United States
Department of
Agriculture

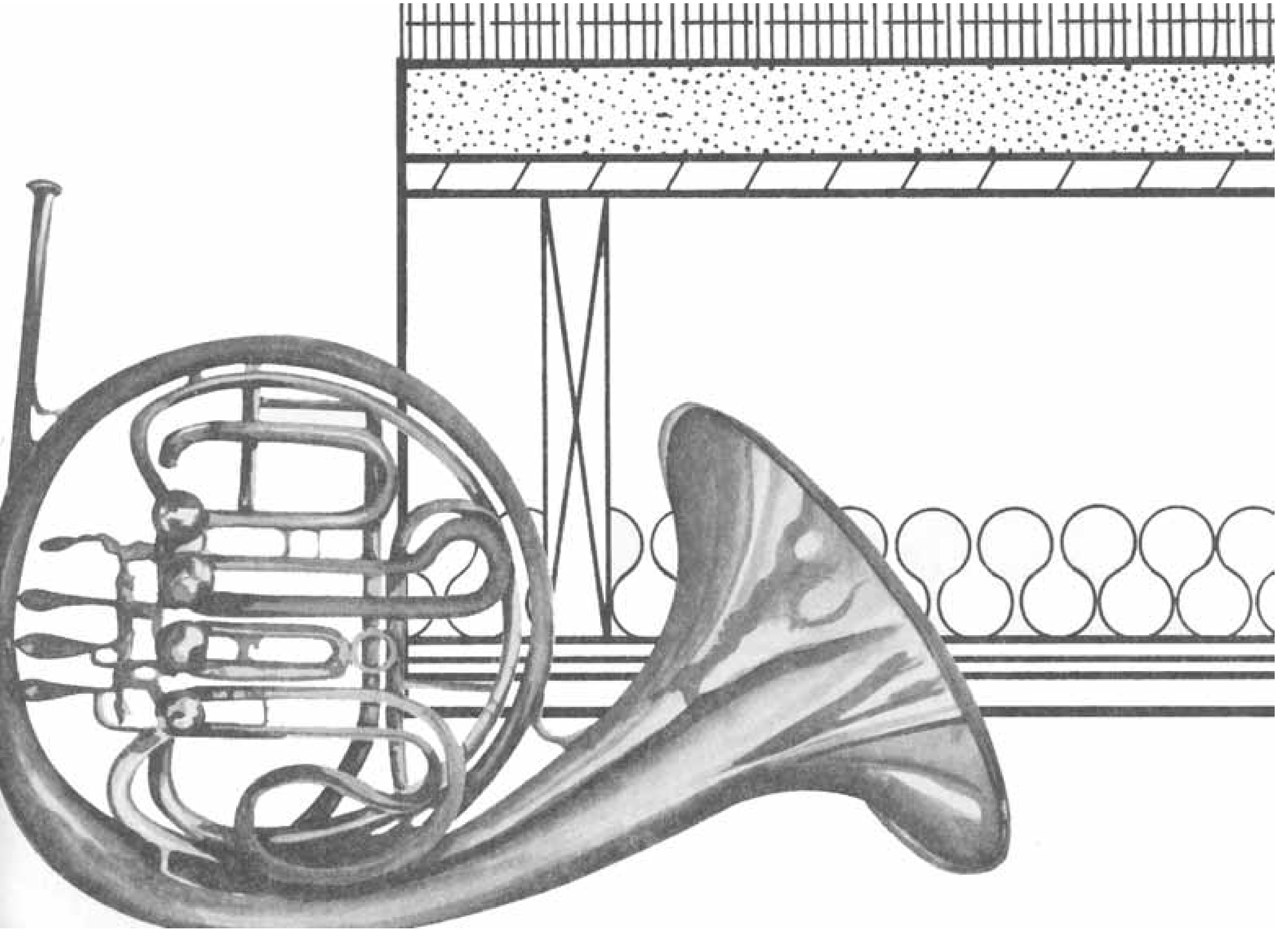
Forest Service

Forest
Products
Laboratory

General
Technical
Report FPL-43

Airborne Sound Transmission Loss Characteristics of Wood-Frame Construction

Fred F. Rudder, Jr.



Summary

This report summarizes the available data on the airborne sound transmission loss properties of wood-frame construction and evaluates the methods for predicting the airborne sound transmission loss. The first part of the report comprises a summary of sound transmission loss data for wood-frame interior walls and floor-ceiling construction. Data bases describing the sound transmission loss characteristics of other building components, such as windows and doors, are discussed.

The second part of the report presents the prediction of the sound transmission loss of wood-frame construction. Appropriate calculation methods are described both for single-panel and for double-panel construction with sound absorption material in the cavity. With available methods, single-panel construction and double-panel construction with the panels connected by studs may be adequately characterized. For double-panel construction with the panels unconnected (double-row-of-stud construction), however, the available prediction methods significantly overestimate the measured sound transmission loss performance. A new prediction method has been developed that appears to yield better results than previously available theoretical methods. This new prediction method is described and illustrated using several examples.

Technical appendices are included that summarize laboratory measurements, compare measurement with theory, describe details of the prediction methods, and present sound transmission loss data for common building materials.

Keywords: Light-frame, wood, construction, acoustic, sound transmission loss, theory, walls, floor-ceiling.

March 1985

Rudder, Fred F., Jr. Airborne sound transmission loss characteristics of wood-frame construction. Gen. Tech. Rep. FPL-43. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1985. 27 p.

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The Laboratory is maintained in cooperation with the University of Wisconsin.

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Airborne Sound Transmission Loss Characteristics of Wood-Frame Construction[1]

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Introduction

Building acoustics is a mature technical discipline. The physics of sound waves and the interaction of sound waves with structures have been extensively researched over the past century. This research has helped us to understand how sound behaves in rooms and how it is transmitted between rooms in buildings. Further, measurement methods to quantify the acoustical properties of many building materials and construction have been standardized and used to generate the extensive data compilations now available for design use.

The sound transmission loss characteristics of building construction are recognized as one aspect of the total design criteria. In the United States, building codes are now being implemented that incorporate quantitative acoustical criteria to ensure adequate sound isolation. Also, as multifamily housing becomes more commonplace, designers and builders will be increasingly faced with providing adequate noise isolation between living units.

Wood-frame construction can achieve levels of noise isolation equal to or greater than more massive construction such as concrete, but to take advantage of that potential it is important to characterize the airborne sound transmission loss properties of wood-frame construction. This report presents such a characterization.

[1]This summary of acoustic technology for wood-frame construction was prepared as a cooperative effort between the Forest Products Laboratory and the National Bureau of Standards. It concludes a 10-year research effort at the Forest Products Laboratory conducted by the late Robert E. Jones.

Summary of Available Data Bases

The laboratory measurement of airborne sound transmission loss in building construction is usually based upon the standards ANSI/ASTM E 90-75 for the United States and Canada or ISO 140/III (American Society for Testing and Materials 1980c; International Organization for Standardization 1978). The present versions of these standards allow for the measurement of the airborne sound transmission loss in standardized one-third-octave bands. The resulting data are presented as a tabulation or plot of sound transmission loss, TL, expressed in decibels, dB, versus the one-third-octave-band center frequency. The 16 standard one-third-octave-band center frequencies from 125 Hz to 4,000 Hz are generally common to all such data measured in the United States. Some laboratories may also report values for the sound transmission loss at 100 Hz and 5,000 Hz.

In addition to the frequency characterization of the airborne sound transmission loss of a test specimen, it is common practice in the United States to determine single-number ratings based upon these measurements. For laboratory measurements the single-number rating for airborne sound transmission loss is the Sound Transmission Class or STC rating (American Society for Testing and Materials 1980a). For field measurements the corresponding rating is the Field Sound Transmission Class or FSTC rating (American Society for Testing and Materials 1980d). An additional single-number rating called the normalized sound level difference and denoted by the symbol D_n is recommended for determining the A-weighted sound level difference between two neighboring rooms in a building (i.e., indoor-to-indoor field conditions) (American Society for Testing and Materials 1980e).

Given the above formats for characterizing the airborne sound transmission loss of building construction, any detailed collection of data for various types of construction is a vast undertaking that is an initial step in obtaining an overview of the data. Fortunately, several data bases have been compiled that are generally available to the public. This paper summarizes a subset of these data as one approach to characterizing the airborne sound transmission loss of wood-frame construction.

Available Data Bases

Several compilations of sound transmission loss data are available for design use. These available data bases cover a wide range of structural configurations, building components, and materials including wood-frame construction. In chronological order, the more complete compilations are as follows:

Berendt et al. (1967) - Octave and one-third-octave TL data, STC, and IIC ratings;[1]

Northwood (1970) - One-third-octave TL data for walls;

Marsh (1971) - One-third-octave TL data for glass;

Sabine et al. (1975) - One-third-octave TL data, STC ratings, and thermal performance data for exterior walls, doors, and windows:

Heeden (1980) - One-third-octave TL data, STC, and IIC ratings;

DuPree (1980) - STC and IIC ratings for walls and floor-ceiling assemblies;

DuPree (1981) - One-third-octave and one-half-octave TL data, STC, and IIC ratings, and the A-weighted level difference using the ASTM E 597 source spectrum shape and the laboratory TL data;

Quirt (1981) - One-third-octave TL data and STC ratings for single-pane and multipane glazing.

Data Summary Format

The above-listed data compilations comprise hundreds of different wall and floor-ceiling designs, window configurations, and doors. To summarize these data for wood-frame construction the following format was selected:

Classify the designs by intervals of STC ratings,

Group the constructions by this classification, and, with this grouping,

Compute the mean value, the data envelope (maximum and minimum), and standard deviation for each center frequency of the data set.

[1]The Impact Insulation Class (IIC) ratings refer to impact noise insulation of floor-ceiling assemblies and are not considered in this report.

The data base compiled by DuPree is the most comprehensive of the above sources for wood-frame construction. This data base is representative of typical wood-frame construction for interior partitions and floor-ceiling assemblies and was selected as the basis for the data summaries described in this report.

DuPree's Data Base

For wood-frame construction, DuPree's (1981) data base comprises 194 interior partition designs and 55 floor-ceiling designs. The majority of the designs used gypsum board as the basic panel material covering the framework. For these data, either one-third-octave- or one-half-octave-band sound transmission loss data are presented. For the interior partitions, 145 designs are characterized by one-third-octave-band data and 49 are characterized by one-half-octave-band data. For the floor-ceiling assemblies, 43 designs are characterized by one-third-octave-band data and 12 designs are characterized by one-half-octave-band data. For each design, DuPree lists the STC rating and the "normalized sound level difference," D_n.

It must be emphasized that DuPree's use of the notation D_n is different from the definition in ASTM E 597. The ASTM procedure for determining D_n is based upon field measurements of the A- weighted sound level difference normalized on the basis of the floor area and sound absorption of the receiving room (American Society for Testing and Materials 1980e). DuPree's value of D_n differs from the ASTM rating in two respects: First, his rating is based upon computing the A-weighted sound level difference using the ASTM E 597 source spectrum shape and the sound transmission loss values obtained from the laboratory measurements; second, he did not normalize the A- weighted sound level difference for receiving room sound absorption. To avoid confusion, this report quotes DuPree's D, value as D*–the A-weighted sound level difference based upon the E 597 source spectrum shape and the laboratory TL data. Using this notation, one could define a normalized sound level difference, D_n^*, using the relationship:

$$D_n^* = D^* + 10 \log (S_{fl}/A_r) \quad (1)$$

where S_{fl} is floor area of the receiving space,

A, is receiving space sound absorption as determined by ASTM E 597.

In this context, DuPree's D_n value represents a benchmark for comparing the field-measured value of D_n using E 597 and an ideal performance based upon laboratory measurements of sound transmission loss and field measurements of the receiving space sound absorption as indicated in equation (1).

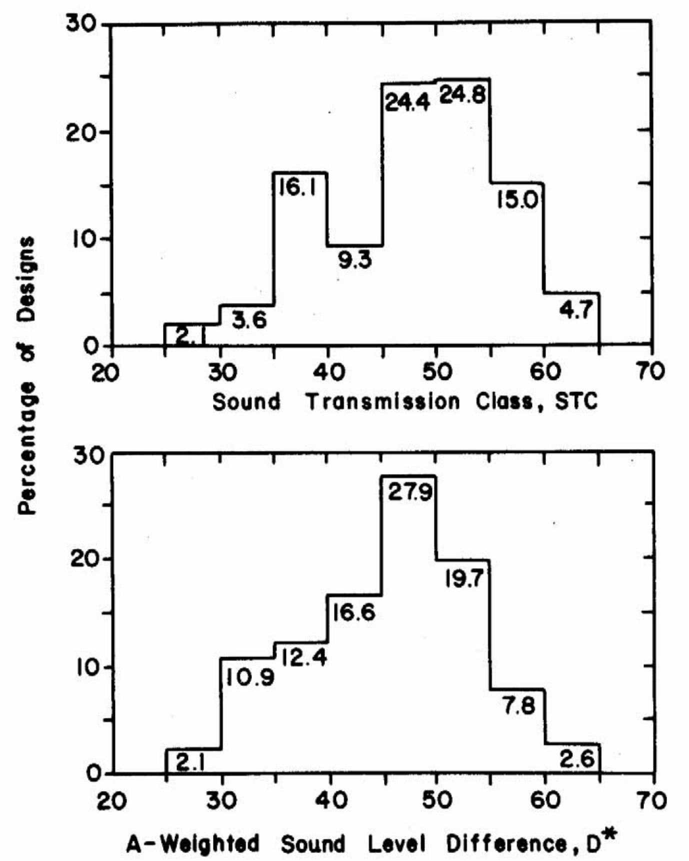


Figure 1.–Distribution of designs with STC and D* for wood-frame interior partitions in DuPree's (1981) data base. (ML84 5557)

Wood-Frame Interior Partitions

DuPree's data for interior partitions were grouped into 5-dB intervals of the STC rating and the A-weighted sound level difference, D*. These data groups represent distributions of the number of designs within the data base in terms of STC rating and D*. Figure 1 presents these distributions in terms of the percentage of the total number of designs grouped within each interval. The grouping scheme used includes the lower limit of the interval but excludes the upper limit. For example, figure 1 indicates that 24.4 percent of the interior partition designs exhibit STC ratings of 45, 46, 47, 48, or 49 corresponding to the interval 45 to 50.

These distributions yield an overview of the data base that is useful for design purposes. For example, over 68 percent of the designs equal or exceed an STC rating of 45, and 58 percent of the designs equal or exceed the A-weighted sound level difference, D*, of 45. At a level of STC equal to or greater than 55, only 19.7 percent of the designs are available for consideration.

Although the same data base is used, the distributions for STC and D* (fig. 1) appear to be quite different in shape. The reason for this difference is that the distribution of designs within each interval is not uniform and that the STC rating and D* are highly correlated. A linear regression analysis of the A-weighted sound level difference, D*, and the STC rating was conducted. (A scatter plot indicated that a linear fit would be adequate for this purpose.) The resulting estimate of D* in terms of the STC rating is:

$$D^* = -0.96 + 0.976(\mathrm{STC}) \quad \text{in dBA} \tag{2}$$

where $28 \leqslant \mathrm{STC} \leqslant 63$,

$N = 193$[2] ; $R^2 = 0.984$

mean STC = 47.3, standard deviation = 8.0,

mean D* = 45.2, standard deviation = 7.9.

As a rule of thumb, the estimate of D* is 1 dBA less than the STC rating for the interior partitions of wood-frame construction.

A plot (fig. 2) of the mean values of the one-third-octave-band sound transmission loss data grouped by the indicated STC interval corresponds to the distribution for STC in figure 1. For example, the curve labeled 50-55 in figure 2 represents the mean values of the data subset (24.8 pct of the designs) exhibiting STC ratings from 50 to 55. It is interesting to note that the mean value of this curve is 52.5 dB at 500 Hz, which is what one might expect—or at least hope for—using a uniform distribution of STC within the interval.

The mean TL curves in figure 2 also indicate the construction characteristics of the designs contained in the data base. For the STC 25-30 curve, the slope of the curve is very close to 6 dB per octave, which is characteristic of single thin panel "mass law" response. For the other STC ranges in figure 2, the slopes of the curves are closer to 12 to 18 dB per octave, which is characteristic of double-panel construction. All of the mean TL curves in figure 2 peak in the frequency range of 1.25 to 1.6 kHz and exhibit a coincidence or critical frequency dip in the frequency range of 2.5 to 3.15 kHz. This general trend is a characteristic of the gypsum board material used for panels covering the framework.

DuPree (1980; 1981) described and illustrated the construction corresponding to each set of TL data in his compilation. For the data grouping indicated in figures 1 and 2, "typical constructions'' (fig. 3) representative of designs included in each STC range for wood-frame interior partitions are presented. These illustrations and descriptions indicate DuPree's extreme attention to detail in compiling his data.

[2]One design (1.2.2.2.3.1. in DuPree's catalog notation) was omitted.

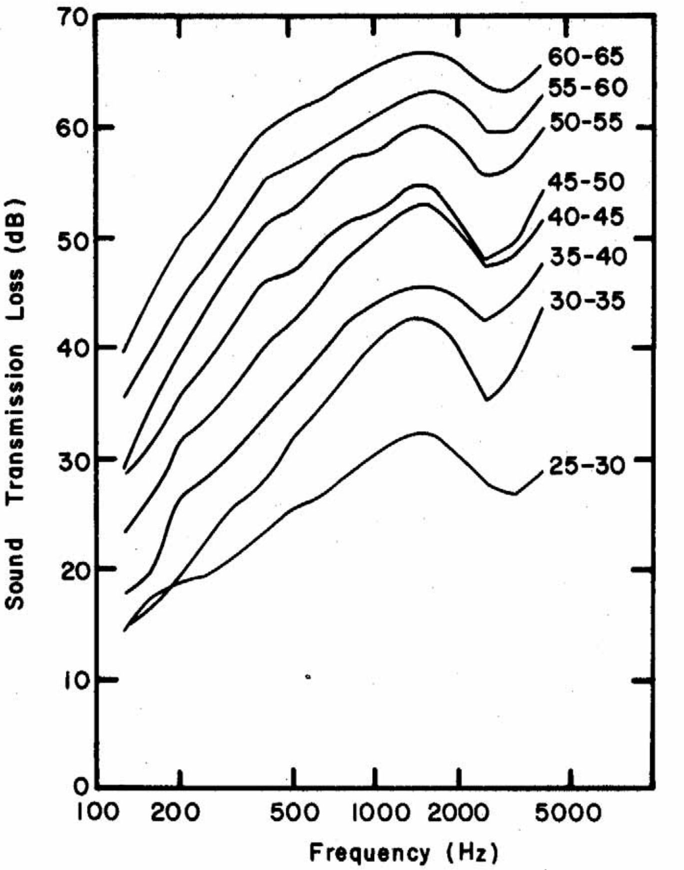


Figure 2.–Mean values of one-third-octave-band sound transmission loss for wood-frame interior partitions; data grouped by intervals of STC rating. (ML84 5558)

Each of the curves in figure 2 may be further described by the standard deviation and the data spread at each one-third-octave-band center frequency. These descriptions of the data indicated in figure 2 are presented in Appendix A.

Wood-Joist Floor-Ceiling Construction

DuPree's data base for wood-joist floor-ceiling construction comprises 55 designs described by one-third- or by one-half-octave TL data. The data summaries and the presentation format are similar to the above discussion concerning interior partitions.

The distributions of the percentage of floor-ceiling designs by STC rating intervals and by A- weighted sound level difference, D* (fig. 4), can be interpreted identically to those discussed for the figure 1 data.

For the floor-ceiling data a scatter plot indicated that a linear relationship between D* and STC rating is an appropriate functional form. A linear regression analysis was conducted with the following estimate for D*:

$$D^* = -2.97 + 1.01(\text{STC}) \quad \text{in dBA} \qquad (3)$$

where $37 \leqslant \text{STC} \leqslant 61$,
$N = 55$; $R^2 = 0.987$,
mean STC = 50.6, standard deviation = 5.5,
mean D* = 48.2, standard deviation = 5.6.

As a rule of thumb, the estimate of D* is 3 dBA less than the STC rating for the floor-ceiling construction described in DuPree's data base.

Figure 5 summarizes the mean values for the one-third-octave-band sound transmission loss data for floor-ceiling assemblies grouped in 5-dB ranges of the STC rating. DuPree (1981) has described and illustrated the typical construction (fig. 6) indicating details of the floor-ceiling designs for each of the STC intervals in figure 5.

The sound transmission loss curves for floor-ceiling construction characteristically slope at an average rate of 12 dB per octave and exhibit no predominant dip at the apparent critical frequency in the range of 2.5 to 3.15 kHz (fig 5). The reason for this similarity is that all of the designs are deep double-panel construction with dissimilar panels on either side. The floor construction is typically a wood subfloor attached to the joists, topped with a finished wood surface or lightweight concrete panel. (Carpeting does not affect the airborne sound transmission loss significantly.) The ceiling construction is generally one or more layers of gypsum board either attached to or suspended from the joists. Sound absorption is usually installed in the cavity between the floor and the ceiling. The close proximity of the two mean curves in figure 5 for the STC ranges 45-50 and 50-55 simply reflects that the designs grouped in these two ranges predominantly exhibited an STC rating close to 50 rather than being uniformly distributed over each of the ranges.

Each of the curves illustrated in figure 5 may be further described by the standard deviation and the data spread at each one-third-octave-band center frequency. These descriptions are presented in Appendix A.

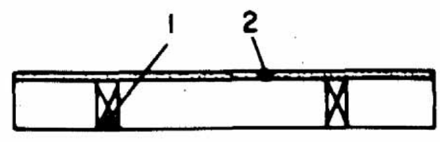
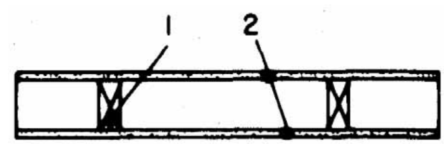
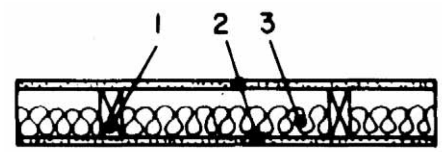
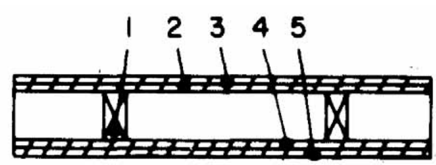
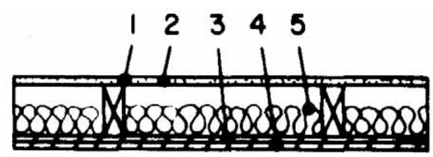
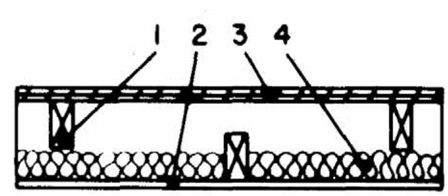
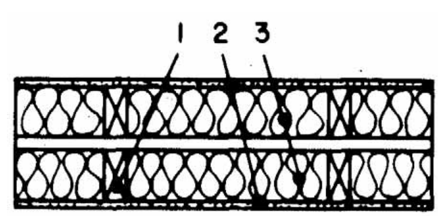
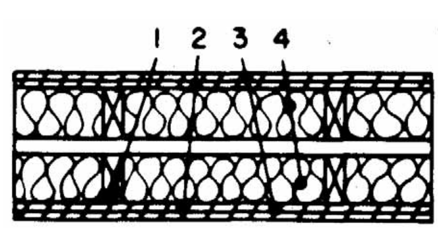
STC Interval	STC of Representative Design		Design Characteristics
25-30	28		1. 2x4 studs, 16"o.c. 2. 5/8" gypsum board screwed to studs.
30-35	34		1. 2x4 studs, 16"o.c. 2. 5/8" gypsum board screwed to studs.
35-40	30		1. 2x4 studs, 16"o.c. 2. 5/8" gypsum board screwed to studs. 3. 2"-thick sound attenuation blanket.
40-45	43		1. 2x4 studs, 16"o.c. 2. 5/8" gypsum board screwed to studs. 3. 5/8" gypsum board laminated to base layer with gypsum joint compound. 4. resilient channels, 24"o.c. 5. 5/8" gypsum board screwed to channels.
45-50	47		1. 2x4 studs, 16"o.c. 2. 5/8"gypsum board screwed to studs. 3. resilient channels 24"o.c. & 1/2x3" gypsum filler strip along base plate. 4. 5/8" gypsum board screwed 12"o.c. 5. 2 -1/4"-thick sound attenuation blanket.
50-55	52		1. 2x4 studs, 24"o.c., staggered 12"o.c. on 2x6 plates. 2. 1/2" type-X gypsum board screwed 12"o.c. 3. 1/2" type-X gypsum board screwed 12"o.c. 4. 2"-thick sound attenuation blanket.
55-60	57		1. double row of 2x4 studs, 16"o.c. on separate plates 1 " apart. 2. 5/8" type-X gypsum board screwed 16"o.c. 3. 3-1/2"-thick sound attenuation blankets in both stud cavities.
60-65	63		1. double row of 2x4 studs, 16"o.c. on separate plates 1 " apart. 2. 5/8" type-X gypsum board screwed 16"o.c. 3. 5/8" type-X gypsum board screwed 16"o.c. 4. 3-1/2"-thick sound attenuation blankets in both stud cavities.

Figure 3.–Representative construction for wood-frame interior partition designs included in the indicated STC interval. (ML84 5568)

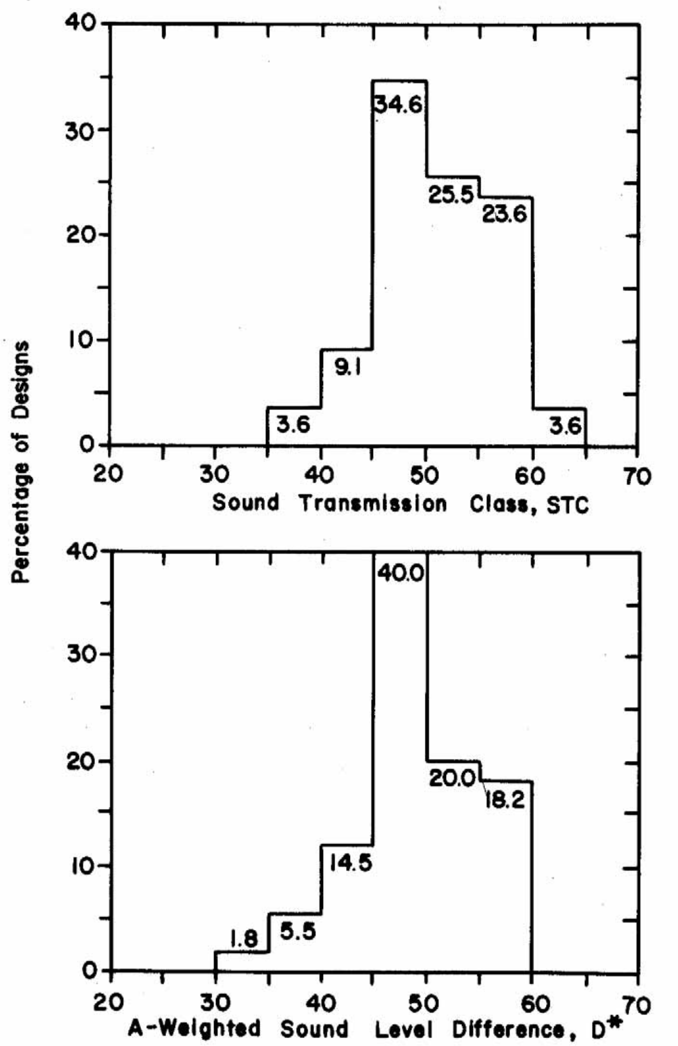


Figure 4.–Distributions of designs with STC and D* for wood-joist floor-ceiling assemblies contained in DuPree's (1981) data base.
(ML84 5559)

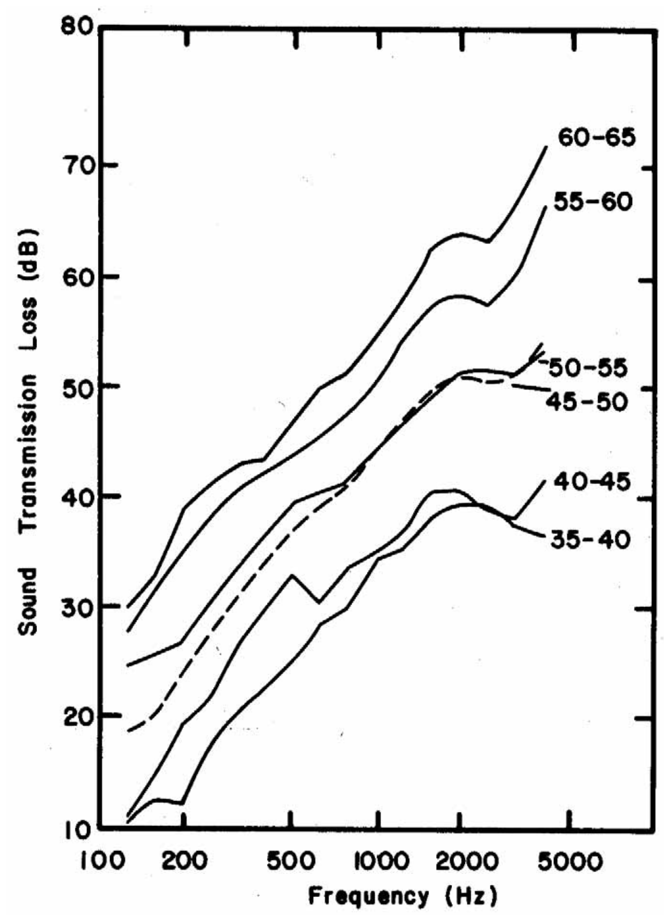


Figure 5.–Mean values of one-third-octave-band sound transmission loss for wood-joist floor-ceiling assemblies; data grouped by intervals of STC rating.
(ML84 5560)

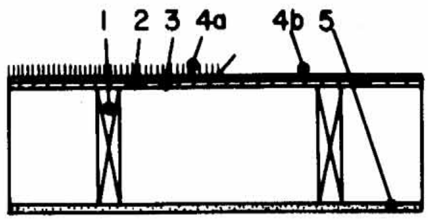
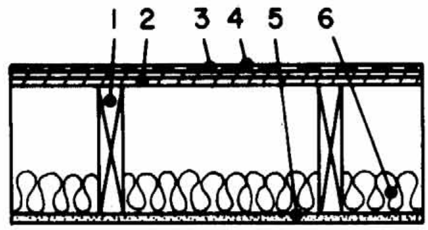
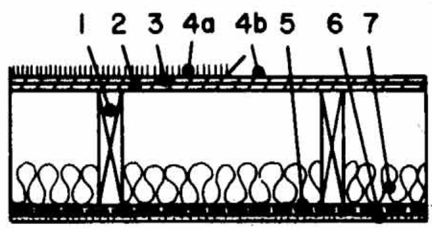
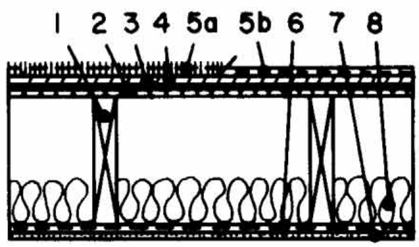
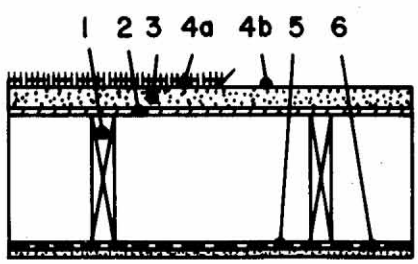
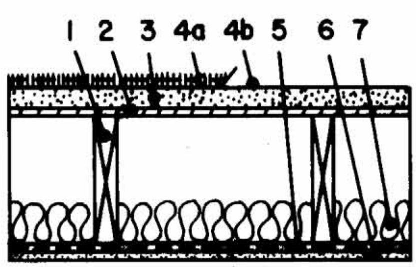
STC Interval	STC of Representative Design		Design Characteristics
35 - 40	37		1. 2x8 joists, 16"o.c. 2. 1/2" plywood nailed to joists. 3. 3/8" plywood nailed to joists. 4a. carpet and pad. 4b. no floor covering. 5. 1/2" type-X gypsum board nailed with 5d nails 6" o.c.
40 - 45	43		1. 2x10 joists, 16"o.c. 2. 5/8" plywood subfloor glued to joists, nailed with 8d nails 12"o.c. 3. 1/4" particleboard glued to plywood. 4. 1/2" parquet wood flooring glued to particleboard. 5. 1/2" type-X gypsum board screwed 12"o.c. 6. 3"-thick sound attenuation blanket.
45 - 50	47		1. 2x8 joists, 16"o.c. 2. 1/2" plywood nailed to joists. 3. 3/8" plywood nailed to joists. 4a. carpet and pad. 4b. no floor covering. 5. resilient channels, 24"o.c. 6. 5/8" type-X gypsum board screwed 12"o.c. 7. 3 "-thick sound attenuation blanket.
50 - 55	51		1. 2x10 joists, 16"o.c. 2. 5/8" plywood glued to joists, nailed with 8d nails 12"o.c. 3. 1/4" particleboard glued to plywood. 4. 1/2" fiberboard glued to particleboard. 5a. 76-oz. carpet on 50-oz. hair pad. 5b. 1/2" parquet wood flooring. 6. resilient channels, 24"o.c. 7. 1/2" type-X gypsum board screwed 12"o.c. 8. 3 "-thick sound attenuation blanket.
55 - 60	56		I. 2x10 joists, 16"o.c. 2. 5/8" plywood subfloor nailed with 8d nails 6"o.c. along edges, 10"o.c. in field. 3. 1-1/2"-thick lightweight concrete over 15-lb. asphalt felt. 4a. 20-oz. carpet on 40-oz. hair pad. 4b. 1/16" thick vinyl-asbestos tile. 5. resilient channels, 24"o.c. 6. 1/2" type-X gypsum board screwed 12"o.c.
60 - 65	61		I. 2x10 joists, 16"o.c. 2. 5/8" plywood subfloor nailed with 8d nails 6"o.c. along edges, 10"o.c. in field. 3. 1-1/2"-thick lightweight concrete over 15-lb. asphalt felt. 4a. 20-oz. carpet on 40-oz. hair pad. 4b. 1/16"-thick vinyl-asbestos tile. 5. resilient channels, 24"o.c. 6. 5/8" type-X gypsum board screwed 12"o.c. 7. 3-1/2-"thick sound attenuation blanket.

Figure 6.–Representative construction for wood-joist floor-ceiling assemblies included in the indicated STC interval. (ML84 5567)

Prediction of Airborne Sound Transmission Loss

The airborne sound transmission loss of building construction has long been recognized as an important design attribute. The extensive data compilations referenced and discussed earlier in this report are evidence of the importance of this design consideration. The development of prediction methods has progressed concurrently with the accumulation of these empirical data. Comparison of predictions with the empirical data has resulted in the development of theoretical models appropriate for specific structural designs. The prediction methods described here apply to structural configurations (fig. 7) common to wood-frame construction used in buildings.

Characteristic Frequencies

The prediction methods described in this report estimate the airborne sound transmission loss of the particular construction as a function of frequency. The assumptions used to develop these models restrict their application to certain frequency ranges, which are defined by a few characteristic frequencies. The characteristic frequencies are estimated by the physical properties of the panel material covering the wood framework and, for double-panel construction, by the cavity depth between the two panels.

For single-panel construction, two frequencies characterize the airborne sound transmission loss: the panel fundamental mode resonant frequency, f_{11}, and the critical frequency of the panel, f_c. These frequencies may be estimated using the relationships:

$$f_{11} = \frac{\pi}{2}\sqrt{\frac{D}{m}}\,[1/a^2 + 1/b^2] \quad \text{in Hz} \tag{4}$$

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{m}{D}} \quad \text{in Hz} \tag{5}$$

where m is mass per unit area of the panel material,

D is bending rigidity of the panel,

a,b are total height and length of the construction,

c is speed of sound in air.

The above expression for the fundamental resonant frequency, f_{11}, is based upon the assumption of simply supported edges for the construction. By assuming clamped edge conditions, a higher value of f_{11} would be estimated. However, in either case, for typical building construction, f_{11} is too low to be of practical importance for the transmission of audio-frequency sound. The expression given for f_{11} is appropriate since this characteristic frequency represents the lower frequency limit for which the prediction methods of this report apply.

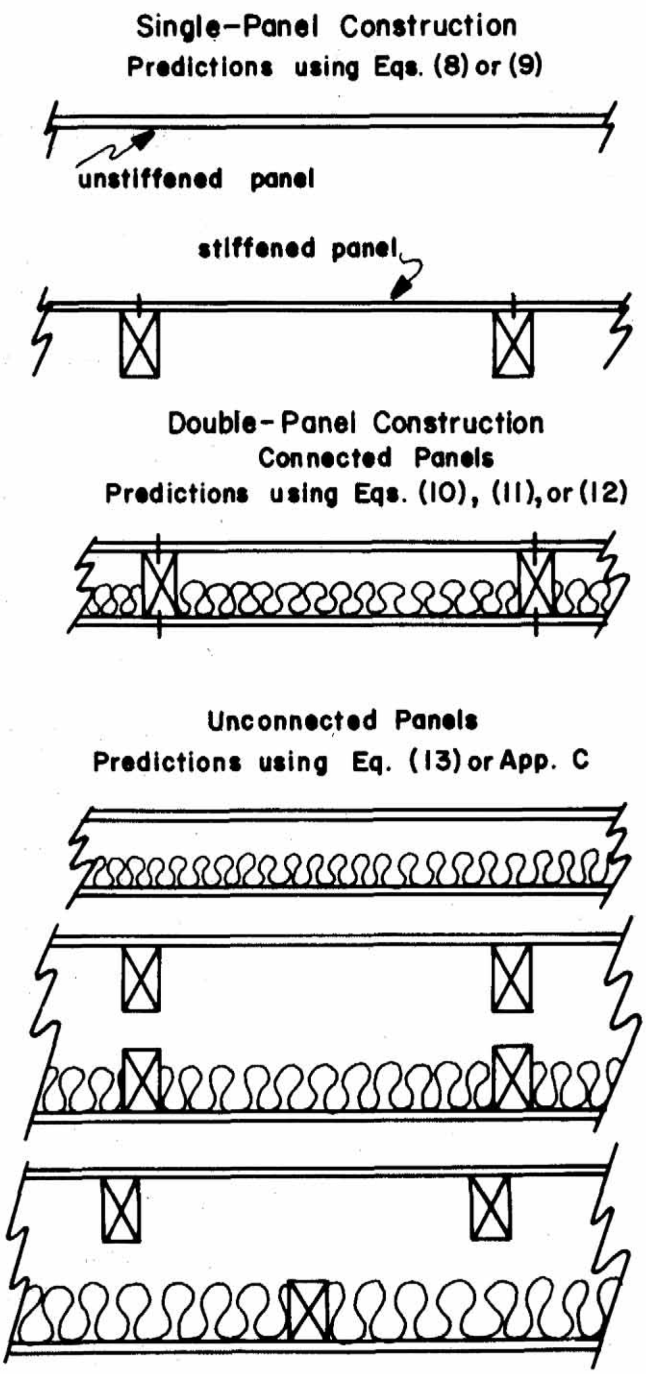


Figure 7.–Panel configurations for which prediction methods apply. ML84 5566)

The critical frequency, f_c, represents the upper frequency limit for the prediction methods described in this report. The expression for f_c (eq. (5)) assumes a thin panel of homogeneous material. From a practical standpoint, f_c is usually estimated on an empirical basis (described in Appendix B). At the critical frequency, the sound transmission loss is significantly less than the performance at lower frequencies. This decrease occurs in a frequency range above and below the critical frequency and is characteristic of both single-panel and double-panel construction. Figure 2 illustrates the characteristic shape of the sound transmission loss curve for double-panel construction and the coincidence dip that occurs in the frequency range around the critical frequency.

For double-panel construction, two additional frequencies are important for characterizing the sound transmission loss of the construction. These frequencies are denoted by f_o and f_l and they occur numerically in the sequence $f_{11} < f_o < f_\ell$ fc for dimensions and materials typical of wood-frame building construction.

The characteristic frequency, f_o, defines the frequency at which the air within the cavity of a double wall acts like a spring, coupling the masses of the panels to form a resonant mechanical vibration response of the system. The theoretical identification of this characteristic frequency has been attributed to Wintergerst (Gösele 1980) although it is also commonly called "London's frequency'' (London 1950; Mulholland et al. 1967).

The other characteristic frequency, f_ℓ, is that at which the cavity depth between the two panels is exactly one-half the wavelength of the incident sound, At this frequency a standing wave occurs in the cavity between the panels. The sound transmission loss is decreased at this frequency unless sound absorption material is installed in the cavity to damp this standing wave. London's theory identified the standing wave frequency, f_ℓ, as well as the resonance frequency, f_o, for the double-panel configuration (London 1950). These characteristic frequencies may be estimated using the expressions:

$$f_o = (c/2\pi)\sqrt{\rho/M_e d} \quad \text{in Hz} \tag{6}$$

and

$$f_\ell = c/2d \quad \text{in Hz} \tag{7}$$

where c is speed of sound in air,

p is density of air,

$M_e \equiv 2m_1 m_2/(m_1 + m_2)$, where m_i is mass per unit area of the i^{th} panel (i = 1,2),

d is cavity depth between the panels.

These expressions for f_o and f_ℓ estimate the lowest frequencies at which either panel/cavity resonance or standing waves can occur. Physically, these expressions correspond to the sound field impinging upon the construction at normal incidence. If the the sound field impinges upon the panel at an angle θ measured from the normal to the panel, the above expressions are modified by dividing the right-hand side of equations (6) and (7) by cos 0. In addition, for any angle of incidence, standing waves will occur in the cavity at all integer multiples (harmonics) of the expression for f_ℓ given by equation (7).

Since laboratory determination of the sound transmission loss is based upon reverberant or diffuse sound fields, the theoretical prediction of laboratory performance must be averaged over angle of incidence. Further, since the sound transmission loss of the construction is usually determined for frequency bands rather than discrete frequencies, the degradation of the sound transmission loss, as predicted at a discrete frequency such as f_o or f_ℓ, is not as predominant as the theory might indicate. The theoretical results must also then be averaged over the frequency bands corresponding to the laboratory measurements in order to obtain valid comparisons between theory and experiment.

The necessary averaging over both angle of incidence, θ, and frequency, f, of the theoretical models requires integration of complicated functions. Only in the case of the single thin panel have explicit integrations been carried out. For the double-panel construction, numerical integrations are required using the complete functional forms of the theoretical models. The development of theoretical models recognizes both the physical mechanisms of airborne sound attenuation for the frequency ranges defined by the characteristic frequencies and the averaging required to incorporate both angle of incidence and frequency-related effects. These considerations are the essential differences between various prediction methods developed to model similar structural configurations.

Single Thin Panel Structures

The prediction of the sound transmission loss of single thin panel structures utilizes the "mass law" theory. This theory assumes that the thin homogeneous panel responds to the incident sound pressure as a "limp may"– that is, the bending stiffness of the panel is neglected (Heckl 1981). Since the bending stiffess is neglected, the classical mass law theory cannot predict the degradation of the panel sound transmission loss near the critical frequency, f_c, of the panel. However, using a limiting form of a more refined model, the mass law prediction can be adjusted to incorporate coincidence effects at frequencies below the critical frequency (Sewell 1970).

For a single thin panel of homogeneous material, the sound transmission loss prediction is given by the expression:

$$TL = 20 \log (mf) + \log [1 - (f/f_c)^2] + 20 \log [\pi/(1.9\rho c)] \text{ in dB} \quad (8)$$

where m is panel mass per unit area,

f is frequency ($f_{11} < f < f_c$),

f_c is critical frequency (eq. (5)),

ρc is characteristic impedance of air.

The second term on the right-hand side of equation (8) is the adjustment to incorporate the decrease in TL for frequencies less than the critical frequency. The factor of 1.9 appearing in the denominator of the third term is an empirical constant accounting for averaging over angle of incidence. This type of adjustment is discussed completely by Jones (1979). Finally, the form of equation (8) is a continuous function of frequency between the indicated frequency limits. This function form also corresponds to the functional relationship obtained by averaging over constant percentage frequency bands such as octave-band and one-third-octave-band intervals. Hence, equation (8) may be used to predict the sound transmission loss of single thin panels as a continuous function of frequency, and the values calculated at the center frequencies of the standard octave bands or one-third-octave bands correspond to the TL values for that band.

For practical applications, any consistent set of units may be used for the parameters appearing in equation (8). It is common practice to use the value of ρc corresponding to standard temperature and pressure conditions of 20° C and 101.325 kPa. For these conditions ρc = 413 SI rayls and m is expressed in units of kg/m^2 (American Society for Testing and Materials 1980b). Expressing the panel "mass" in units of pounds per square foot, one uses ρc = 84.6 fps rayls. For normal ranges of temperature and pressure, the variation in pc would not alter the TL estimate more than ± 1dB. This variation is within the range of interlaboratory variation and may be neglected for all practical purposes (Jones 1979; Sharp et al. 1980).

Depending upon the units selected for expressing the panel mass per unit area, equation (8) becomes:

$$TL = 20 \log (mf) + 20 \log [1 - (f/f_c)^2] - 48 \quad \text{in dB} \quad (9a)$$

or

$$TL = 20 \log (wf) + 20 \log [1 - (f/f_c)^2] - 34 \quad \text{in dB} \quad (9b)$$

where m is panel mass per unit area (kg/m^2),

f is frequency ($f_{11}<f<f_c$),

w is panel weight per unit area (lb/ft^2).

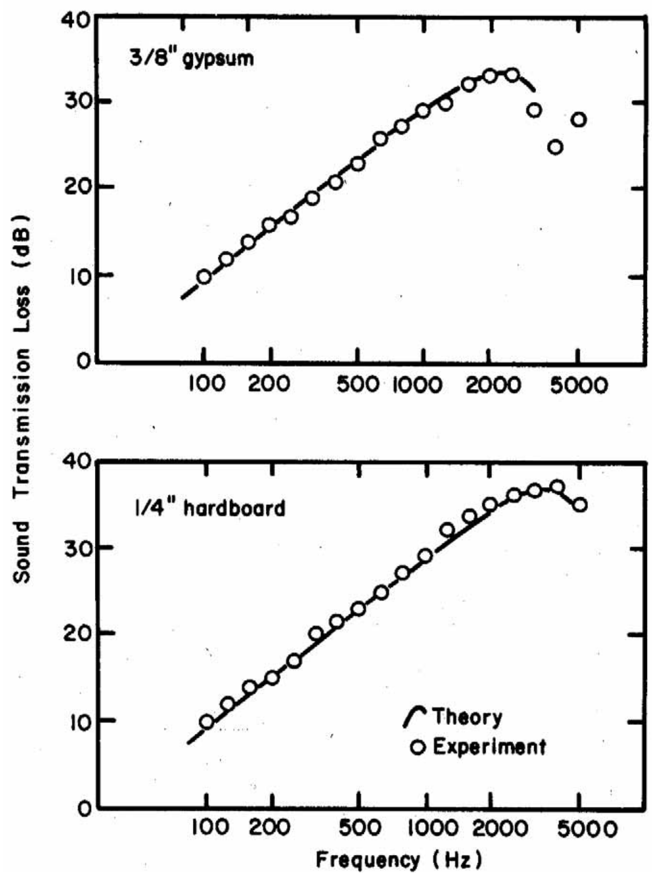


Figure 8.–Comparison of theory and measurement for homogeneous and isotropic materials: Upper—Single 3/8-inch-thick gypsum board; Lower—Single 1/4-inch-thick hardboard. (ML84 5561)

Figure 8 is the comparison between theory using equation (9b) and experimental data for 3/8-inch-thick gypsum board (upper) and for 1/4-inch-thick hardboard (lower). Similar comparisons for these and other single-layer gypsum board and hardboard data in Appendix B yield agreement between theory and experiment as good as that indicated in figure 8.

If the theory is used improperly, significant differences between simple mass law theory and experiment can occur (fig. 9). For 1/2-inch-thick plywood (fig. 9 upper), since plywood is an inhomogeneous material, the mass law relationship (based upon the assumption of a homogeneous material) does not apply. For laminated gypsum board construction (fig. 9 lower) the laminations result in a significant shearing deformation that is characteristic of thick panels. The mass law accurately predicts the sound transmission loss for frequencies below 400 Hz for this construction. However, above 400 Hz, shearing deformations result in rather significant differences between the thin panel mass law and the experimental data. Theories are available for predicting the sound transmission loss of thick panels

(Heckl 1981; Jones 1981; Sharp et al. 1980). However, these theories will not be discussed here since wood-frame construction usually incorporates thin panels covering the framework; the discussion of thick panels would deviate too far from the primary objective of this report.

The prediction methods described in this paper are based upon the mass of the panels covering the framework and do not include the mass of the framework.

To illustrate, theory and experiments for single-panel construction supported by a wood-stud framework are described (figs, 3,7) and illustrated (fig. 10). The experimental data are for a single layer of 5/8-inch-thick gypsum board attached to 2 x 4 wood-stud framework, for two different stud spacings. The theoretical curve is based upon the mass law relationship of equation (8) assuming that the studs are massless. Agreement between theory and experiment is good (fig. 10).

Double-Panel Construction

The sound transmission loss characteristics of double-panel construction differ significantly from the characteristics of single thin panels. These differences, if properly utilized, allow double-panel light-frame construction to achieve noise attenuation equal to or exceeding that of more massive forms of construction such as masonry or concrete (Jones 1975; Rudder et al. 1982). However, to design wood-frame construction to achieve high values of sound transmission loss, it is necessary to understand the physical basis underlying double-panel sound attenuation. Prediction models have been developed that apply to the double-panel configurations shown in figure 7. As described above for the single thin panel construction, the double-panel prediction models assume a forced vibration of the structure and, hence, are restricted to frequencies below the critical frequencies of the panels covering the framework (Gösele 1981; Heckl 1981; Mulholland 1967; Sharp et al. 1980). Two double-panel configurations are considered in this report: connected double panels and unconnected double panels. More information is detailed in Appendix C.

Connected Double Panels

Sharp has developed a theory for predicting the sound transmission loss of double-panel construction with both panels directly attached to the framework (Sharp 1973; 1978; Sharp et al. 1980). His original theory (1973) encompassed two types of mechanical connection between the panels and the framework. Sharp extended the model (1978) to incorporate a more general type of connection such as a resilient channel separating the panel from the framework. The prediction method described in this report corresponds to the "line connection" model of Sharp. The "line connection" model corresponds to the direct attachment of the panels to the framework along the entire length of the studs using either nails or screws. Further, the model assumes that at sound absorption material is installed in the cavity.

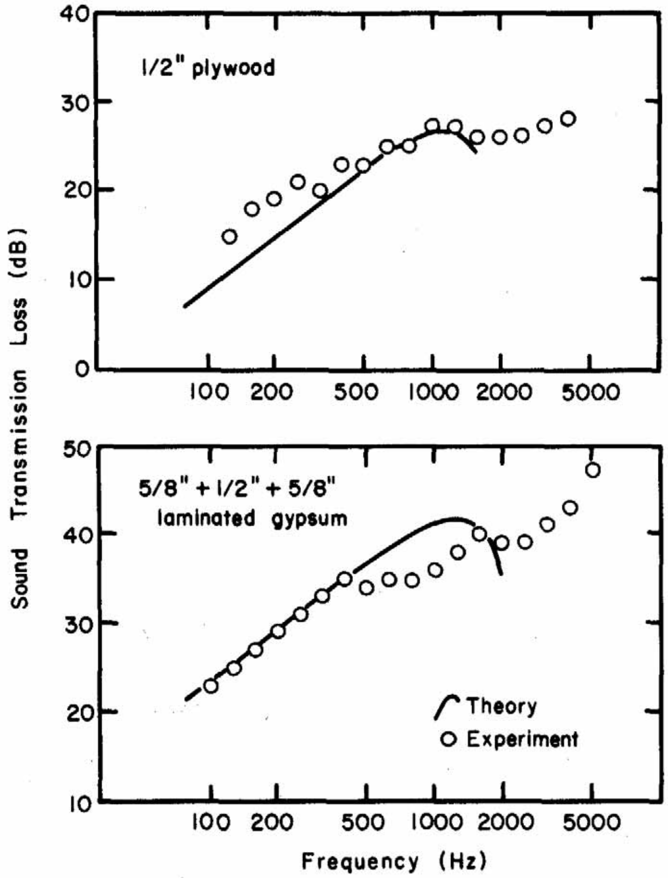


Figure 9.–Comparison of theory and measurement for anisotropic materials (theory does not strictly apply): Upper—Singlesheet of 1/2-inch-thick plywood; Lower—Three-layer gypsum board laminations, 5/8- + 1/2- + 5/8-inch thick. (ML84 5556)

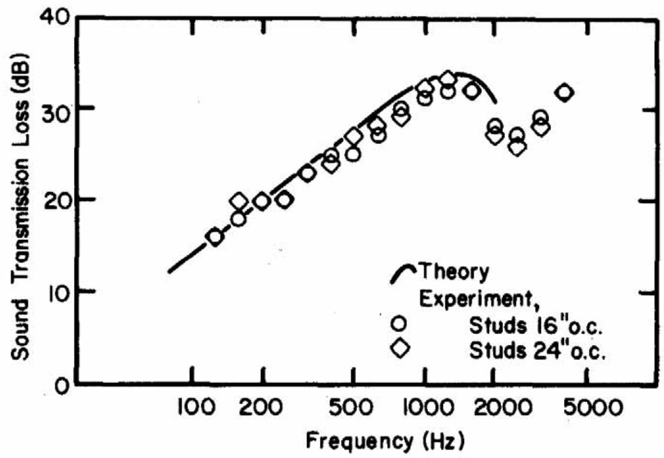


Figure 10.–Comparison of theory and measurement for a single panel of 5/8-inch-thick gypsum board supported by 2 x 4 studs spaced 16 and 24 inches o.c. Studs are assumed to be massless. (ML84 5554)

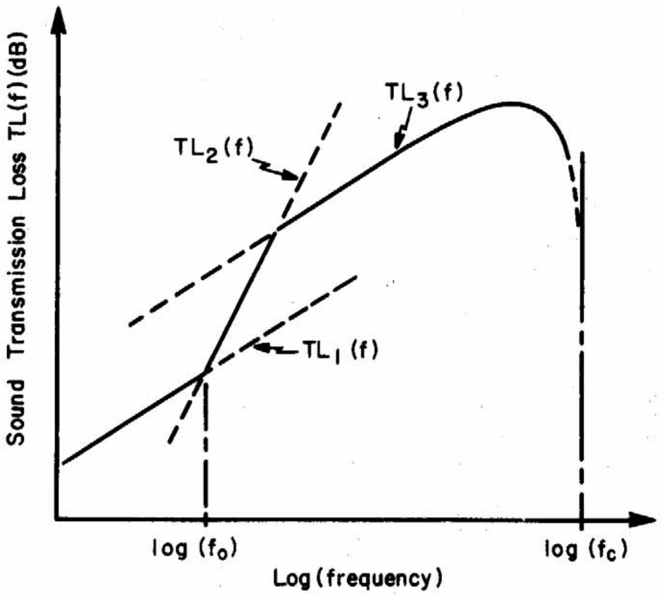


Figure 11.–Qualitative description of TL(f) for connected double-panel construction (prediction is indicated by solid curves). (ML84 5553)

Using Sharp's theory and comparing the predictions to the experimental data, it was necessary to incorporate a constant adjustment to the prediction equations to obtain better agreement. The basic prediction method and the functional relationships among the parameters, however, were unaltered. The prediction method (qualitatively represented in fig. 11) to estimate TL(f) requires the calculation of three functions: $TL_1(f)$, $TL_2(f)$, and $TL_3(f)$. $TL_1(f)$ and $TL_2(f)$ are linear functions of log(frequency) and intersect at London's frequency, f_o (see eq. (6)). $TL_1(f)$ is the low frequency estimate; $TL_2(f)$ is the high frequency estimate. The function $TL_3(f)$ is a linear function of log(frequency) as stated by Sharp's model but also incorporates an adjustment for the rapid decrease in TL(f) at frequencies near the critical frequency, f_c.

The prediction equations for these are:

$$TL_1(f) = 20 \log (f) + 20 \log (m_1 + m_2) + 20 \log (\pi/1.9\rho c) - 6 \quad \text{in dB, } f \leqslant f_o \quad (10a)$$

$$TL_2(f) = 60 \log (f) + 20 \log (m_1 m_2) + 20 \log (d) + \log [(\pi/1.9\rho c)^2 (4\pi/c)] - 6 \quad \text{in dB} \quad (10b)$$

$$TL_3(f) = 20 \log (f) + 20 \log (m) + 10 \log (b) + 10 \log (f_c) + 20 \log [1 - (f/f_c)^2] + 10 \log [(\pi/1.9\rho c)^2 (\pi/2c)] + 5 \quad \text{in dB} \quad (10c)$$

where m_1, m_2 are mass per unit area of panels on side 1 and side 2,

m is mass per unit area of the panel with the

b is stud spacing,

f_c is the higher critical frequency of the two panels.

Any consistent set of units may be used in equation (10). The low frequency function, $TL_1(f)$, indicates that the sound transmission loss is characterized by a "mass law" relationship based upon the total mass per unit area of the

equations (10a) and (10b) has been incorporated as a result of the present study to improve prediction agreement with experimental results. The function $TL_3(f)$ represents the sound transmission loss of the construction for the frequency range for which the mechanical coupling provided by the studs is important. The stud spacing, b, is an important parameter in this frequency range. The + 5 dB correction indicated in equation (10c) was determined by Sharp (1973) and the term containing the ratio f/f_c has been incorporated here to improve the prediction at frequencies near the critical frequency, f_c (Sewell 1970).

For SI or metric units, the above expressions become (ρc = 413 SI rayls, c = 344 m/s):

$$TL_1(f) = 20 \log (f) + 20 \log (m_1 + m_2) - 54 \quad \text{in dB} \quad (11a)$$

$$TL_2(f) = 60 \log (f) + 20 \log (m_1 m_2) + 20 \log (d) - 131 \quad \text{in dB} \quad (11b)$$

$$TL_3(f) = 20 \log (f) + 20 \log (m) + 10 \log (b) + 10 \log (f_c) + 20 \log [1 - (f/f_c)^2] - 66 \quad \text{in dB} \quad (11c)$$

where m_1, m_2, and m are in kg/m^2,

d and b are in meters.

For fps system of units, the prediction equations are (ρc = 84.6 fps rayls and c = 1,130 ft/s):

$$TL_1(f) = 20 \log (f) + 20 \log (w_1 + w_2) - 40 \quad \text{in dB} \quad (12a)$$

$$TL_2(f) = 60 \log (f) + 20 \log (w_1 w_2) + 20 \log (d) - 135 \quad \text{in dB} \quad (12b)$$

$$TL_3(f) = 20 \log (f) + 20 \log (w) + 10 \log (b) + 10 \log (f_c) + 20 \log [1 - (f/f_c)^2] - 69 \quad \text{in dB} \quad (12c)$$

where w_1, w_2, and w are in lb/ft[2],

d and b are in inches.

The above relationships are quite simple to apply in practice. One calculates the values of $TL_1(f)$, $TL_2(f)$, and $TL_3(f)$ and plots the individual functions. Since each of the functions is linear with log(frequency) if the f/f_c term in $TL_3(f)$ is ignored, the calculations may be limited to a few points. The term $20 \log [1 - (f/f_c)^2]$ in the expression for $TL_3(f)$ is significant only in the range $f_c/4 \leqslant f < f_c$ and may be calculated separately.

A comparison between prediction and experiment (DuPree 1981) for a 2 x 4 wood-stud partition with a 16-inch-on-center stud spacing and 1/2-inch-thick gypsum board panels, with and without cavity sound absorption (fig. 12), emphasizes that the prediction method applies only to connected double panels with cavity sound absorption material installed.

Figure 13 compares prediction and experimental data (DuPree 1981) for a 2 x 4 wood-stud construction with unequal distribution of panel thickness on each side. The prediction is based upon the assumption that the two 1/2-inch-thick gypsum board laminations behave as a single panel with twice the mass of one layer. As indicated in figure 9 (lower), laminated wall board may exhibit significant shear deformation and not behave as a single uniform panel. The present theory, however, does not allow for such details to be incorporated into the prediction. Additional comparisons are presented in Appendix D.

For the most part, the theoretical predictions in figures 12 and 13 and in Appendix D are in excellent agreement with the experimental data.

The theoretical model described above is one approach to the prediction of the sound transmission loss of connected double panels. Green and Sherry (1982) have taken an alternate approach based solely upon measurements. Their method predicts the sound transmission loss for each one-third-octave-band center frequency between 125 Hz and 4,000 Hz using the total surface density of the construction as the only variable. However, their approach does distinguish details of the panel attachment to the studs (screwed attachment or adhesive bonding) and the cavity filled or unfilled with sound absorptive material. Their method yields predictions consistent with the model presented above.

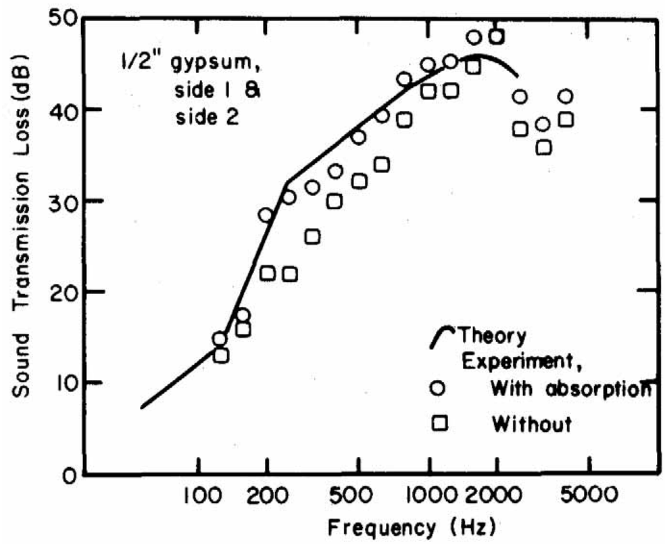


Figure 12.–Comparison of theory and measurement for a single-row-of-stud wall with 1/2-inch-thick gypsum board attached directly to each side of a 2 x 4 wood-stud frame 16 inches o.c., with and without cavity sound absorption (DuPree 1981). (ML84 5552)

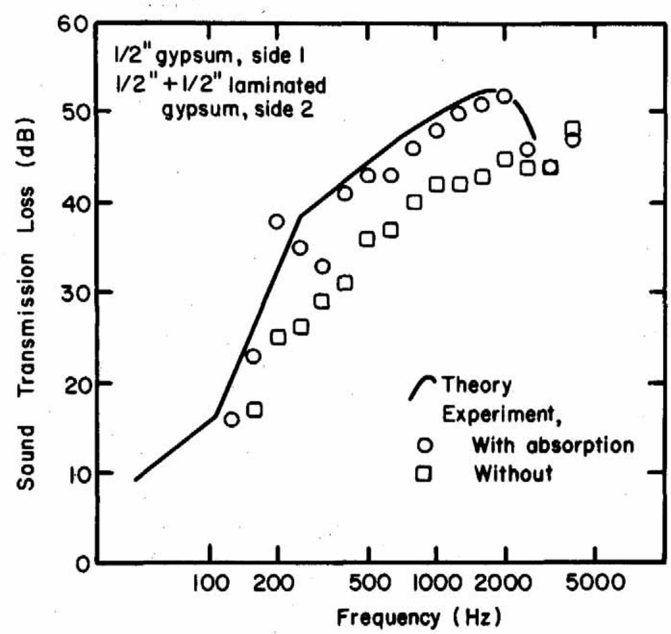


Figure 13.–Comparison of therory and measurement for a single-row-of-stud wall with unequal panels–one side is a two-layer lamination of 1/2-inch-thick gypsum board, the other side is one layer of 1/2-inch-thick gypsum board, both sides directly attached to 2 x 4 wood studs 16 inches o.c., with and without cavity sound absorption. (ML84 5551)

Unconnected Double Panels

The prediction of the sound transmission loss of unconnected double panels has received considerable attention in the literature (Gösele 1980; Heckl 1981; London 1950; Mulholland et al. 1967). Sharp has developed a design-oriented method for predicting the sound transmission loss of unconnected panels with sound absorption installed in the cavity (Sharp 1973). This method has been widely reported as an acceptable design method (Jones 1976; Rudder et al. 1982; Sharp 1978; Sharp et al. 1980). However, during the present study, comparisons between theoretical predictions with experimental data indicated that Sharp's method consistently overpredicted the sound transmission loss of this type of construction for much of the frequency range of interest. Generally, the differences between theory and experiment become significant above 200 Hz with 10- to 20-dB overprediction quite common. Figure 14 presents one such comparison for a staggered stud partition (note that the vertical scale is different from previous ones). The most disturbing aspect of this comparison is that the theory predicts that TL should increase at 12 dB per octave at high frequencies, and the experimental data indicate an increase of approximately 6 dB per octave. The average data presented in figure 2 also indicate this 6 dB per octave increase for construction with STC ratings above 50; as indicated in figure 3, the typical construction for STC greater than 50 is an unconnected double-panel construction.

Since unconnected double-panel light-frame construction is required to achieve high sound transmission loss performance, it was necessary to examine other prediction models to determine their accuracy (Gösele 1981; Heckl 1981; London 1950; Mulholland et al. 1967). All of these methods require extensive numerical calculations, but the method described by Mulholland et al. (1967) appeared to be the most appropriate model. Their model was extended to incorporate unequal thin panels on each side of the construction. To avoid extensive numerical integration, an approximate integration was developed to account for diffuse sound fields characterizing the experimental data. Physically, the approximate integration applies to unconnected double-panel construction *with sound-absorption material installed within the cavity*. Details of this approximate model are described in Appendix C.

The double-panel prediction model described in Appendix C is rather easily used to estimate the sound transmission loss as a function of frequency. The TL estimates are conducted on a point-by-point basis for the frequency range of interest below the lower critical frequency of the two panels. Since the model predicts the decrease in sound transmission loss at London's frequency, f_o, and the standing wave frequencies, f_ℓ (eq. (7)), the method provides a rather detailed description of the sound transmission loss performance of the construction.

To use the method described in Appendix C, one first predicts the normal incidence sound transmission loss, $TL_o(f)$, at the desired frequencies using equation (C-10a) for $\theta = 0$. The sound transmission loss for a diffuse sound field is then estimated using the relationship:

$$\overline{TL}(f) = TL_o(f) + \Delta\overline{TL}(f) \quad \text{in dB} \qquad (13)$$

where $\Delta\overline{TL}(f)$ is a function of $TL_o(f)$ as tabulated in table C-1 and illustrated in figure C-3. The function $\Delta\overline{TL}(f)$ is the diffuse sound field correction obtained by an integration over angle of incidence. This correction, however, applies only for double panels with sound absorption treatment in the cavity. The use of this model is illustrated here by comparisons of predictions to experiment.

Figure 14 shows the predicted values of $\overline{TL}(f)$ using equation (13). Over the frequency range of 125 Hz to 1,600 Hz, the prediction using equation (13) is in close agreement with the experimental data. Both of the predictions illustrated in figure 14 are based upon 5/8-inch-thick gypsum board panels weighing 2-1/2 pounds per square foot; panel separation is 5-5/8 inches. The predictions and the experimental data are also presented in table 1. The measured values presented in table 1 are from DuPree (1981). The data include the effectiveness parameter characterizing the cavity sound absorption. Physically, this parameter represents the cavity reflection coefficient as described in Appendix C.

Appendix D presents additional comparisons of predictions and measurements for double-panel construction. For each of these predictions using the present method, the cavity reflection coefficient has been taken equal to 1 for frequencies below 250 Hz and equal to 0 for frequencies above 250 Hz.

In each of these comparisons, the prediction method described in Appendix C yields a reasonable estimate of the sound transmission loss of unconnected double-panel construction. This estimate applies to the frequency range below the lower critical frequency of the two panels.

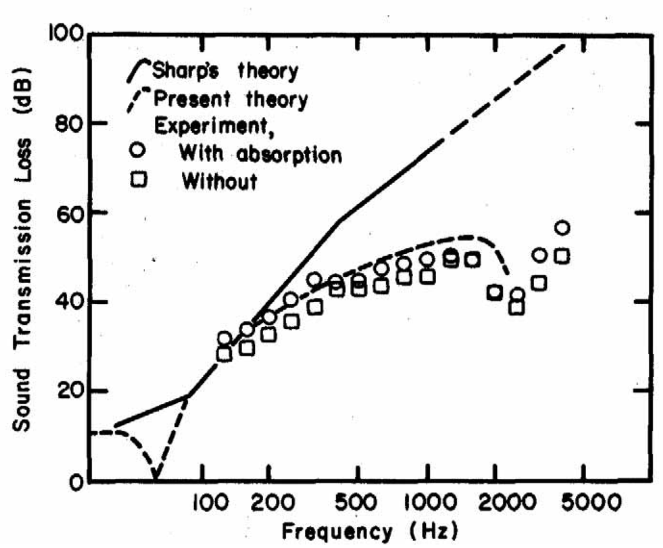


Figure 14.– Comparison of Sharp's theory, our theory, and measurement for a double-row staggered-stud wall with a single layer of 5/8-inch-thick gypsum board attached directly to 2 x 4 wood studs 16 inches o.c., staggered 8 inches o.c. on a 2 x 6 plate, with and without cavity sound absorption. (ML84 5555)

Table 1.—Predictions and measurements for data in figure 14 for the one-third-octave-band frequencies between 125 Hz and 4,000 Hz

f	Cavity reflection coefficient, r	Present method			Sharp's (1978) method	Measurements (DuPree 1981)	
		$TL_o(f)$ (Eq. (C-10a))	$\Delta\overline{TL}(f)$ (Fig. C-3)	$\overline{TL}(f)$ (Eq. (13))	TL(f)	With cavity absorption	Without cavity absorption
Hz							
125	1	36.1	- 8.4	27.7	27.7	32	29
160	1	43.5	- 10.8	32.7	30.4	34	30
200	1	49.7	- 12.9	36.8	36.2	37	33
250	0	54.5	- 14.7	39.8	42.0	41	36
315	0	58.4	- 16.2	42.2	48.0	45	39
400	0	62.3	- 17.7	44.6	54.2	45	43
500	0	66.0	- 19.3	46.7	60.0	45	44
630	0	69.5	- 20.6	48.9	65.6	48	44
800	0	73.0	−22.1	50.9	69.7	49	46
1,000	0	75.7	−23.0	52.7	73.6	50	46
1,250	0	77.6	−23.9	53.7	77.5	51	50
1,600	0	77.7	−23.9	53.8	(81.8)	50	50
2,000	0	73.0	- 22.2	50.8	(85.6)	43	43
2,500	–	–	–	–	(89.5)	42	39
3,150	–	–	–	–	–	51	45
4,000	–	–	–	–	–	57	51

Conclusions

The research described in this report focuses on the characterization of the airborne sound transmission loss of wood-frame construction. Two separate approaches have been used. First, an empirical approach has been used to obtain certain average sound transmission loss characteristics, which are described and illustrated in the main text and Appendix A. Second, prediction models have been developed to characterize the sound transmission loss of wood-frame construction. These methods are described and the predictions are compared to measurements. The comparisons indicate that the prediction models developed as a result of this research represent an improvement over previously available methods.

The two approaches to characterization of the airborne sound transmission loss have direct application to the selection or the design of light-frame construction. Using distributions such as presented in figures 1 and 4, it is rather easy to determine both the range and the design options (as a percentage of total designs) of airborne sound transmission loss of wood-frame construction. The prediction methods allow the user to estimate the sound transmission loss characteristics for detailed design variations. The methods are easily utilized, and since they are more accurate than methods previously available, the methods represent an advancement in the design of light-frame construction to achieve higher levels of sound insulation.

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Appendix A
Mean Values, Standard Deviations, and Data Envelopes for Wood-Frame TL Data Grouped by STC Interval

This appendix presents additional detail for each of the mean curves in figure 2 for partitions and in figure 5 for floor-ceiling assemblies. All data are from DuPree (1981).

Wood-Frame Interior Partitions

Figure A-1 presents the mean values and data envelopes of the sound transmission loss data for wood-frame interior partitions at each one-third-octave-band center frequency from 125 Hz to 4,000 Hz. The envelope curves for the sound transmission loss data do not necessarily correspond to any specific design included in the data subset. The standard deviation of the TL data (denoted by S.D. in these figures) is expressed in dB and has been adjusted for sample size or number of specific designs included in each subset. Figure A-2 is a similar presentation based upon one-half-octave-band TL data.

Wood-Joist Floor-Ceiling Assemblies

Figure A-3 plots the mean values, data envelopes, and standard deviations for wood-joist floor-ceiling assemblies. The mean curves illustrated in figure A-3 are those from figure 5 for the one-third-octave-band TL data of DuPree (1981). Figure A-4 shows corresponding summaries for his one-half-octave-band TL data.

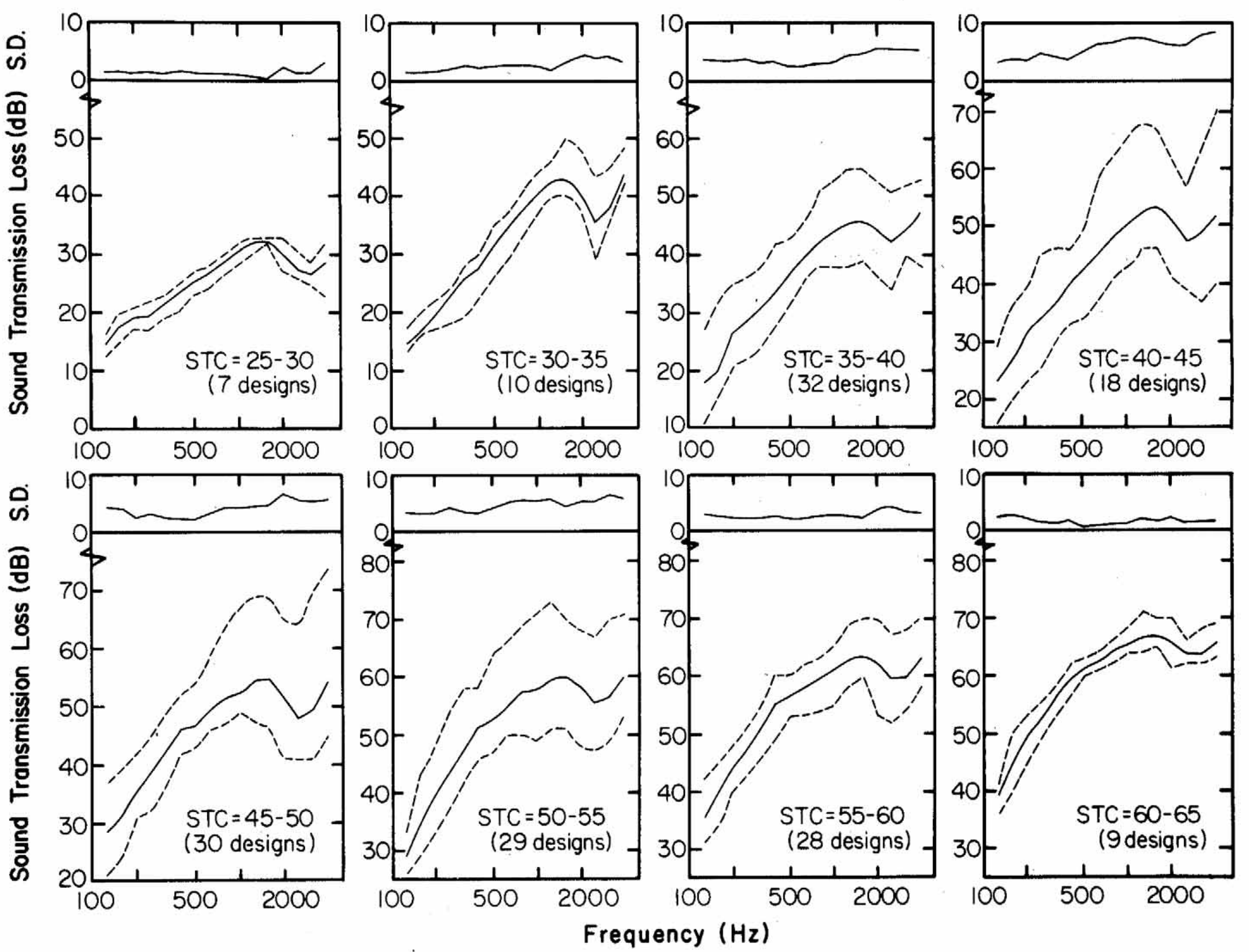

Figure A-1 .–Mean values, data envelopes, and standard deviations of one-third-octave-band sound transmission loss for wood-frame interior partitions at eight STC rating intervals.
(ML84 5574)

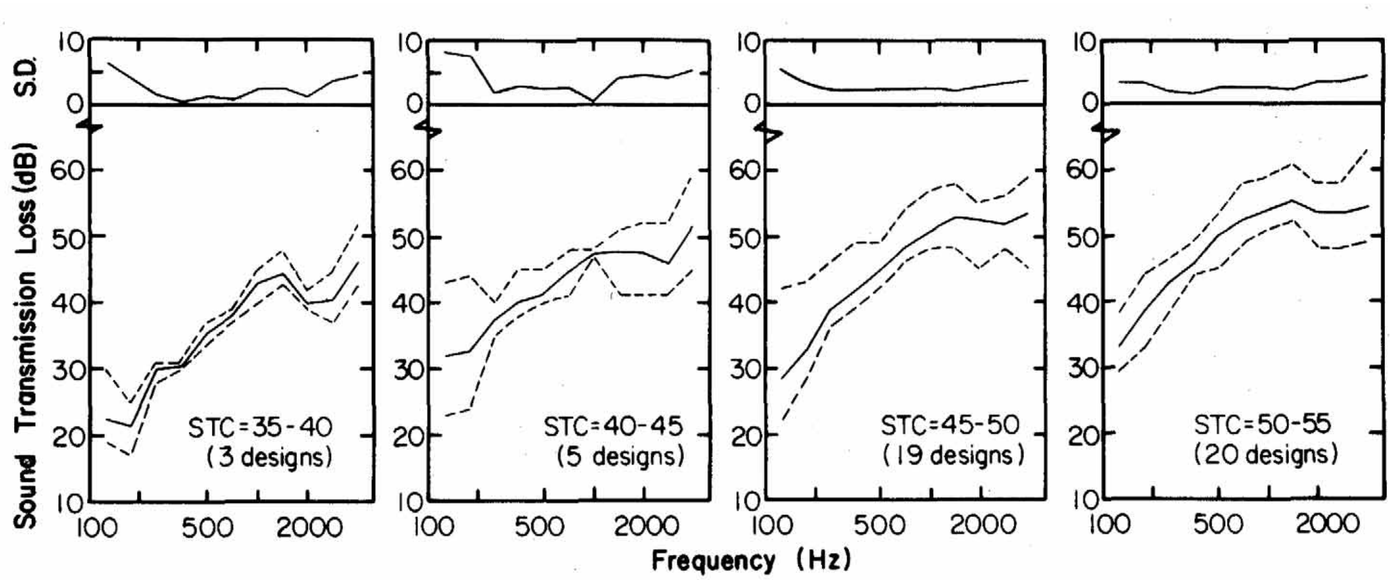

Figure A-2.–Mean values, data envelopes, and standard deviations of one-half-octave-band sound transmission loss for wood-frame interior partitions at four STC rating intervals.
(ML84 5572)

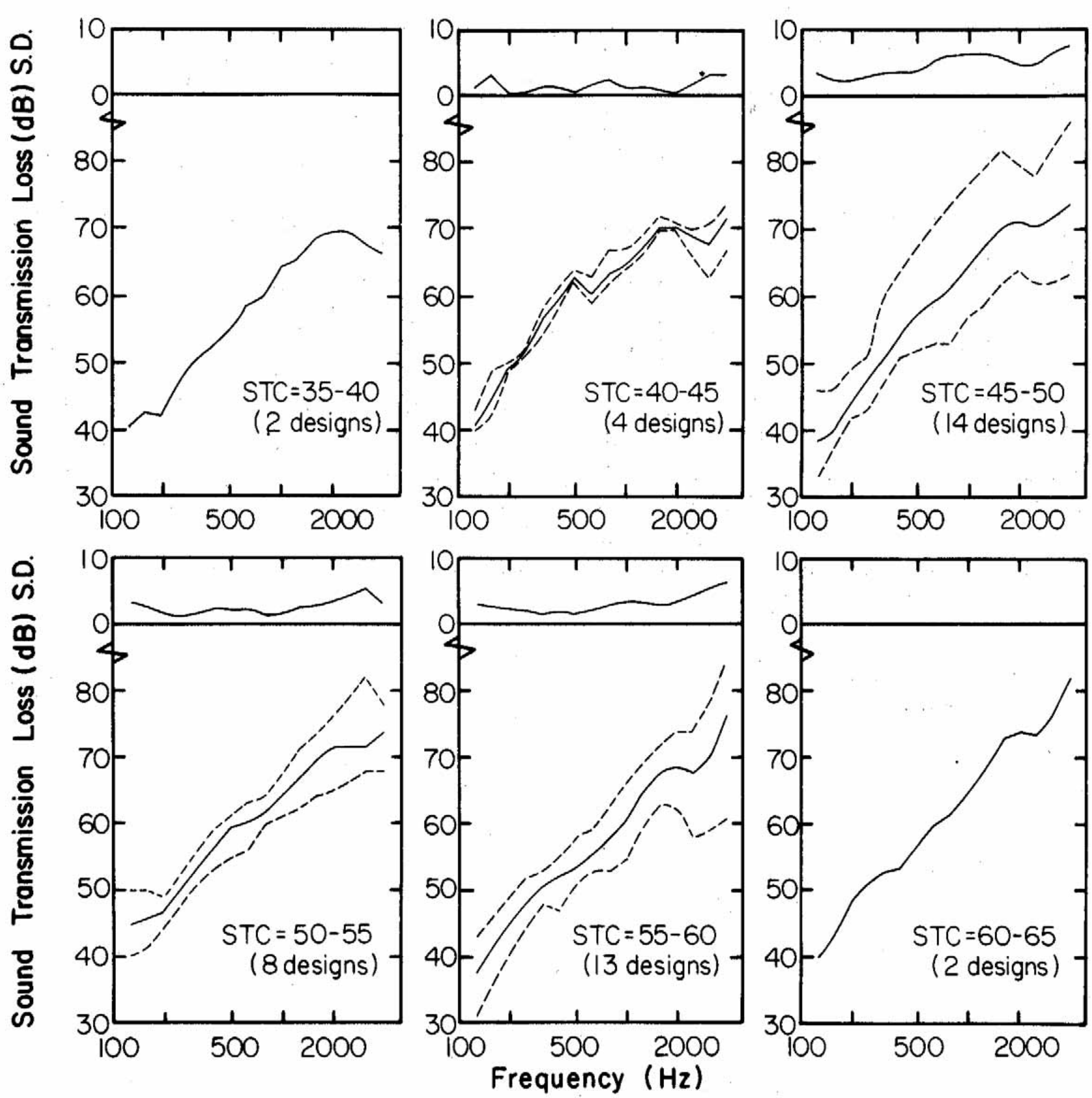

Figure A-3.–Mean value of one-third-octave-band sound transmission loss for wood-joist floor-ceiling assemblies for six STC rating intervals. (ML84 5573)

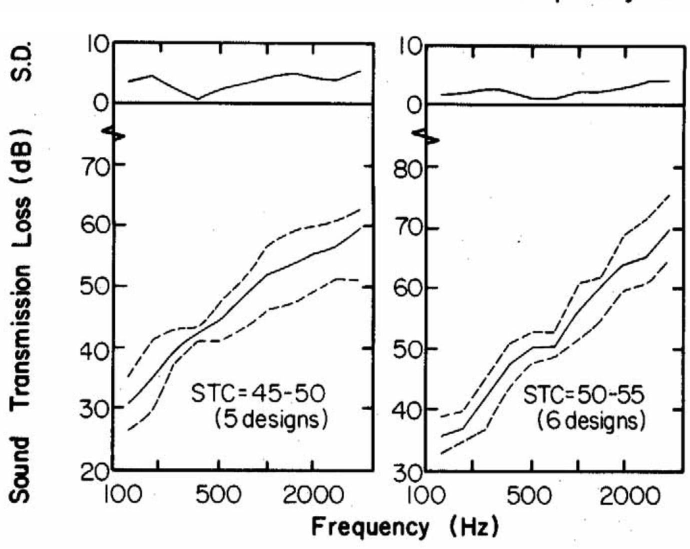

Figure A-4.–Mean values, data envelopes, and standard deviations of one-half-octave-band sound transmission loss for wood-joist floor-ceiling assemblies for two STC rating intervals. (ML84 5562)

Appendix B
Data for Common Building Materials

These data for common building materials (Rudder et al. 1981) may be used in connection with the prediction methods described in this report. Additional data of a similar nature is contained in Heckl (1981).

For any particular material, the critical frequency, f_c, may be estimated using the data in table B-1. The values of the critical frequency listed in table B-2 are the one-third-octave-band center frequency of the band containing the critical frequency.

Table B-1.–Data for common building materials

Material	Density	wf_c[1]
	Lb/ft³	Hz · *lb/ft²*
Concrete[2]	150	9,000
Brick	120-140	7,000-12,000
Glass	156	7,800
Gypsum board	48	6.300

[1]w = surface weight of thin panel, lb/ft².

[2]Density of concrete depends upon aggregate.

Table B-2.–Measured values of transmission loss for a number of conventional building materials (Rudder et al. 1981)

Construction	Surface weight	Critical frequency	Transmission loss at one-third-octave-band center frequencies (Hz) of																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
	Lb/ft²	*Hz*[1]	*db*																	
Gypsum board																				
1/4 in.	1.0	6,300	7	9	10	12	14	16	17	19	21	23	25	27	28	30	32	33	32	25
3/8 in.	1.5	4,000	10	12	14	16	17	19	21	23	26	27	29	30	32	33	33	29	25	28
1/2 in.	2.0	3,150	12	15	17	18	20	22	24	25	27	28	31	32	33	33	29	25	27	31
5/8 in.	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
Gypsum board lamination																				
1/4 in. + 1/4 in.[2]	2.0	5,000	13	15	17	19	20	22	24	26	27	29	31	32	34	35	36	37	37	33
1/2 in. + 1/2 in.[2]	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
1/2 in. + 5/8 in.[3]	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	40
5/8 in. + 1/2 in. + 5/8 in.[3]	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
Hardboard																				
1/8 in.	.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 in.	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
Reinforced concrete[4]																				
2 in.	24	630	34	35	36	38	37	36	38	39	41	43	46	49	51	52	54	56	58	59
4 in.	48	315	39	42	42	42	42	43	43	46	50	53	54	55	57	59	60	64	66	68
6 in.	72	200	39	39	42	42	42	46	48	50	53.5	55.5	58	60	62	64	64	66	68	70
Plywood[5]																				
1/2 in.	1.4	1,250 to 2,500		15	18	19	21	20	23	23	25	25	27	27	26	26	26	27	28	

[1]Center of the one-third-octave band within which the critical frequency lies.

[2]Spot laminations–12 in. o.c.

[3]Spot laminations–24 in. o.c.

[4]Assuming a density of concrete of 144 lb/ft³. This will vary according to the aggregate.

[5]From FPL files.

Appendix C
Sound Transmission Loss Prediction for a Double-Panel Wall

The prediction method described here was developed as an approximation technique for estimating the sound transmission loss of double panels without resorting to extensive numerical integrations. For the approximation to be valid, it is necessary to assume that sound absorption treatment is present within the cavity between the double panels. However, we believe that the present model could also be applied to double panels without cavity sound absorption treatment if numerical integration is used in the frequency domain.

The model described in the text assumes a forced vibration response of the panels covering the framework. This assumption restricts the frequency range to which the model applies. This restriction is based on the assumption that panels are to be thin and of infinite extent. For the panels to be considered thin, the bending wavelength of the forced vibration is at least six times the panel thickness. For the panels to be considered to be of infinite extent, the lateral dimensions must be much greater than the bending wavelength of the forced vibration. Further, it is assumed that the panels are of constant thickness and the panel material is homogeneous and isotropic.

Basic Theory

The sound transmission loss or TL of the construction is defined in terms of the sound transmission coefficient, τ, as:

$$TL \equiv -10 \log(\tau) \quad \text{in dB} \tag{C-1}$$

The sound transmission coefficient is a function of both the angle of incidence of the sound field and the frequency. (The angle of incidence, θ, is measured from the normal to the plane of the panel.) Since the incident sound field is composed of waves arriving at possibly a range of both angles and frequencies, it is necessary to average both the incident and the transmitted intensities over both frequency and angle of incidence. At a fixed frequency the incident intensity, $I(\theta)$, establishes both the average incident intensity, I_n (subscript n denotes the normal to the panel), and the average transmitted intensity, I_t (subscript t denotes transmitted). The average sound transmission coefficient, $\bar{\tau}$, is then defined as:

$$\bar{\tau} \equiv I_t/I_n \tag{C-2}$$

and the average sound transmission loss is defined as:

$$\overline{TL} \equiv -10 \log(\bar{\tau}) \quad \text{in dB} \tag{C-3}$$

The average incident intensity and the average transmitted intensity are defined, respectively, as:

$$I_n \equiv \int_\Omega I(\theta) \cos\theta \, d\Omega \tag{C-4}$$

and

$$I_t \equiv \int_\Omega \tau(\theta) I(\theta) \cos\theta \, d\Omega \tag{C-5}$$

The integrations indicated in equations (C-4) and (C-5) are over the hemispherical solid angle ($d\Omega = \sin\theta d\theta d\phi$: $0 \leqslant \phi \leqslant 2\pi$; $0 \leqslant \theta \leqslant \pi 2$).

For a diffuse incident sound field, $I(\theta)$ is independent of direction ($I(\theta) = p^2/4\rho c$) and the expression for the average sound transmission coefficient given by equation (C-2) is:

$$\bar{\tau} = \int_0^{\theta_l} \tau(\theta) \sin(2\theta) d\theta / \sin^2 \theta_l \tag{C-6}$$

The angle θ_l is an empirical limit for the integration. If the sound field is truly diffuse, then $\theta_l = \pi/2$ radians or 90°. However, based on laboratory measurements of the sound transmission loss for a wide range of construction, it appears that an empirical value of θ_l is in the range of 78° to 85°. The only difficulty in applying equation (C-6) is that numerical integration is generally necessary to evaluate $\bar{\tau}$ since $\tau(\theta)$ is usually a complicated function of θ. The average sound transmission loss for the diffuse sound field is obtained using equation (C-3).

Approximation of $\bar{\tau}$

To obtain an estimate of the average sound transmission coefficient, an approximation to the required numerical integration was developed. This approximation is based on the shape of the TL function with angle of incidence, θ, at a fixed frequency below the critical frequencies of the panels. Based on numerical studies, it appears that the shape of the TL function with angle of incidence may be approximated by an elliptical curve. This approximate shape appears to be reasonable for thin single panels and unconnected thin double panels with sound-absorptive treatment in the cavity. Using this approximate shape, the sound transmission coefficient may be expressed as:

$$\tau(\theta) \cong e^{-a\sqrt{b^2 - \theta^2}} \qquad 0 \leqslant \theta \leqslant \theta_l \tag{C-7}$$

where $a = \ell n(10) TL_o/(5\pi)$,

$b = \pi/2$ radians.

The normal incidence sound transmission loss, TL_O, at the given frequency is obtained from $\tau(\theta = 0)$ using the appropriate expressions given below.

The degree of approximation may be judged by the comparisons given in plots of the ratio $TL(\theta)/TL_O$ for the mass law relationship for a thin single panel and for a double panel (fig. C-1). The elliptical shape appears to be reasonable for the single-panel construction and for the double-panel construction with cavity-sound-absorptive treatment.

Substituting the approximate expression for $\tau(\theta)$ given in equation (C-7) into equation (C-4), the average value of the sound transmission coefficient is approximated as:

$$\bar{\tau} \cong \int_0^{\theta_l} \sin(2\theta) e^{-a\sqrt{b^2 - \theta^2}} d\theta / \sin^2 \theta_l \tag{C-8}$$

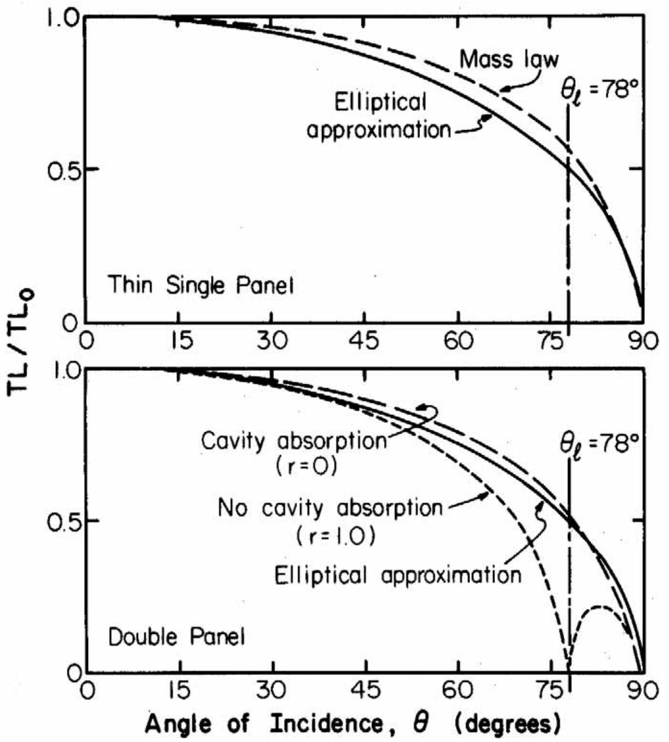

Figure C-1.–Plot of TL/TL_o versus angle of incidence, θ, for single thin panel mass law, and for double-panel mass law. (ML84 5563)

which is a function of TL_o and θ_l.

The integral in equation (C-8) must also be evaluated numerically; however, for a fixed value of θ_l, equation (C-8) defines a functional relationship between the normal incidence sound transmission loss, TL_o, and the sound transmission loss averaged overangle of incidence. Hence, an adjustment term is defined, $\Delta\overline{TL}$, which, when added to the normal incidence sound transmission loss, TL_o, provides an estimate of the average sound transmission loss, $\overline{TL}$. The adjustment is, simply,

$$\Delta\overline{TL} = -10\log(\overline{\tau}) - TL_o \qquad \text{(C-9)}$$

where $\overline{\tau}$ is given by equation (C-8) numerically evaluated for θ_l and TL_o.

The usefulness of this approach is that $TL_o(f)$ is easily calculated for a specific panel design and the numerical integration for $\overline{\tau}$ (eq. (C-8)) is easily tabulated as a function of TL_o and θ_l. Using equation (C-9), $\Delta\overline{TL}$ may then be tabulated as a function of TL_o and θ_l. Hence, to estimate the diffuse sound field performance, it is only necessary to add the adjustment, $\Delta\overline{TL}$, to the value of TL_o at each frequency. Table C-1 is a listing of the numerical values of $\Delta\overline{TL}$ for a range of TL_o values with θ_l = 78°. Figure C-2 is the plot of $\Delta\overline{TL}$ versus TL_o. Since θ_l = 78° is a commonly used value for the limiting angle, table C-1 or figure C-2 may be used to determine the value of $\Delta\overline{TL}$ and the sound transmission loss for diffuse sound field conditions.

For single-panel construction, the approximation is somewhat academic since the integration indicated in equation (C-6) may be explicitly evaluated. For double-panel construction, however, the approximation is useful since it is not possible to explicitly evaluate the integral, and one must resort to numerical integration for each structural configuration.

Sound Transmission Coefficient

Using the approach of Mulholland and coworkers (1967) for modeling the forced vibration of a double-panel construction, the expression for the sound transmission coefficient at frequencies below the critical frequency is:

$$\tau(\theta) = [R_\theta^2 + I_\theta^2]^{-1} \qquad \text{(C-10a)}$$

where $$R_\theta = 1 - \overline{\Omega}_1\overline{\Omega}_2[1 - r^2\cos(2\pi(f/f_\ell)\cos\theta)], \qquad \text{(C-10b)}$$

$$I_\theta = \overline{\Omega}_1 + \overline{\Omega}_2 - r^2\,\overline{\Omega}_1\overline{\Omega}_2\sin(2\pi(f/f_\ell)\cos\theta), \qquad \text{(C-10c)}$$

where

$\overline{\Omega}_i = \Omega_i\cos\theta$; $\Omega_i = (\pi m_i/\rho c)f(1 - \beta_i^2)$; i = 1, 2;
$\beta_i = f/f_{ci}$; f_{ci} = critical frequency of the i^{th} panel;

$f_\ell = c/2d$; c = speed of sound; d = panel separation.

Table C-1.–Values of $D\overline{TL}$ for 0l = 78°

TL_o	$D\overline{TL}$	TL_o	$D\overline{TL}$
0	0	40	- 9.64
2.5	−0.40	45	−11.33
5.0	- 0.83	50	- 13.10
7.5	- 1.28	55	- 14.95
10.0	- 1.75	60	- 16.86
12.5	- 2.26	65	- 18.84
15.0	- 2.79	70	- 20.86
17.5	- 3.34	75	- 22.92
20.0	- 3.93	80	- 25.02
22.5	- 4.54	85	- 27.16
25.0	−5.19	90	−29.32
27.5	−5.86	95	−31.50
30.0	- 6.56	100	−33.71
32.5	−7.29	105	−35.93
35.0	- 8.05	110	- 38.17
37.5	- 8.83	115	- 40.43

The sound transmission coefficient for a single-panel construction is obtained by setting one of the panel masses, m_i, in equations (C-10a) through (C-10c) equal to 0. For any frequency and angle of incidence, equation (C-10a) may be easily evaluated for the physical parameters of a given problem. The parameter r in equations (C-10b) and (C-10c) attempts to account for the effect of sound absorption in the cavity between the two panels and is a function of frequency ($r = 1 - \bar{\alpha}$, where $\bar{\alpha}$ is the average sound absorption coefficient of the cavity material).

Effect of Cavity Sound Absorption

The physical effect of introducing sound absorption into the cavity of a double panel is to damp the standing waves within the cavity and increase the sound transmission loss of the construction for the frequencies and angles of incidence at which standing waves occur. Using numerical integration, Mulholland claims good agreement between the above theory and experiment. (Mulholland's model is restricted to double panels with identical panels on each face, whereas the above theory is extended to incorporate dissimilar panels.) Based upon Mulholland's numerical studies, the present model may be expected to yield reasonable estimates even for double-panel construction without cavity sound absorption (i.e., $r = 1$). However, the approximation indicated by equation (C-7) does not apply for the frequency range $f_l<f<f_c$ for double panels without cavity sound absorption. The approximation is valid for frequencies less than the standing wave frequency, f_1, since the cavity sound absorption is generally very small either with or without sound absorption material within the cavity.

In view of the above discussion, it is necessary to reinterpret the parameter r when using the approximate numerical integration leading to the adjustment term, $\Delta\overline{TL}$, given by equation (C-9). The present model applies only to double panels with cavity sound absorption treatment. At low frequencies ($f<f_l/2$), the sound absorption material is essentially ineffective and $\bar{\alpha} = 0$ or $r = 1$. At frequencies greater than $f_l/2$, the sound absorption material is assumed to be fully effective and $\bar{\alpha} = 1$ or $r = 0$. This reasoning is the basis for the design equations presented in the text.

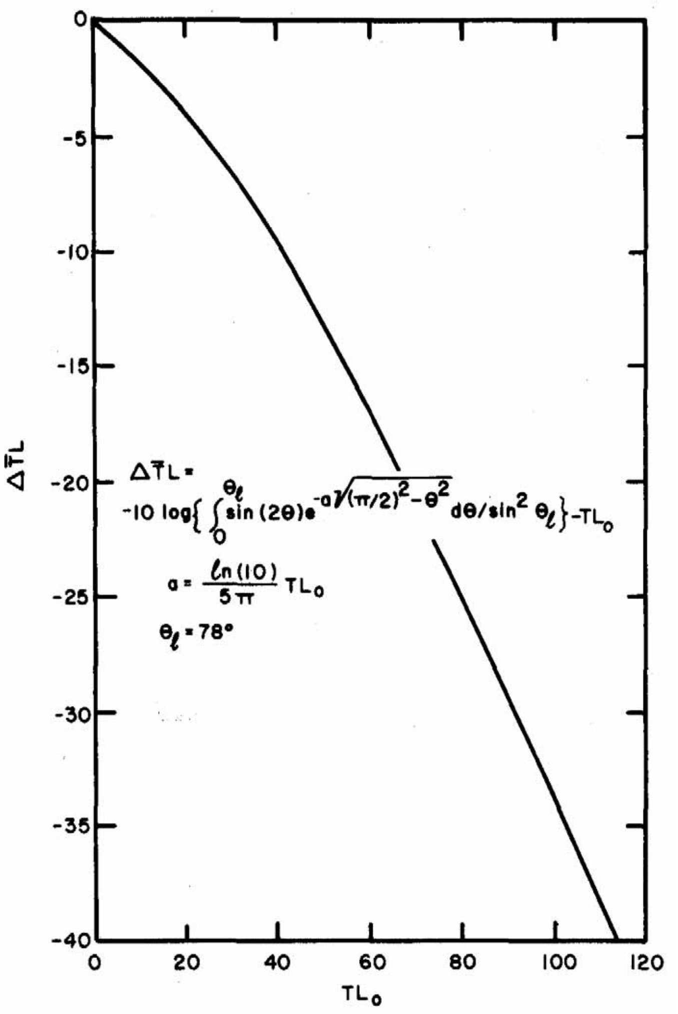

Figure C-2.–Plot of $\Delta\overline{TL}$ versus TL_o for $\theta_1 = 78°$. (ML84 5564)

Connected Double Panels

The above theory applies to double-panel construction with unconnected panels such as double-row-of-stud construction. If the two panels are both connected to a single row of studs, the sound transmission loss of the construction will be less than that for the unconnected double-panel configuration. The degradation is usually attributed to the presence of "sound bridges" formed by the studs connecting the two faces or panels. This connection results in a more direct transmission path for the forced panel vibration than that realized for unconnected double panels.

By incorporating resilient metal channels into one side of the construction, one attempts to decouple the direct transmission of vibration and hence reduce the reradiated sound in order to retain the higher sound transmission loss characteristics of the unconnected double-panel construction. Prediction methods have been developed that attempt to incorporate various detail connection methods related to sound transmission loss characteristics (Sharp 1978; 1980). These prediction methods are generally unverified except for the case of direct connection of the two panels to the studs. As a result, the prediction methods described in the text are limited to double-panel construction without resilient connections between the studs and the panels.

Appendix D
Additional Comparisons of TL Predictions with Measurements

These additional comparisons of the theoretical prediction of sound transmission loss and the laboratory-measured values presented in DuPree (1981) are for both connected and unconnected double panels.

Connected Double Panels

Figure D-1 is comparisons of the predicted sound transmission loss with measured data for the indicated double-panel construction. The predictions are based upon equations (10), (11), and (12), depending upon the physical units one wishes to use. Figure D-1 (upper) may be compared with figure 12 since each construction is 2 x 4 wood studs 16 inches on center with the figure 12 data corresponding to 1/2-inch-thick gypsum board and figure D-1 (upper) corresponding to 5/8-inch-thick gypsum board.

Figure D-1 (central) may also be compared to figure 12 since the variation in this case is the stud spacing. Similarly, figures D-1 (upper) and (lower) may be compared since the variation is stud spacing with 5/8-inch-thick gypsum board panels attached directly to each side of the wood frame.

Unconnected Double Panels

Figure D-2 is comparisons of the predicted sound transmission loss with the measured data for studless constructions with a variety of gypsum board combinations. The predictions are based on equation (13) and the results of Appendix C.

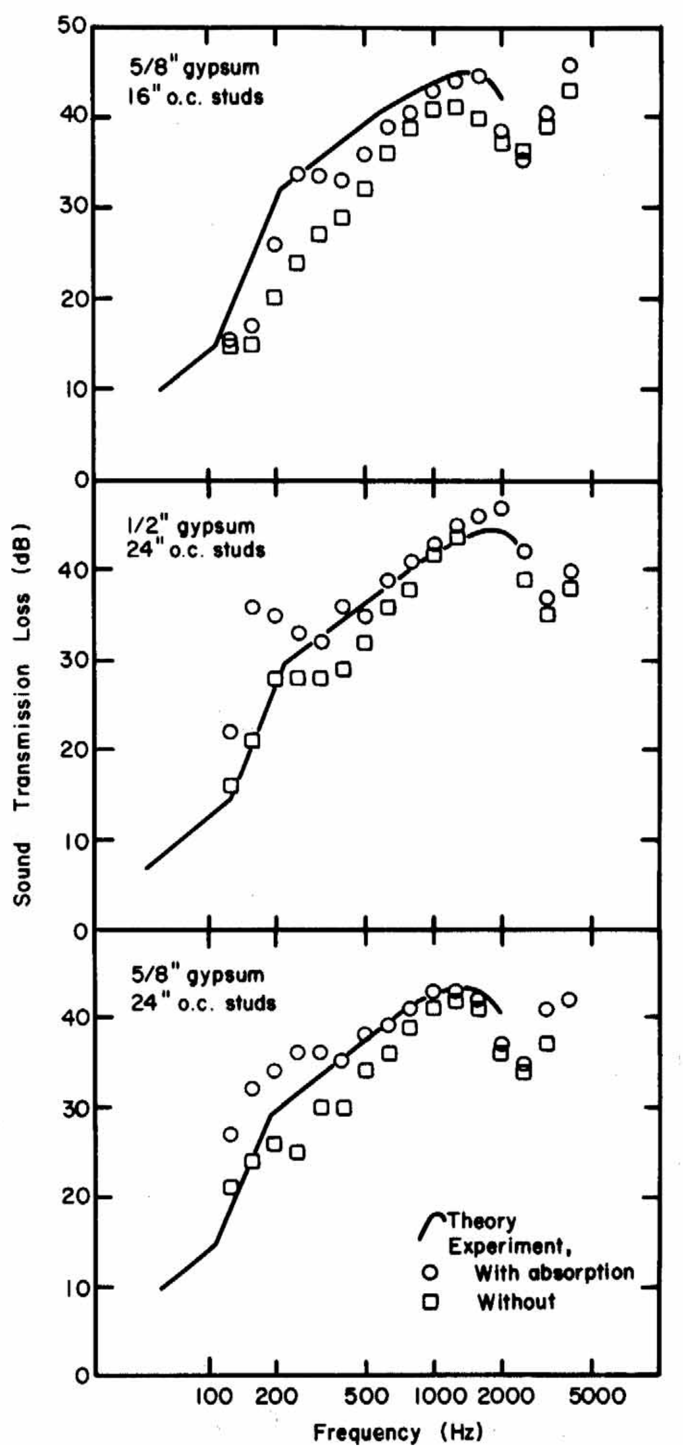

Figure D-1.–Comparison of theory and measurement for a single-row-of-stud wall with gypsum board attached directly to each side of a 2 x 4 wood-stud framework:
Upper–5/8-inch-thick gypsum board on each sid of studs 16 inches o.c.
Central–1/2-inch-thick gypsum board on each side of studs 24 inches o.c
Lower–5/8-inch-thick gypsum board on each side of studs 24 inches o.c. (ML84 5565)

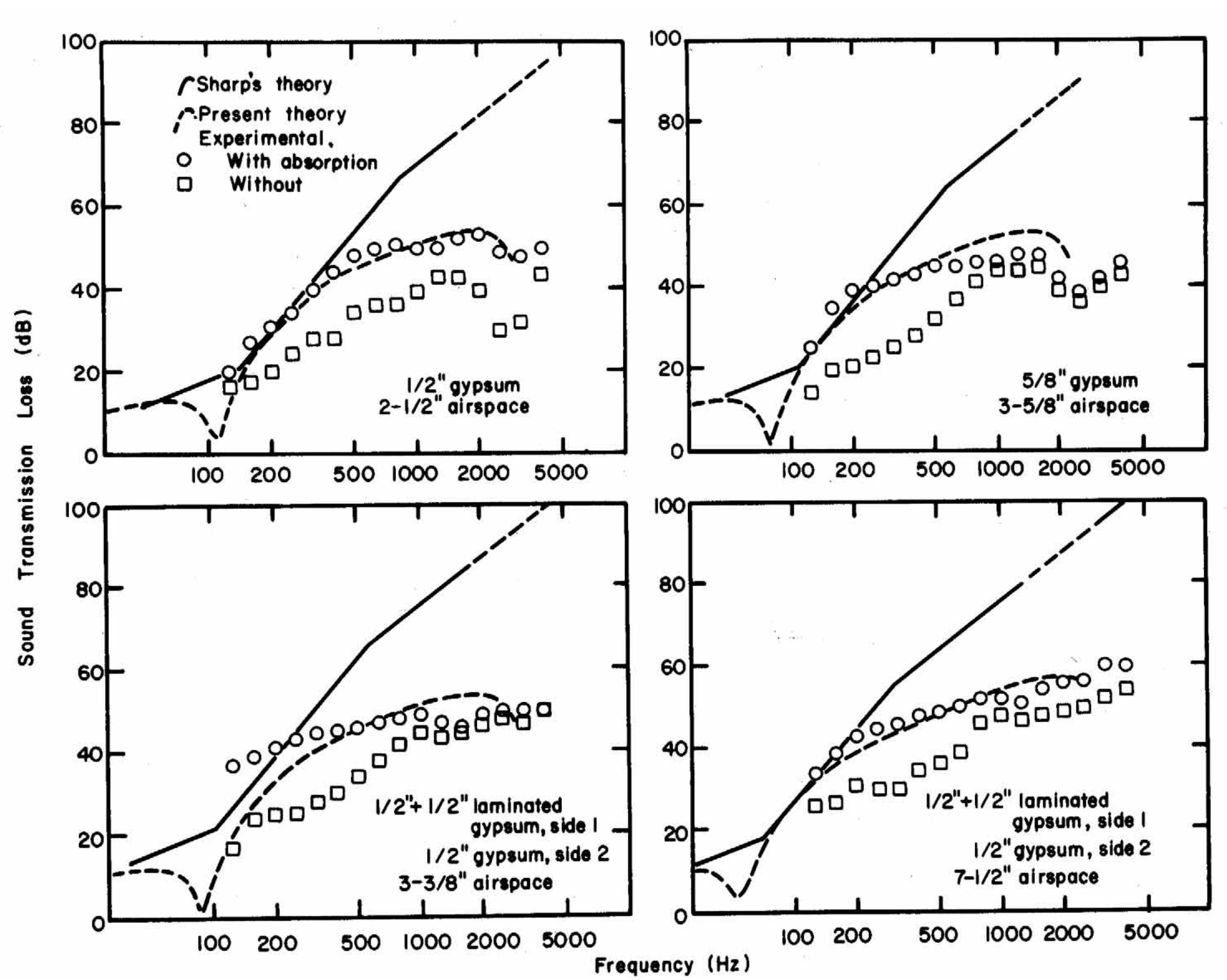

Figure D-2.–Comparison of theories and measurements for studless double-panel construction with gypsum board and airspace combinations with and without cavity sound absorption:
Upper left–l/2-inch-thick gypsum board panels separated by a 2-1/2-inch airspace,
Upper right–5/8-inch-thick gypsum board panels separated by a 3-5/8-inch airspace,
Lower left–Two layers of 1/2-inch-thick gypsum board on one side of a 3-5/8-inch airspace, and one layer of 1/2-inch-thick gypsum board on the other,
Lower right–Two layers of 1/2-inch-thick gypsum board on one side of 7-1/2-inch airspace, and one layer of 1/2-inch-thick gypsum board on the other. (ML84 5569)

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Unanswered questions remain and new ones will arise because of changes in the timber resource and increased use of wood products. As we approach the 21st Century, scientists at the Forest Products Laboratory will continue to meet the challenge posed by these questions.

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