}$$

where m is the mass of the panels – assumed equal – and d is the panel spacing. It is important to note that the value of the resonant frequency is dependent on the angle of incidence of the sound waves. This means that there is a different resonant frequency for every angle of incidence. Since the transmission loss of a double panel is low at the frequency of this resonance, it would be expected that low values would be obtained at all frequencies; in fact, this is the result obtained if the integration is carred out. This is not born out by measured results. Even when there is little or no absorption in the cavity, the transmission loss does not fall below values given by the mass law.

It would therefore appear that there are some inconsistencies in the simple theory of sound transmission loss which can be eliminated only in the case of single panels by the application of an empirical correction factor. The simple theory does, of course, assume that the panels are of infinite lateral dimensions. At low frequencies, the majority of panels tested in transmission loss facilities are not very large compared to the bending wavelength; therefore they cannot be considered as infinite. In this case the resonant frequencies or modes of the panel and the coupling of the incidence sound waves to these modes must be taken into consideration.

The transmission of sound through a finite single panel has been treated in the published literature (References B1, B2). In Reference B1, a classical approach is adopted by considering a plane wave incident to a panel in a baffle; the solution is obtained in matrix form. In Reference B2, the panel is taken to be the common wall between two reverberation chambers. The solution is determined by evaluating the coupling between the sound fields in both rooms and the panel. An approximation in this solution is that the sound pressure on the incident side of the panel is much greater than that on the receiving side. Presumably the solution is valid only for panels of high transmission loss, although how high has yet to be determined. At frequencies below the critical frequency, both methods give similar results. In this frequency range, the major portion of sound energy is transmitted by forced vibration of the panel rather than by resonance vibration. It also turns out that the major transmission is from sound energy that is incident at small angles to the normal of the panel. The expression for the transmission loss given in Reference B2 is

$$TL(\omega) = 20 \log \left(\frac{\omega m}{2\rho c}\right) - 10 \log \left[\frac{3}{4} + \frac{1}{2} \ln \left(\frac{2f}{\Delta f}\right)\right] \qquad (B2)$$

where Δf is the bandwidth of the noise signal used for testing. If one-third octave bands of noise are utilized, then Equation (B2) becomes:

$$TL(\omega) = 20 \log \left(\frac{\omega m}{3.6\rho c}\right) \qquad f < f_c \qquad (B3)$$

Thus the "effective" mass of a single panel for providing sound transmission loss at frequencies below the critical frequency is a factor of 1.8 less than the actual mass.

At frequencies greater than the critical frequency, the transmission loss is quite dependent on the internal losses in the panel. In this frequency range, the transmission loss is given by the expression — see Reference B2:

$$TL(\omega) = 20 \log \left(\frac{\omega m}{2\rho c}\right) + 10 \log \left(\frac{2\eta}{\pi} \frac{\omega}{\omega_c}\right) \qquad f > f_c \qquad \text{(B4)}$$

where η is the loss factor for the panel material. This expression is identical to that derived by Cremer (Reference B3).

The expressions given in Equations (B3) and (B4) give values of transmission loss that agree well with the measured values — see Figure 3. Equation (B3) is valid only at frequencies less than approximately one-half the critical frequency ($1/2\ f_c$). At frequencies between $1/2\ f_c$ and f_c resonance transmission assumes a greater importance in determining the transmission loss and analytical expressions do not seem to give good agreement with the measured results. Until more accurate expressions are available, an approximate method that can be used to predict the transmission loss in this frequency range is to describe a straight line between the value of transmission loss at the frequency $1/2\ f_c$ (Equation B3) and the value at the frequency f_c (Equation B4). It should be noted that this is only approximate.

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APPENDIX C

THE TRANSMISSION LOSS OF A DOUBLE PANEL

Starting with the familiar expression for the transmission coefficient of an infinite double panel, this Appendix contains a derivation of the transmission loss of a finite double panel when excited by a reverberant sound field. In this derivation, use is made of the results for single panels discussed in Section 2.1.3.

The transmission coefficient τ_θ for a sound wave incident at an angle θ to the normal of an infinite double panel is given by the expression (Reference C1).

$$\tau_\theta = \left| 1 + \left(X_1 + X_2\right) + X_1 X_2 \left(1 - e^{-j\sigma}\right) \right|^{-2} \tag{C1}$$

where

$$X_{1,2} = \frac{Z_{1,2} \cos\theta}{2\rho c}$$

$Z_{1,2}$ = transmission impedances of panels 1 and 2

$\sigma = 2kd\cos\theta$

$k = 2\pi f/c$

d = panel separation

At low frequencies, where the wavelength of sound is much greater than the panel separation d, Equation (C1) can be written as:

$$\tau_\theta \approx \left| 1 + \left(X_1 + X_2\right) \right|^{-2} \tag{C2}$$

At frequencies below the critical frequency, the impedance of the panels is given by:

$$Z_{1,2} = j\omega m_{1,2} \tag{C3}$$

where m_1 and m_2 are the masses of the two panels. In this frequency range, Equation (C2) can be written as:

$$\tau_\theta = \left| 1 + \frac{j\omega(m_1 + m_2)}{2\rho c} \cos\theta \right|^{-2} \tag{C4}$$

The expression given in Equation (C4) is exactly similar to that of Equation (3). The double panel acts as a single panel of mass $(m_1 + m_2)$. In Section 2.1.3 and Appendix B, it is shown that the transmission loss of a finite single panel excited by a reverberant sound field is given by the expression of Equation (6). In the same way, the transmission loss of a finite double panel at very low frequencies is given by the expression:

$$TL \approx 10 \log \left[1 + \left(\frac{\omega M}{3.6\, \rho c} \right)^2 \right] \tag{C5}$$

where $M = m_1 + m_2$

At higher frequencies, but still under the condition that the wavelength is less than the panel separation d, the exponential term in Equation (C1) can be expressed as:

$$e^{-j\sigma} \approx 1 - j\sigma$$

In this frequency range, the third term of Equation (C1) rapidly assumes major importance and the transmission coefficient is given as:

$$\tau_\theta \approx \left[\left(\frac{\omega m_1 \cos\theta}{2\rho c} \right) \left(\frac{\omega m_2 \cos\theta}{2\rho c} \right) 2kd \cos\theta \right]^{-2} \tag{C6}$$

and

$$TL_\theta \approx 20 \log \left(\frac{\omega m_1 \cos\theta}{2\rho c} \right) + 20 \log \left(\frac{\omega m_2 \cos\theta}{2\rho c} \right) + 20 \log (2kd \cos\theta) \tag{C7}$$

Equation (C7) indicates that the transmission loss of the double panel construction is equal to the sum of the transmission losses of the two component panels plus – or more usually minus – a contribution for the effect of the cavity. The contributions from the two panels to the total transmission loss are therefore effectively independent. Taking into account that for the transmission of sound at frequencies below the critical frequency, the most important angles θ are those approaching normal incidence, i.e., $\theta = 0$, the transmission loss in this frequency range is given by the expression:

$$TL \approx 20 \log\left(\frac{\omega m_1}{3.6\, \rho c}\right) + 20 \log\left(\frac{\omega m_2}{3.6\, \rho c}\right) + 20 \log (2kd) \qquad \text{(C8)}$$

or

$$TL = TL_1 + TL_2 + 20 \log (2kd) \qquad \text{(C9)}$$

where TL_1 and TL_2 are the transmission losses of the single panels 1 and 2.

At frequencies where the wavelength is equal to or smaller than the panel separation, Equation (C1) indicates the presence of an harmonic series of cavity resonances, the first of which occurs at a frequency f_1 given by:

$$f_1 = \frac{c}{2d}$$

The effect of these resonances can be greatly diminished by the addition of absorption material in the cavity. Thus, to a first approximation, the cavity resonances can be ignored and the transmission loss in this region determined by allowing the bracket containing the exponential term in Equation (C1) to assume its maximum value. In this manner, with the third term of Equation (C1) dominating the expression, the transmission coefficient for the double panel at frequencies where the wavelength is small compared with the panel spacing is given by the expression:

$$\tau_\theta \approx \left[2\left(\frac{\omega m_1 \cos\theta}{2\rho c}\right)\left(\frac{\omega m_2 \cos\theta}{2\rho c}\right)\right]^{-2} \qquad \text{(C10)}$$

By the method described above, the transmission loss for a double panel of finite size subject to a reverberant sound field is therefore given as:

$$TL = 20 \log\left(\frac{\omega m_1}{3.6 \rho c}\right) + 20 \log\left(\frac{\omega m_2}{3.6 \rho c}\right) + 6 \quad \text{dB} \qquad \text{(C11)}$$

or

$$TL = TL_1 + TL_2 + 6 \quad \text{dB} \qquad \text{(C12)}$$

Examination of Equations (C1), (C5), and (C8) show that the overall expression at any frequency for the transmission coefficient for a finite double panel is given by:

$$\tau = \left\{ 1 + \left[\frac{\omega M}{3.6 \rho c} - \frac{\omega^2 m_1 m_2}{(3.6 \rho c)^2} \left(1 - e^{-2kd}\right) \right]^2 \right\}^{-1} \qquad \text{(C13)}$$

and the transmission loss by $TL = 10 \log (\tau^{-1})$.

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APPENDIX D

THE TRANSMISSION LOSS OF A TRIPLE PANEL

Starting with the expression for the transmission coefficient of an infinite triple panel, this Appendix contains a derivation of the transmission loss of a finite triple panel excited by a reverberant sound field. The derivation proceeds along the same lines as described in Appendix C.

A matrix solution has been established for the transmission coefficient τ for a construction containing N infinite panels – see Reference D1. The expression for the transmission coefficient τ_θ for an angle of incidence θ is given as:

$$\tau_\theta = \left| 1 + \left(X_1 + X_2 + X_3\right) + X_1 X_2 \left[1 - e^{-j\sigma_1}\right] + X_2 X_3 \left[1 - e^{-j\sigma_2}\right] + X_1 X_3 \left[1 - e^{-j(\sigma_1 + \sigma_2)}\right] + X_1 X_2 X_3 \left[1 - e^{-j\sigma_1}\right]\left[1 - e^{-j\sigma_2}\right] \right|^{-2} \qquad \text{(D1)}$$

where

$$X_{1,2,3} = \frac{Z_{1,2,3} \cos\theta}{2\rho c}$$

$Z_{1,2,3}$ = transmission impedance of panels 1, 2 and 3

$\sigma_{1,2} = 2kd_{1,2} \cos\theta$

$d_{1,2}$ = cavity dimensions

k = wave number = $2\pi f/c$

At extremely low frequencies, when kd_1 and kd_2 are much less than unity, Equation (D1) becomes:

$$\tau_\theta \approx \left| 1 + \left(X_1 + X_2 + X_3\right) \right|^{-2}$$

$$= \left| 1 + \left(Z_1 + Z_2 + Z_3\right) \frac{\cos\theta}{2\rho c} \right|^{-2} \qquad \text{(D2)}$$

If, as is usual, this frequency range lies well below the critical frequency, then the impedance of the individual panels will be dominated by the mass. Therefore, Equation (D2) can be written as:

$$\tau_\theta = \left[1 + \frac{j\omega M \cos\theta}{2\rho c}\right]^{-2} \qquad f < f_c \tag{D3}$$

where $M = m_1 + m_2 + m_3$

The transmission loss for a finite triple panel can be obtained in the manner discussed in Section 2.1.3 and Appendix C, by inspection of the result for a single panel. The transmission loss is given by:

$$TL = 10 \log \left[1 + \left(\frac{\omega M}{3.6 \rho c}\right)^2\right] \qquad f < f_c \tag{D4}$$

Without repeating the operations involved–they can be determined by examination of Appendix C – the transmission loss of the triple panel at higher frequencies, but still under the condition that the wavelength is greater than the panel separations, is given by the expression:

$$TL \approx 20 \log \left(\frac{\omega m_1}{3.6 \rho c}\right) + 20 \log \left(\frac{\omega m_2}{3.6 \rho c}\right) + 20 \log \left(\frac{\omega m_3}{3.6 \rho c}\right)$$

$$+ 20 \log (2kd_1) + 20 \log (2kd_2) \tag{D5}$$

or

$$TL \approx TL_1 + TL_2 + TL_3 + 20 \log(2kd_1) + 20 \log(2kd_2) \tag{D6}$$

where TL_1, TL_2 and TL_3 are the transmission loss values for the panels 1, 2, and 3.

At higher frequencies, where the wavelength is equal to or smaller than the panel separation, the transmission loss of a finite triple panel is given by (see Appendix C):

$$TL \approx TL_1 + TL_2 + TL_3 + 12, \quad \text{dB} \tag{D7}$$

The expression for the transmission loss of a triple panel as given by Equation (D 5) is approximate in the frequency region of the two low frequency resonances. The more exact expression is given in Equation (D 1), which can be used to determine the optimum configuration of panel masses and separations. At low frequencies, when the acoustic wavelength is much less than the panel separations, the quantities in the square brackets of Equation (D 1) can be approximated as follows:

$$1 - e^{-j\sigma} \approx j\sigma$$

In this low frequency region, it is usual for the transmission impedance Z of the panels to be dominated by the mass reactance $j\omega m$, so that the effect of reverberant sound field excitation can be taken into account by introducing the factor 1.8 – see Appendix B. With these simplifications, the expression for τ can be set equal to zero to determine the values of the two low frequency resonances f_+ and f_-.

The resulting expression is complicated because there are five variables involved – the masses of the three panels and the two cavity dimensions. Examining the results obtained for double panel constructions, it seems logical that each of the cavity dimensions should be as large as possible, so that the fundamental resonances are as low as possible for a given overall thickness. The only way that this can be achieved is for the two cavity dimensions to be equal, i.e., $d_1 = d_2 = d$, even though the high frequency cavity resonances in the two cavities will occur at the same frequencies. In a similar manner, it seems logical for the triple panel construction to be symmetrical about the center panel, i.e., $m_1 = m_3$, so as to achieve the lowest possible values for the fundamental resonances for a given total mass. Thus, the optimum configuration for the lowest fundamental resonant frequencies is obtained with the following relationships:

$$\begin{aligned} m_1 &= m_3 = m \\ d_1 &= d_2 = d \end{aligned} \qquad \text{(D8)}$$

In this way the expression for the fundamental resonant frequencies can be simplified as follows:

$$
\left.
\begin{aligned}
f_{+} &= \frac{1}{2\pi} \sqrt{\frac{1.8\rho c^2}{m d}\left(\frac{2}{p} + 1\right)} \\[2em]
f_{-} &= \frac{1}{2\pi} \sqrt{\frac{1.8\rho c^2}{m d}}
\end{aligned}
\right\rbrace \qquad \text{(D9)}
$$

where $p = \frac{m_2}{m}$

Furthermore, for a given total mass and overall dimension, it is easy to show that the lowest value of the frequency f_+ is obtained when $p = 2$.

REFERENCES

D1. Sharp, B.H.S. and Beauchamp, J.W., "The Transmission Loss of Multilayer Structures," J. Sound Vib., Vol. 9, No. 3, pp 383-392, 1969.

APPENDIX E

THE DETERMINATION OF THE RATIO OF PANEL VELOCITIES FOR A DOUBLE PANEL CONSTRUCTION

This Appendix contains the derivation of the expression for the velocity ratio of the two panels in a double panel construction. The ratio is required so that the reduction in the transmission loss of a double panel construction with sound bridges can be determined. Simple expressions for the reduction in transmission are subsequently developed.

Consider a double panel construction consisting of panels with masses m_1 and m_2 separated by a distance d. At low frequencies where the wavelength of sound waves in air is much greater than the panel separation d, the construction can be conveniently represented by its electrical analog circuit for the purpose of analysis. In this analog, the mass of each panel is analogous to an inductance element, and the stiffness of the airspace is represented by a capacitive element. In keeping with the discussion of Section 2.1 and Appendix B, the finite size of the panels will be taken into account by assuming that the masses of the panels are reduced from their absolute value by the factor 1.8.

The electrical analog circuit for a double panel construction is illustrated in Figure E1 where the individual elements are represented in terms of the specific impedance.

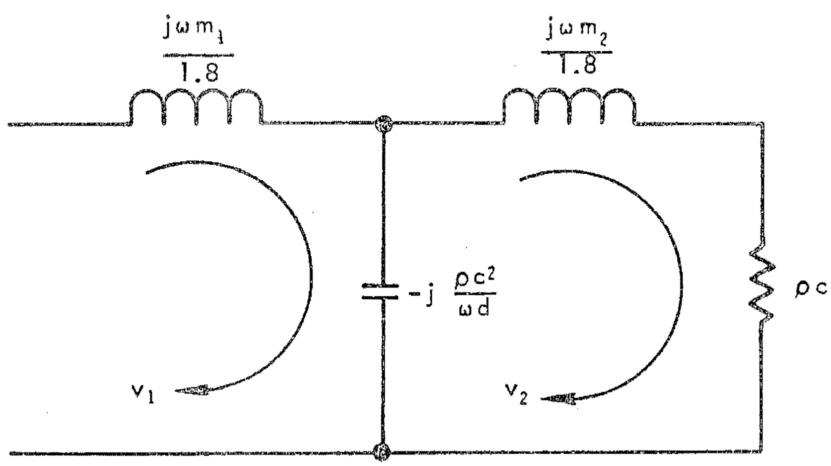

Figure E1. Equivalent Electrical Circuit for a Double Panel at Low Frequencies ($\lambda >> d$)

Analysis of the circuit will show that the ratio of the velocities of the two panels is given by:

$$\frac{v_1}{v_2} = \frac{\rho c + j\frac{\omega m_2}{1.8} - j\left(\frac{\rho c^2}{\omega d}\right)}{-j\left(\frac{\rho c^2}{\omega d}\right)}$$

$$= 1 + j\left(\frac{\omega d}{c}\right) - \left(\frac{f}{f_o}\right)^2 \left(\frac{m_1 + m_2}{m_1}\right) \qquad \text{(E1)}$$

where $f_o = \frac{1}{2\pi}\sqrt{\frac{1.8\rho c^2}{d}\left(\frac{m_1 + m_2}{m_1 m_2}\right)}$ is the fundamental resonant frequency for the double panel construction. By definition, the second term in Equation (E1) is much smaller than unity and hence can be ignored, with the result that the Equation can be rewritten as:

$$\left|\frac{v_1}{v_2}\right| \approx 1 - \left(\frac{f}{f_o}\right)^2 \left(\frac{m_1 + m_2}{m_1}\right) \qquad \text{(E2)}$$

Equation (E2) indicates that the velocity ratio approaches unity at frequencies much less than f_o. In this frequency range the two panels vibrate in phase and with the same velocity. At frequencies much greater than f_o, the velocity ratio is negative and large, indicating that the two panels are vibrating 180 degrees out of phase and that the velocity of the second panel is much less than that of the first. In this frequency range:

$$\left|\frac{v_1}{v_2}\right| \approx -\left(\frac{f}{f_o}\right)^2 \left(\frac{m_1 + m_2}{m_1}\right)$$

$$= -\frac{\omega^2 m_2 d}{1.8\rho c^2} \qquad f_o < f < f_\ell \qquad \text{(E3)}$$

where the upper limiting frequency f_ℓ is given by the expression:

$$f_\ell = \frac{c}{2\pi d}$$

At frequencies greater than f_ℓ where the acoustic wavelength is comparable to the separation of the panels, the equivalent circuit and the resulting velocity ratio given above are no longer valid. Inspection of the straight-line approximation to the transmission loss characteristics of a double panel – see Equations (16), (17), and (19) – shows that the transmission loss of a double panel with no sound bridges increases at a rate of 18 dB per octave at frequencies between f_o and f_ℓ, and 12 dB per octave at frequencies greater than f_ℓ. This represents a change from a transmission loss that is proportional to the sixth power of the frequency (f^6) to one proportional to the fourth power of the frequency (f^4). Clearly, the frequency dependence of the mass terms – proportional to the square of the frequency – cannot have changed, so that the term replacing the cavity stiffness in this region must be independent of frequency. Accordingly, the electrical analog circuit is as illustrated in Figure E2, with the impedance Z representing the cavity element.

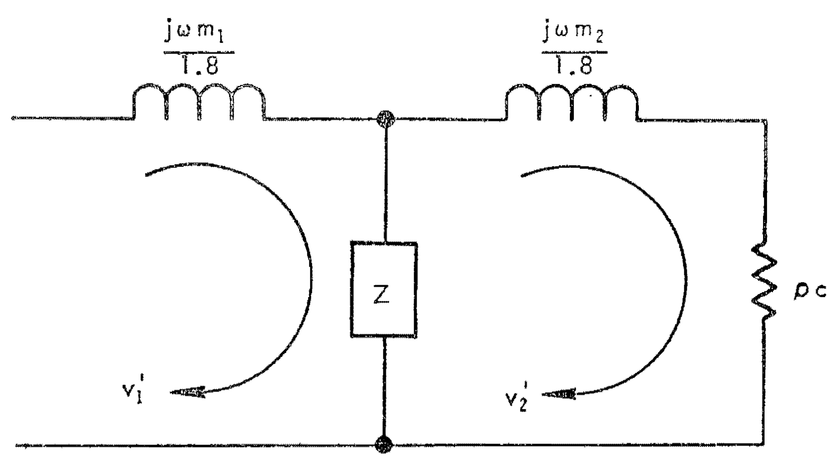

Figure E2. Equivalent Electrical Circuit for a Double Panel at High Frequencies ($\lambda \leq d$)

The ratio of the velocities v_1' and v_2' can be written as:

$$\left| \frac{v_1'}{v_2'} \right|^2 = \left(1 + \frac{\rho c}{Z}\right)^2 + \left(\frac{\omega m_2}{1.8 Z}\right)^2 \tag{E4}$$

At the frequency f_ℓ, by definition,

$$\left| \frac{v_1}{v_2} \right|^2 = \left| \frac{v_1'}{v_2'} \right|^2 \tag{E5}$$

Inserting Equations (E1) and (E4) into (E5) and solving for R gives the result that:

$$\underline{Z \approx \rho c}$$

The velocity ratio at frequencies greater than f_ℓ is therefore given by the expression:

$$\left| \frac{v_1'}{v_2'} \right|^2 = 4 + \left(\frac{\omega m_2}{1.8 \rho c}\right)^2$$

$$\approx \left(\frac{\omega m_2}{1.8 \rho c}\right)^2 \tag{E6}$$

if $\omega m_2 >> 3.6 \rho c$

The expressions given in Equations (E3) and (E6) can then be inserted into Equation (31) to calculate the transmission loss of a double panel with sound bridges in the frequency ranges $f_o < f < f_\ell$ and $f > f_\ell$. The square of the panel velocity ratio is proportional to f^4 at frequencies less than f_ℓ and to f^2 at frequencies greater than f_ℓ. At frequencies greater than f_o, when the velocity ratio rapidly becomes much greater than unity, the reduction TL_B in the transmission loss of a double panel construction with sound bridges is – see Equation (31)

$$TL_B \approx 10 \log \delta$$

$$TL_B = 20 \log \left(\frac{v_1}{v_2}\right) + \text{constant}$$

Thus the reduction TL_B increases at a rate of

12 dB/octave	$f_o < f < f_\ell$
6 dB/octave	$f > f_\ell$

The transmission loss of the unbridged double panel from which the values of TL_B have to be subtracted to give the transmission loss of the bridged construction increases at a rate of 18 dB per octave and 12 dB per octave at frequencies less than and greater than f_ℓ respectively. As a result, the transmission loss of a bridged double panel increases at a rate of 6 dB per octave at all frequencies.

The general form of the transmission loss of a bridged double panel is illustrated in Figure E3. The discontinuity at the frequency f_B – termed the bridging frequency – shown in this figure is a straight line approximation to the more gradual transition between the two slopes that is exhibited in practice. To determine the value of the frequency f_B it is necessary to return to the more exact expression for the reduction in transmission loss due to bridging, namely:

$$TL_B = 10 \log (1 + \delta)$$

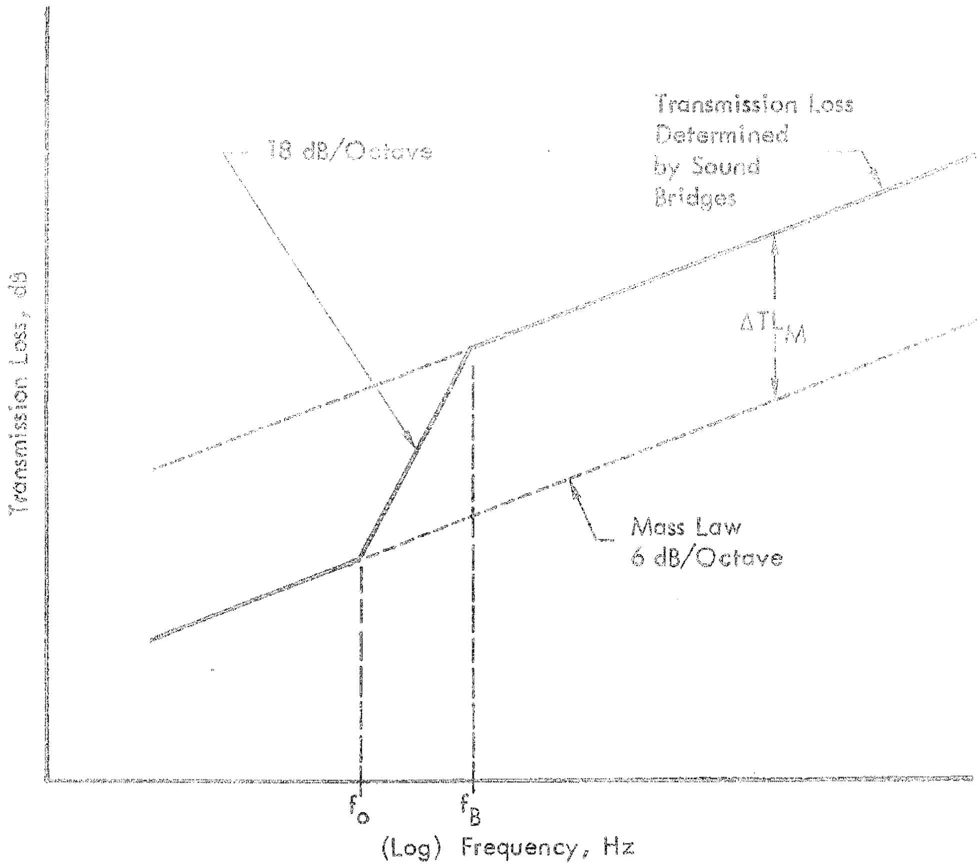

Figure E3. The General Form of the Transmission Loss of a Bridged Double Panel

where

$$\delta = \frac{n\varkappa}{S}\left(\frac{v_1}{v_2}\right)^2$$

$\varkappa$ = the radiation factor for point or line force excitation as given by Equation (27)

The frequency f_B can be determined by inserting the expression for the velocity ratio at frequencies less than f_ℓ as given in Equation (E3), and allowing δ to assume the value unity. By this method,

$$\delta = \frac{n\varkappa}{S}\left(\frac{f}{f_o}\right)^4 \left(\frac{m_1 + m_2}{m_1}\right)^2 = 1$$

or

$$f_B = f_o\left(\frac{m_1}{m_1 + m_2}\right)^{1/2} \left(\frac{S}{n\varkappa}\right)^{1/4} \tag{E7}$$

Equation (E7) can be further simplified by introducing the expressions for $\varkappa$. Two cases are of interest:

a. Point Connections

$$\varkappa = \frac{8}{\pi^3}\lambda_c^2 \qquad \text{(Equation (27))}$$

- $$f_{BP} = f_o\left[\frac{\pi^3 e^2}{8\lambda_c^2}\left(\frac{m_1}{m_1 + m_2}\right)^2\right]^{1/4} \qquad m_1 \neq m_2 \tag{E8}$$

where $e^2 = S/n$ is the effective lattice spacing constant for the point connections. For the optimum double panel configuration where $m_1 = m_2$.

- $$f_{BP} \approx f_o\sqrt{\frac{e}{\lambda_c}} \qquad m_1 = m_2$$

Since the transmission loss curve at frequencies greater than f_{BP} is parallel to the mass law – assuming that the motion of the two individual panels is controlled by the mass – a convenient way of describing the acoustical performance is by means of the quantity ΔTL_M, which is the amount in dB that the transmission loss exceeds the mass law value. In this case, with reference to Equation (17), ΔTL_M is given by the expression:

$$\Delta TL_M = 20 \log \left[\frac{\omega^2 m_1 m_2}{(3.6 \rho c)^2} \; 2kd \right] - 20 \log \left(\frac{\omega m}{3.6 \rho c} \right) \tag{E9}$$

With the value of f_{BP} inserted, Equation (E9) reduces to the expression:

$$\Delta TL_M = 20 \log (e f_c) + 20 \log \left(\frac{m_1}{m_1 + m_2} \right) - 55 \text{ dB} \tag{E10}$$

If $m_1 = m_2$,

$$\Delta TL_M = 20 \log (e f_c) - 61 \text{ dB} \tag{E11}$$

b. Line Connections

$$\varkappa = \frac{2}{\pi} \ell \lambda_c \qquad \text{(Equation (27))}$$

$$f_{BL} = f_o \left[\frac{\pi b}{2 \lambda_c} \left(\frac{m_1}{m_1 + m_2} \right)^2 \right]^{1/4} \tag{E12}$$

where $b = S/n\ell$ is the mutual spacing of typical vertical wooden or metal studs of length ℓ.

For the case where $m_1 = m_2$:

$$f_{BL} = f_o \left(\frac{\pi b}{8 \lambda_c} \right)^{1/4} \tag{E13}$$

In a similar manner to that described above for point connections, it can be shown that:

$$\Delta TL_M = 10 \log (b f_c) + 20 \log \left(\frac{m_1}{m_1 + m_2} \right) - 28 \text{ dB} \tag{E14}$$

If $m_1 = m_2$:

$$\Delta TL_M = 10 \log (b f_c) - 34 \text{ dB} \quad \text{(E15)}$$

A question arises at this point as to which value of the critical frequency must be inserted into the above expressions if the construction contains panels of differing critical frequencies. In the case of both point and line connections, the assumption is made that the motion of the panel exposed directly to the source of sound is unaffected by the presence of any connections. In other words, the connections are considered to be massless and to move with the same velocity as the first panel. However, if the two panels have different values for the critical frequency, this assumption appears to conflict with the principle of reciprocity, which states that the transmission loss must be the same whichever side is exposed directly to the sound source. The reason for the conflict is evident since the connections between the panels do have an impeding effect on the motion of the first panel, and the velocity of the connection is less than that of this panel. These two effects can only increase the transmission loss of the structure and as a result it is considered satisfactory to select the highest value of the critical frequencies of the two panels to insert into the above expressions for transmission loss. However, if the point connections to one of the panels are merely point projections from the familiar line connections to the other panel, then the critical frequency that has to be inserted in the above expressions is that for the panel supported by the points.

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APPENDIX F

DERIVATION OF THE EXPRESSIONS FOR THE STC DESIGN METHOD

This Appendix contains the derivation of the expressions by which the STC rating of a double panel construction can be defined in terms of its important parameters.

To determine the STC rating of a construction, the STC weighting contour is superimposed upon the measured values of transmission loss and adjusted so that the sum of the deficiencies (i.e., deviations of the transmission loss values below the STC weighting contour) does not exceed 32 dB, with the additional constraint that no single deficiency exceeds 8 dB. With the contour adjusted to its highest value that meets these requirements, the STC rating of the construction corresponds to the value of the transmission loss in dB given by the weighting contour at a frequency of 500 Hz.

The general form of the transmission loss curve for a double panel with sound bridges as a function of frequency is characterized by a slope of 18 dB per octave at the low frequencies and 6 dB per octave at the higher frequencies, neglecting for the moment the effects of coincidence. The changeover between the two distinct slopes occurs at the bridging frequency f_B. Since the STC weighting contour also has a standardized form, it is possible to adjust the general transmission loss characteristic of the double panel to its highest value such that it just meets the requirements for the STC rating method. This is demonstrated in Figure F1 where both the standard STC contour and the general transmission loss characteristic are shown.

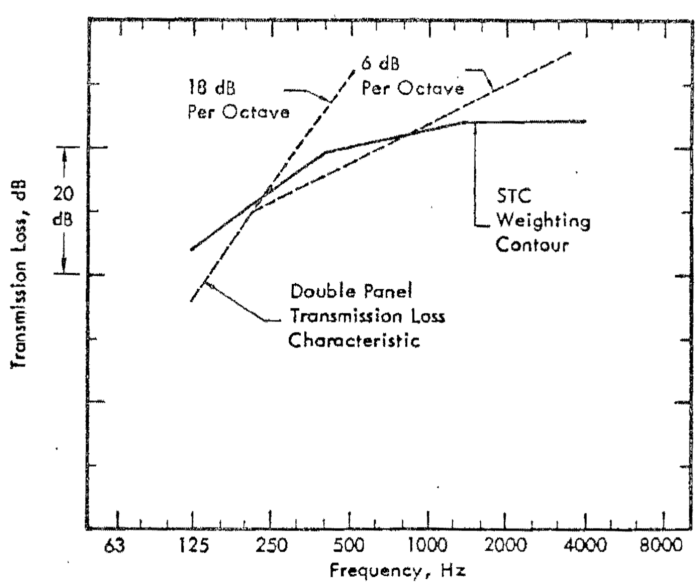

Figure F1. The General Transmission Loss Characteristic of a Double Panel with Sound Bridges Adjusted so as to Just Provide a Given STC Rating

The maximum allowable deficiency of 8 dB is taken at 125 Hz, which then sets the location of the 18 dB per octave characteristic precisely. The 6 dB per octave characteristic is then inserted so that the sum of the deficiencies is as close as possible to 32 (in this case it is 29). The transmission loss characteristic thus derived is the minimum that corresponds to the STC rating given by the location of the contour.

Referring to Figure F1, the difference in dB between the ordinate values of the STC contour at 125 Hz and 500 Hz is given by:

$$L(500) - L(125) = 16 \text{ dB} \tag{F1}$$

For the transmission loss characteristic:

$$TL(125) = TL_1(125) + TL_2(125) + 20 \log(125d) - 39 \tag{F2}$$

where d is the spacing of the panels. The transmission loss characteristic has been adjusted (see above) such that:

$$L(125) - TL(125) = 8 \tag{F3}$$

Substituting the values of $L(125)$ and $TL(125)$ given in Equations (F1) and (F2), and remembering that the STC rating is equal to the value of $L(500)$

$$STC = TL_1(125) + TL_2(125) + 20 \log(125d) - 15, \quad \text{dB}$$

Inserting the expression for TL_1 and TL_2 given by Equation (53), it can be shown that

$$m_1 m_2 d = \text{antilog}\left(\frac{STC - 44}{20}\right) \qquad \text{lbs}^2/\text{ft}^3 \tag{F4}$$

where m_1, m_2 are the masses of the two panels, and d is the panel separation.

This expression effectively describes the relationship of the 18 dB per octave portion of the transmission loss characteristic to the STC contour for this particular minimum condition. To complete the design method, a relationship is required between the STC contour and the transmission loss characteristic at the higher frequencies (i.e., the 6 dB per octave portion). Referring again to Figure F1, it can be deduced that:

$$STC = TL(500) + 2$$

$$= TL_M(500) + \Delta TL_M + 2$$

Thus

$$\Delta TL_M = STC - 20 \log (m_1 + m_2) - 22.5, \quad dB$$

For a particular configuration of the construction, the value of the quantity ΔTL_M can be written as (see Equation (35)):

$$\Delta TL_M = 20 \log (e f_c) + 20 \log \left(\frac{m_1}{m_1 + m_2}\right) - 55, \quad dB$$

Eliminating ΔTL_M from the above two expressions leads to the equality:

$$m_1 \, e f_c = \text{antilog} \left(\frac{STC + 32.5}{20}\right) \qquad \text{lbs/ft/sec} \qquad (F5)$$

The expression given in (F4) and (F5) can now be used to relate the various construction parameters to the STC rating. It is difficult, however, to retain the individuality of the panel masses m_1 and m_2 in the overall relationship. Therefore, it is assumed that $m_1 = m_2 = m$ (i.e., the optimum distribution of mass).

A design chart for a double panel construction with point connections to one panel, based on the above expressions, is shown in Figure 41 (a).

A similar derivation for a double panel with line connections results in a design expression similar to that given in Equation (F5):

$$m^2 b f_c = \text{antilog}\left(\frac{STC}{10}\right) \ \text{lbs}^2/\text{ft}^3/\text{sec} \qquad \text{(F6)}$$

A design chart for the transmission loss of a double panel with line connections is shown in Figure 41 (b).