

Sound Insulation Evaluation Of High-Performance Wood-Frame Party Partitions Under Laboratory And Field Conditions



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ABSTRACT

Several building codes require airborne and impact sound Insulation of Sound Transmission Class (STC) and impact insulation Class (IIC) ≥ 50 , 5 points higher than minimum property standards. This report describes lab and field data for wood-frame party walls and floors well in excess of the higher requirements. To explain and justify the high transmission loss (TL) performance, a combination of recent improvements in approximate TL theory and lab-field technologies is used. This combination proves a powerful tool in providing new insights into previous and current data. An abbreviated summary of these technologies is provided in the appendix.

Three types of partition design were studied:

1. Three double-row-of-stud walls (absorption in cavities) with gypsum board faces gave lab STC = 55 to 63 (significantly higher than some reported data) depending on the wall thickness and single or double layers of gypsum board. Field data for the STC = 55 design gave an average FSTC = 48, more than the 5 points below lab STC allowed by some codes.

2. Double-row-of-stud walls with center layers were evaluated in the field. These walls performed well below their potential without a center layer, as suggested by theory.

3. Lab tests of two floor designs gave STC = 55 to 58, with the higher value corresponding to absorption in the joist cavity. Field FSTC data were equal or better (by 2 points) showing an unexpected absence of flanking. Impact sound insulation of the floors with carpet and pad was in excess of IIC = 65.

Several new conclusions on the technology of lab-field correlations are summarized.

SOUND INSULATION EVALUATION OF HIGH-PERFORMANCE WOOD-FRAME PARTY PARTITIONS UNDER LABORATORY AND FIELD CONDITIONS

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INTRODUCTION

Acoustical Privacy

Noise, like other forms of pollution, continues to receive the attention of the public, Government, and industry. Residential acoustical privacy is no exception where the trend to multifamily dwellings with their "party" walls and "party" floors continues. Successful privacy design requires consideration of the noise source, the noise path(s), and the receiver. To illustrate, the noise source is affected by the personal habits of speech and movement as well as the preferred sound levels for hi-fi and TV. The source is also affected by room furnishings and geometry. The noise paths include not only the performance of the installed party partitions but also flanking (sound transmission by paths other than directly through the party partition). The response to intruding noise by a person receiving noise depends on both personal factors and the background noise levels (21,37).² The receiver is also affected by his room furnishings and geometry.

Two conditions provide a special challenge to acoustical privacy implementation. First, the practical considerations of cost and the intrinsic limits to design typically provide privacy to about the level of a raised voice. Thus, lacking any significant safety factors, a failure in any element in the source (noisy tenant), path (inadequately installed partition and/or poor building design), or receiver (sensitive person, low background noise) can result in inadequate privacy. Se-

cond, when privacy is inadequate, no special equipment or sensors are required to determine that inadequacy, beyond the hearing of the occupant. Thus, discomfort and complaints may result.

This study concerns only the path part of the source-path-receiver system for potentially high performance walls and floors. Even these higher performance partitions do not negate the need for total privacy design. They may provide potential for improved performance, or make the total system less prone to the occurrence of annoyance or even failure, but they do not eliminate that possibility.

Criteria and Codes

Important laboratory criteria for determining the performance of party partitions are the Sound Transmission Class (STC), as defined in ASTM E 413 (7) and the impact insulation Class (IIC), as defined in ASTM E 492 (8). Higher STC or IIC values indicate improved sound insulation. For example, the HUD Minimum Property Standards for Multifamily Dwellings (33) requires $STC \geq 45$ and $IIC \geq 45$ for living unit to living unit. These are minimum standards and many architects and builders prefer improved performance—and STC or IIC improvements of 5 points can be significant

¹ Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

² Numbers in parentheses refer to Literature Cited at end of this report.

(21). The ICBO Uniform Building Code (20) requires the STC and IIC of party walls to be ≥ 50 . The States of California and Minnesota make these higher requirements mandatory for most multifamily dwellings.

Scope of Study

The requirements in these codes are based on the performance of construction assemblies rated under laboratory conditions with the provision that field tests can be up to 5 points lower. This 5 dB allowance, for field conditions, however, is not fully consistent with actual experience. For example, it has been shown (21,22,24) that field STC performance can vary from 4 points higher to 20 points lower depending on the type of partition design and field conditions. Thus, for a given partition or partition type, it is important to characterize both its lab and field performance and relate them to each other through more theoretical considerations. To this objective, this study provides various lab and field evaluations of three high-performance double-row-of-wood-stud walls (STC = 55 to 63) and two high-performance wood-joint floors (STC = 55 and 58, IIC = 51 to 92 depending on floor covering). In addition, field data for two double-row-of-stud designs—one providing inadequate performance and the other minimum performance—are included to illustrate less-than-optimum design.

The wall designs are double-row-of-stud with absorption in the stud cavities and single or double layers of gypsum board (fig. 1). While these types of walls have been previously evaluated in the laboratory, the literature is somewhat ambiguous about the actual level of their performance. Recent improvements in approximate TL theory and new laboratory data are used to better characterize these walls and affirm their high lab performance. Wall A is a replicate of a wall that was field tested by the U.S. Forest Products Laboratory (FPL) in 1971. Walls A and B are similar to some previously reported data. Wall C is unique and provides a very high lab performance.

While some other field data have been obtained for walls similar to Wall A (19), they were not adequately related to lab tests so that the low field performance in relation to lab tests was not recognized. The FPL field tests

affirm this performance, and reasons are suggested—allowing a reinterpretation of the previous data and an understanding of the need for further research. The less-than-optimum wall designs are double-row-of-stud walls with septum (center) layer(s) between the studs; the approximate TL theory is used to validate their low field performance in comparison to walls without septum layers.

The wood joist designs for Floors A and B are based on 1-1/2-inch lightweight concrete over a plywood subfloor and a gypsum board ceiling mounted via resilient metal channels to the joist (fig. 1). Floor A differs from Floor B in that it has absorption in the joist cavities. (While the addition of absorption to the joist cavity tends to increase acoustical ratings, this addition tends to decrease fire ratings according to ASTM E 119, "Fire Tests of Building

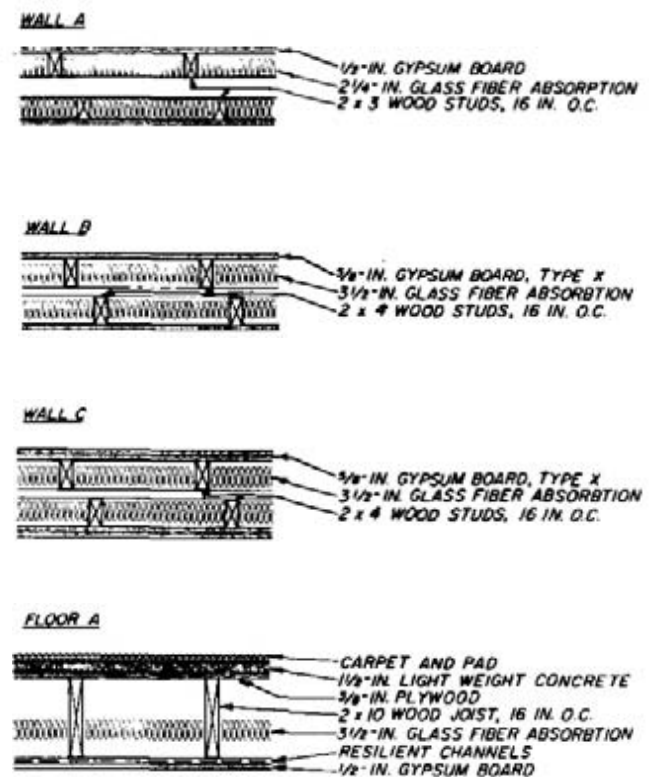


Figure 1.—Cross-sectional sketches for walls and floors for which laboratory data were obtained. Floor B differs from Floor A in that no joist cavity insulation is used. See tables 1 and 3 for descriptions of these constructions.

(M 146 137)

Construction and Materials" (10). Thus, both acoustical and fire tests should be considered when evaluating the effects of adding absorption to the joist cavity.) The high performance of both these floors is indicated by occupant experience and by previous laboratory data referenced here. The main purpose of the floor evaluation was to validate the existing lab TL data with the approximate TL theory and compare lab and field data for replicate structures. Contrary to the wall TL data, the field floor TL performance is equal to the lab performance.

Summary

This report contains lab and field data for various wood-frame partitions and abbreviated summaries of recent developments in lab-field correlation and approximate TL theories. In the larger sense, the technology plus the data are an inseparable pair. Full understanding of either requires knowledge of both. However, not all audiences want or even need this fuller comprehension. To facilitate the needs of several potential audiences this report is organized as follows:

1. The body of the report is primarily empirical, emphasizing the specific types of partitions investigated and the resulting data and an interpretation of the data. Thus, if an architect or code official needs laboratory STC or IIC values to demonstrate compliance with a

guide or code requiring lab demonstration, then it is necessary only to go to tables 1 and 2 and note the appropriate lab values. Similarly, if one wishes to know how some of these partitions performed under field conditions, that information is also contained in the tables.

However, if one wishes to understand why equivalently high field values are obtained for floors but not for the walls that were field evaluated, that is more complex. For this task a reading of the entire body of the report should provide some explanations.

2. The appendix is a summary of the theories—concepts and relationships—used in analyzing the TL data in the report. This summary is not only much abbreviated from the original references, but also contains some corrections and additions. Thus if one desires to check the TL analysis herein, or apply it to other data. It would be important to read the appendix. It probably appeals especially to acousticians and engineers involved in acoustical work.

in fact, some of the novel conclusions about the data may not be fully acceptable until the appendix is read. However, the math is not complex and the uninitiated may also find it helpful with some study. Going beyond the descriptive approach of the body of the report is more complex, but leads to coherent explanations and correlations of lab and field data.

SOUND INSULATION POTENTIAL OF SINGLE- AND DOUBLE- PANEL CONSTRUCTIONS

To understand the data and analysis for this study, certain concepts are necessary. This section presents the elementary concepts for airborne and impact noises. More technical and complex relationships are elucidated in the appendix.

Airborne Sound Control

Airborne sound insulators, such as party walls and floors, perform their function by maintaining acoustical separation between adjoining enclosed spaces. The effectiveness of the sound insulator can be quantified by ob-

taining the transmission loss (TL) in dB³ at 16 frequencies as described in ASTM E 90 (9) for laboratory tests and E 336 (4) for field tests. The TL can be plotted against frequency (fig. 2), noting that increased transmission loss (a higher TL number) represents increased sound insulation. A single number rating scheme, as described in ASTM E 413 (7) can be used to obtain a Sound Transmission Class (STC)(fig. 2). The system provides a generally

³All sound pressure measurements in decibels are referenced to 2×10^{-5} N/m².

useful single number rating, and the STC or the Field Sound Transmission Class (FSTC) can be related to privacy (28.37). The circumstances in which problems can develop are those in which the STC rating contour is 8-point-deficiency-limited at one frequency, with a low total deficiency count. In this case, the rating system is sensitive to variability in test

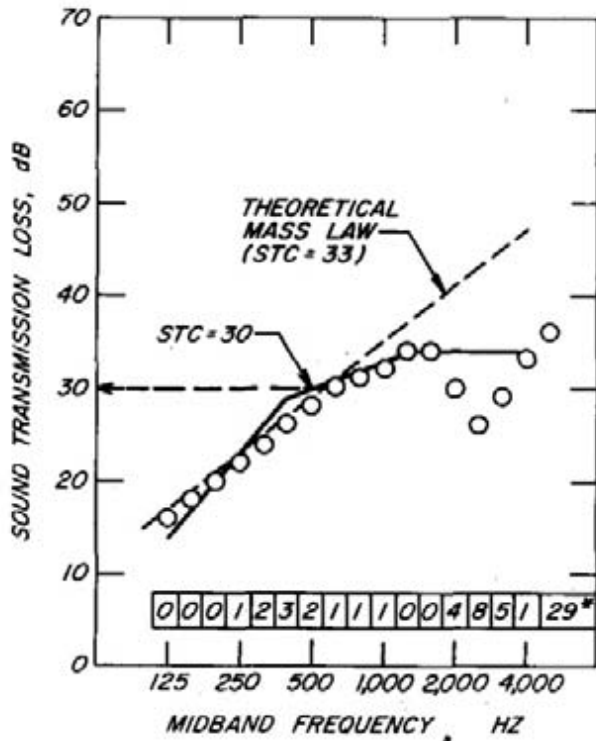


Figure 2.—Example of lab airborne transmission loss vs. frequency for 5/8-inch gypsum board (32). Note coincidence dip at 2,500 Hz. Solid line contour shows sound transmission class (STC) rating position for these data. The STC rating contour deficiencies at each frequency are obtained by subtracting the TL values below the rating contour from the rating contour itself. The deficiency points are shown in the boxes; the total, *, is to the right. The rating contour is placed as high as possible without exceeding a total of 32 deficiency points, and with no more than 8 points at any one frequency. The horizontal dashed line shows the FSTC value corresponding to 500 Hz for the rating contour.

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results and may be overly severe with respect to privacy (14). Examples of this are discussed in "Conclusions."

Two types of design are single-leaf and double-leaf walls. A single-leaf wall design may be defined as a design for which the entire thickness of the wall acts as an integral structure (e.g., moves in phase) over most of the frequency range of sound excitation. Examples are single plywood and gypsum board panels. In a double-leaf design, the two leaves do not act integrally over most of the frequency range, though they will be acoustically coupled to each other by the air cavity separating them and by any mechanical ties. An example of a double-leaf design would be a double-row-of-stud wall (e.g., 1-in. separation between rows of studs and plates).

To obtain a general idea of the acoustical efficiencies of single- and double-panel partitions, STC has been plotted against surface weight (fig. 3). The STC values for single-panel constructions rarely, if ever, exceed the theoretical mass law and more typically are limited to the empirical mass law (fig.3). Examples of partitions with single-leaf performance are a 5/8-inch gypsum board panel, conventional stud walls, and an 8-inch hollow concrete block. Efficient single-panel design results in STC values close to theoretical mass law and involves high mass, low stiffness and high damping, and thin sections. Examples are 1/8-inch hardboard, 5/8-inch gypsum board, and many other 'panel' materials.

A broad quantification of single-leaf design can be taken from figure 3 using the empirical mass law. For more exact calculations, see the appendix.

When double-panel designs (fig. 1, Walls A, B, and C) are used, a much improved STC is obtained (fig. 3). For example, if two pieces of 1/2-inch gypsum board at 2.0 pounds per square foot (lb/ft²) (STC = 28) were spot laminated 12 inches on center, the resulting STC of this single-leaf construction would be 34 (32, p. 69). In a double-panel construction (2 in. of insulation in 8-in. cavity), an STC = 55 could be obtained with the same amount of gypsum board. Thus, double-panel design has a clear STC advantage over single-panel design. For example, an acoustically designed double-row-of-stud wall at 6 to 8 lb/ft² will perform better than an 8-inch lightweight concrete block wall at 33 lb/ft².

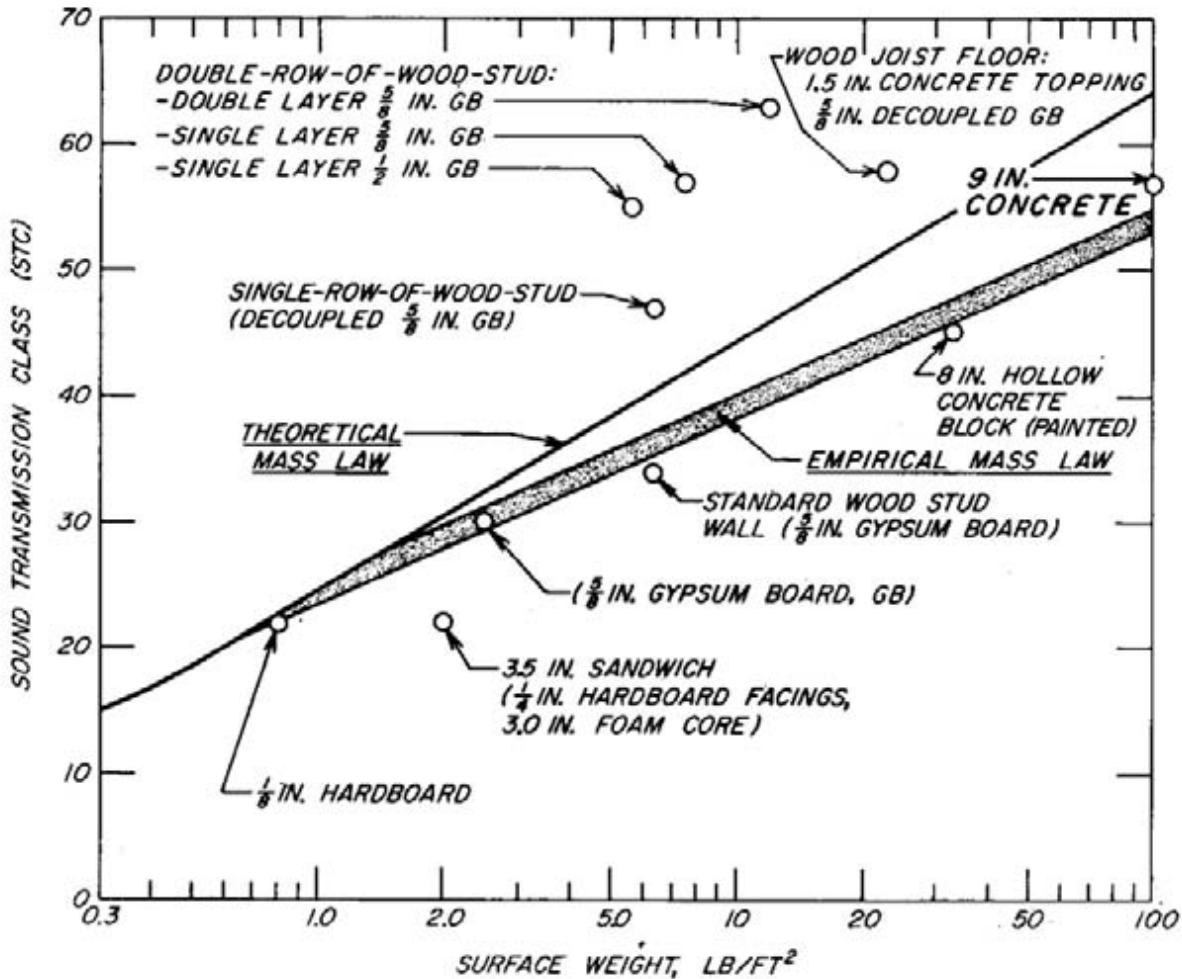


Figure 3.—Graph of theoretical and empirical field incidence mass laws expressed as sound transmission class vs. panel or partition surface weight, w (25). Examples of typical constructions are also shown. Shaded area is ± 1 dB with respect to $STC = 14.5 \log w + 25$ and indicates approximate nature of relationship.

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Good wood-framed double-panel party partition design broadly involves:

1. Good panels whose performance is as close to theoretical mass law as practical.
2. Adequate panel separation of 4 to 8 inches.
3. Cavity insulation at least 2 inches thick.
4. Minimized mechanical ties in the wall field and around the perimeter.
5. Adequate acoustical seal around wall-mounted fixtures and around the perimeter of the wall.

Quantification of double-panel design TL response is more complex than for single-

panel design. As a rule of thumb, the double-panel response can be obtained from the sum of the panel STC values (assuming at least 2 in. of absorption, cavity thickness at least 4 in., and minimization of structure-borne transmission paths). The appendix contains more exact calculations.

As a special case of a double-panel design, an approximate theory is available for point and line stud connections as given in the appendix. An example of line connections is a single row of wood studs (absorption in the cavity) with gypsum board attached directly to the studs with nails or screws. A point connection consists of one or more connections

whose cross-sectional area approximates a point. In practice this might be a 1- by 1- by 1/4-inch piece of plywood that separates a gypsum board panel from one side of a stud. If a resilient-point connection, such as neoprene rubber or resilient metal channel, is used, some additional benefits over the rigid-point connection can be obtained.

Impact Transmission

A floor-ceiling partition requires some type of impact test which simulates footfall in addition to airborne noise evaluation. One type of impact test is based on the tapping machine as described in ASTM E 492 (8). Impact noise characterization of a floor is complex in comparison with airborne noise evaluation. For impact, there is not only a multiplicity of sources—from soft heels to hard heels to falling objects—but, for a wood-joint floor, there are several different impact transmission phenomena. For example, there is the click of the heel as it locally excites the floor, the boom or rumble of the body weight exciting the gross floor structure, and the squeak or creak of elements of the floor moving across each other. While E 492 is the only current standard test method, and the evaluative method used briefly in this study, its ability to meaningfully characterize floor impact phenomena or even to rank different types of floors has been questioned. New methods involving changes in both the type of excitation and the method of measurement of impact transmission are subjects of current development in ASTM Committee E 33 on Environmental Acoustics.

Using ASTM E 492 the normalized impact sound pressure levels (SPL) can be obtained at 16 frequencies and plotted (fig. 4), noting that low impact SPL values represent increased sound insulation. A single number rating scheme described in ASTM E 492 can

be used to obtain an Impact Insulation Class (IIC) where *high* IIC values represent increased sound insulation (fig. 4).

Impact design strategies for wood-joint floors tend to be qualitative and empirical, as approximate theories of the type presented for airborne noises have not been developed. There are several summaries of STC and IIC data for a wide variety of wood-frame designs that are available from Government sources (12,30) and industry associations (7,2,3,17,36).

Impact design based on the ASTM E 492 tapping machine is profoundly influenced by the presence of carpet and pad. For example, a conventional wood-joint floor with a vinyl-asbestos tile has an STC \cong 37 and IIC \cong 34. The addition of carpet and pad gives STC \cong 37 and IIC \cong 56. Unfortunately, this design is not only inadequate for airborne noises but also gives an unsatisfactory boom. Nevertheless, any floor that will pass the STC \cong 45-50 requirements will also, with carpet and pad, pass IIC \geq 45-50 requirements. Impact design for floors finished with wood or vinyl-asbestos tile requires additional treatments for the floor deck and ceiling and may also require insulation in the joist cavities. For the floor deck, a resilient layer such as 1/2-inch fiberboard between the subfloor and underlayment or a high mass layer such as 1-1/2-inch lightweight concrete is required to provide an impedance mismatch with the impacting source. For the ceiling, attachment of gypsum board with resilient channels is generally used (also necessary for airborne noise).

The use of lightweight concrete as part of the floor deck is particularly interesting because it seems to solve part of the boom problems for wood-joint floors, as well as satisfying ASTM E 492 IIC \geq 45 with a vinyl-asbestos floor covering. Lab and field data for this floor are given in the data analysis section.

FIELD TEST SITE EFFECTS

The discussion thus far has concerned the airborne and impact sound insulation of partitions as they might occur under classical laboratory (ASTM E 90 and E 492) conditions. In field tests it cannot be assumed that all significant intruding sound energy is from the

test partition under consideration. Also, the physical characteristics of the room (e.g. room geometry and absorptive materials) may interact with the flanking TL characteristics and with the sound field, changing the effective TL of the test partition. Thus full characteriza-

tion of field performance involves flanking transmission and test environment factors as well as the partition transmission.

Flanking

In real structures, sound energy arriving in the receiving room can come via various flanking and partition paths (fig. 5) for airborne transmission. A flanking TL (and corresponding flanking FSTC) can be obtained experimentally in much the same way as a partition TL when a high STC partition is available (22,24). When the flanking TL is known, it can be plotted (fig. 6) along with the partition TL (and corresponding partition STC). The separate contributions of the flanking and partition TL to the sound energy in the receiving room can be combined by a logarithmic process to give a field TL (and corresponding field FSTC)(fig. 6). The field TL cannot exceed the flanking or partition TL (whichever is lower) and can be lower, giving a field TL curve that is very different from either the partition or flanking TL, due to their interaction. In this example (fig. 6), the partition STC = 52 resulted in a field FSTC four points lower due to flanking interaction. Similar effects might be expected for impact transmission, though the location of the impact source and structural damping would affect the extent of flanking involved.

Test Environment

In the absence of flanking, the field partition TL at most frequencies can be assumed to be about the same as the laboratory TL for a replicate structure. There are, however, some important exceptions due to test environment effects that were noted (22,24) for airborne noise (fig. 7).

At low frequencies where the wavelength of sound is of the order of magnitude of the room dimensions in the field, the lack of sufficient modes creates an uneven distribution of sound energy within the room. This condition is likely to reduce the coupling between the room modes and partition modes. Also, the wall-wall, ceiling-floor dimensions of the test partition provides a restricted range of angles of sound incidence on the wall, particularly near the wall boundaries. These effects result in the test partition receiving proportionately

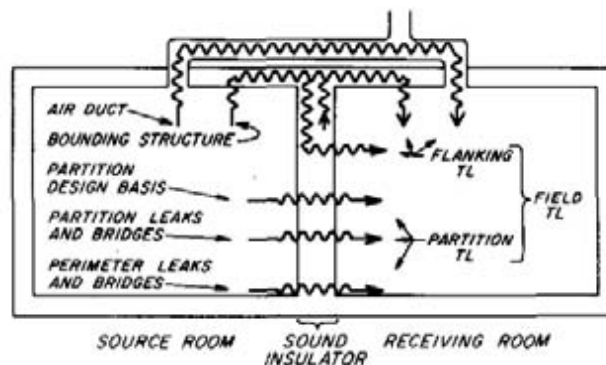


Figure 5.—Examples of partition TL and flanking TL noise transmission paths from source to receiving room (24).

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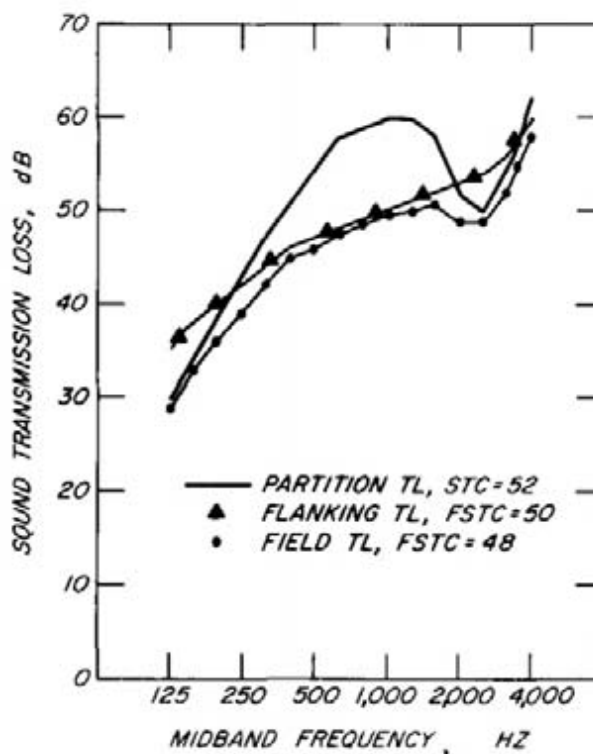


Figure 6.—Transmission loss (TL) vs. frequency showing the field TL data resulting from the mutual contributions of the partition and flanking TL. Note that the field TL can never exceed the flanking TL and that the field FSTC in this example is 4 points lower than the partition STC (24).

(M 142 444)

less sound energy than if it were in a laboratory test arrangement, and the resultant field TL is then proportionately higher. Of course, if field data are being compared with field data, a change in modal distribution of the sound field could cause the TL to increase or decrease, depending on whether the change improves or deteriorates the coupling of the sound fields to the partition. At higher frequencies where a panel coincidence dip may occur, the addition of absorptive material (such as carpet and pad), may again make the TL higher. This is due to a change in the diffuseness of the sound which is likely to limit the amount of sound energy at grazing angles to the panel which determines the extent of the TL dip at or near the coincidence frequency. Some evidence of

low frequency modal distribution TL effects under laboratory conditions will also be noted in "Conclusions."

RESEARCH MATERIALS

Wall Constructions

Five types of double-row-of-wood-stud walls were evaluated in this study (table 1). Walls A, B, and C (fig. 1) were tested at Riverbank Acoustical Laboratories (RAL), Geneva, Ill. For these three walls, single lots of materials were used for the studs, cavity absorption, and gypsum board. Laboratory test data for the studs and gypsum board are given in table 2. The studs were pre-tested in flexure. Those with a crook greater than 1/2 inch or with a modulus of elasticity (MOE) outside the range 1.1 to 2.2×10^6 psi for 2- by 3-inch studs, or 1.0 to 2.3×10^6 psi for 2- by 4-inch studs, were culled. Based on the MOE, the remaining studs were statistically randomized with respect to position in the wall. FPL carpenters built the walls in the RAL test frames. A commercial drywall screwgun was used to insert and dimple screws, similar to field practice. Normal gypsum board joint compound and tape procedures for "smooth wall" edge contours were followed according to manufacturer's published instructions.

Wall A was a replicate of a field-tested series of six walls with 2 x 3 studs, 1/2-inch gypsum board, and double 2-1/4-inch absorption (table 1). Wall B was similar to A except that 2 x 4 studs, 5/8-inch type-X gypsum board, and double 3-1/2-inch absorption were used. Wall B is commonly used, except for the full thick absorption which is replacing 2-1/2-inch absorption in the field due to the increased importance of energy savings in outside walls. Wall C is the same as Wall B except that a layer of 5/8-inch type-X gypsum board has been added to each side in an attempt to provide a very high STC wall.

Walls D and E are examples of designs with septums or dividing panels between the double row of studs. Lab tests were not run because the theory suggests that in the geometries of residential party walls triple-panel walls would not perform as well as double-panel walls.

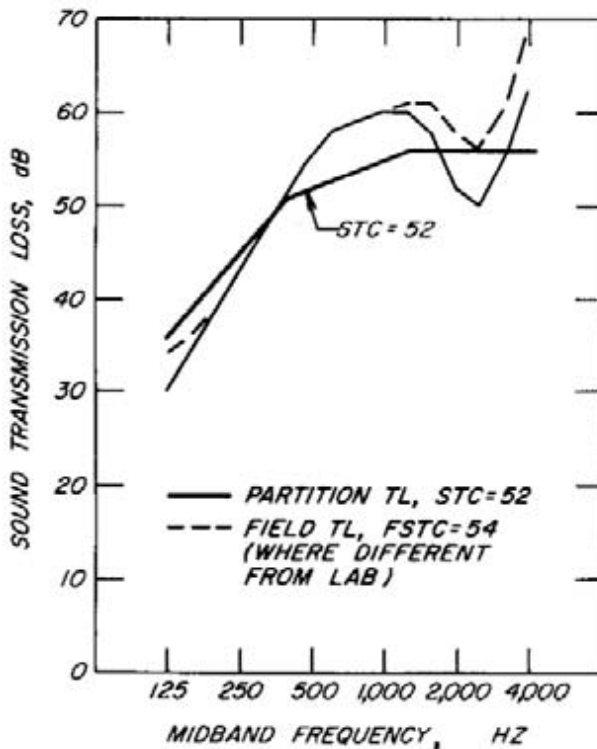


Figure 7.—Graph of transmission loss (TL) vs. frequency, illustrating the magnitude of duplex test environment effects on the partition TL that occurred at low frequencies (room geometry) and in a coincidence dip frequency range (absorptive room condition) (24).

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Table 1.--Summary of laboratory and field data for double-row-of-wood-stud walls with gypsum board faces.

Walltype ¹	Wall thickness	Laboratory data					FPL field data			
		Wall construction	Surface weight	STC	STC deficiencies		Wall type	FSTC	FSTC deficiencies	
					Total	8-Point			Total	8-Point
	In.		Lb/ft ²			Hz			Hz	
Wall A (TL 75-84)	8.5	1/2-in. gypsum board	1.75	55	27	125	A-1B ²	50	29	160
		Double row 2x3 studs, 16 in. o. c.					A-2B	47	19	160
		(2-1/2-in. plate separation)	1.86				A-3B	48	31	160
		Double 2-1/4-in. R-7					A-4A ²	49	31	160
		absorption	0.33				A-5A	48	27	—
		1/2-in. gypsum board	<u>1.75</u>				A-6A	53	30	160
		Total	5.7				A-7A ³	48	32	125
							A-8A ³	49	20	160
							A-9A ³	50	26	125
Wall B (TL 75-83)	9.25	5/8-in. gypsum board	2.31	57	27	—				
		Double row 2x4 studs, 16 in. o. c.								
		(1-in. plate separation)	2.62							
		Double 3-1/2-in. R-11								
		absorption	0.38							
5/8-in. gypsum board	<u>2.31</u>									
Total	7.6									
Wall C (TL 75-82)	10.5	Double 5/8-in. gypsum board	4.62	63	24	—				
		Double row 2x4 studs, 16 in. o. c.								
		(1-in. plate separation)	2.62							
		Double 3-1/2-in. R-11								
		absorption	0.38							
Double 5/8-in. gypsum board	<u>4.62</u>									
Total	12.2									
Wall D ~ 8.5	~ 8.5	1/2-in. gypsum board	-1.75	—	—	—	D-1B	50	28	200
		Double row 2x3 studs, 16 in. o. c.					D-2B	46	18	160
		(2-1/2-in. plate separation)	1.86				D-3B	44	19	200
		2-1/4-in. R-7 absorption	.16							
		1/2-in. sound-deadening- board septum	.7							
		1/2-in. gypsum board	<u>1.75</u>							
		Total	6.2							
Wall E ~9.5	~9.5	1/2-in. gypsum board	-1.75	—	—	—	E-1B	42	20	125
		Double row 2x4 studs, 16 in. o. c.					E-2B	43	24	160
		(1-1/2-in. plate separation)	2.62				E-3B	42	25	160
		Double 1/2-in. sound. deadening-board septum	1.4							
		1/2-in. gypsum board	<u>1.75</u>							
		Total	7.5							

¹ Walls A, B, and C were tested at Riverbank Acoustical Laboratories. Geneva, Illinois.

² Final letter B indicates bare room data and final letter A indicates absorptive room data.

³ Field data obtained by Pacific Northwest Forest and Range Experiment Station. Forest Service, USDA, Seattle, Washington.

Table 2.-Summary of properties for components used in laboratory tested walls.

Material	Nominal dimensions			Moisture content ¹	Specific gravity ²	Surface weight ³	Static bending	
	Thickness	Width	Length				MOE ⁴	MOR ⁴
	<u>In.</u>	<u>In.</u>	<u>Ft.</u>	<u>Pct</u>		<u>Lb/ft²</u>	<u>Psi</u>	<u>Psi</u>
Studs								
White-fir (Stud grade)	2	4	8	11.4 ⁵ (1.1)	0.45 (0.06)	⁶ 1.31	1,620,000 (570,000)	—
White-fir (Stud grade)	2	3	8	10.6 (2.3)	0.45 (0.07)	.93	1,630,000 (470,000)	—
Gypsum board								
Type-X, smooth wall, edge contour	5/8	4	8	—	—	2.31 (0.05)	⁷ 345,000 (50,000)	946 (73)
							⁸ 216,000 (72,000)	300 (38)
"Stay smooth," edge contour	1/2	4	8	—	—	1.75 (0.04)	⁷ 335,000 (76,000)	921 (52)
							⁸ 195,000 (53,000)	245 (14)

- ¹ Moisture content by moisture probe at time of static bending test, 75° F and 64 pct relative humidity.
- ² Specific gravity adjusted to 0 pct moisture content.
- ³ Surface weight based on weight, 75° F and 64 pct relative humidity.
- ⁴ Modulus of elasticity (MOE) for studs obtained by an Irvington Model 267 dynamic E-computer by transverse vibration. MOE and modulus of rupture (MOR) obtained by ASTM D 1037 (6) for gypsum board.
- ⁵ Numbers in parentheses are 2σ (standard deviation of a sample of 24 specimens for the studs and 12 specimens for the gypsum board).
- ⁶ Values for single row of studs 16 in. o. c. for an 8-ft-high wall with single bottom plate and double top plate.
- ⁷ Value obtained with length of specimen parallel to 8-ft panel dimension.
- ⁸ Value obtained with length of specimen perpendicular to 8-ft panel dimension.

Table 3-Summary of laboratory and field data for wood joist floors with a lightweight concrete topping and decoupled gypsum board ceiling

Floor construction		Laboratory data ¹								FPL field data											
General description ²	Surface weight	Floor type	Floor covering		STC		STC deficiencies		IIC	IIC deficiencies		Floor type	Floor covering		STC		STC deficiencies		IIC	IIC deficiencies	
			Type	Surface weight	Total	8-Point	Total	8-Point		Total	8-Point		Type	Surface weight	Total	8-Point	Total	8-Point			
	<u>Lb/ft²</u>			<u>Lb/ft²</u>		<u>Hz</u>		<u>Hz</u>			<u>Lb/ft²</u>		<u>Hz</u>		<u>Hz</u>		<u>Hz</u>		<u>Total</u>	<u>8-Point</u>	<u>Hz</u>
Floors A																					
1-1/2 to 1-5/8 -in lightweight concrete	1.51	Floor A (PNW/G&H 3A)	None	—	58	27	—	—	—	—	A-18	None	—	58	26	—	—	—	—	—	—
5/8-in plywood subfloor	2.1		Nylon '500' carpet and 40 oz half pad	0.4							A-28	None	—	59	24	—	—	—	—	—	—
2x10 joist	3.4	Floor A (CCA/G&H 3MT)	Vynal asbestos tile	—	57	26	—	51	17	2,500	A-1A	Nylon carpet 1/2-in urethane foam pad	0.4	0.1	58	30	—	77	16	125	—
16 in o c	—																				
3-1/2-in R-11 absorption	0.2																				
Resilient channels	—																				
5/8-in gypsum board	2.4	Floor A (CCA/G&H 2M)	Carpet and Carpetmate Supreme "Quietcushion"	—	58	28	—	92	9	100	A-2A	Nylon carpet 1/2-in urethane foam pad	0.4	0.1	60	27	—	—	—	—	—
Total	232																				
Floor B																					
1-1/2-in lightweight concrete	1.51	Floor B (PNW/G&H 2)	None	—	55	25	—	—	—	—	B-1A	Nylon carpet 1/2-in urethane foam pad	0.4	0.1	56	30	—	—	—	—	—
5/8-in plywood subfloor	2.1																				
2x10 joists	3.4																				
16 in o c	—																				
Resilient channels	—																				
5/8-in gypsum board	2.4																				
Total	230																				

¹ Tested at Geier and Hamme, Inc. Acoustical Testing Ann Arbor Michigan
² All floors were 128 in thick

Floor Constructions

Two types of wood-frame floors with lightweight concrete toppings (table 3) were evaluated in this study. A cross section of Floor A is given in figure 1. Floor B differs from A in

that no joist space absorption is used. Floors A and B are examples of commercial floor-ceiling systems that should provide good noise reduction based on lab data and field experience.

RESEARCH METHODS

Laboratory transmission loss tests for the walls were conducted at Riverbank Acoustical Laboratories (RAL), during 1975, in explicit compliance with ASTM E 90 (9). No special test conditions were used, except that the walls were 8 feet high (as in the field) rather than 9 feet high, as is the practice for commercial building walls. The precision of the TL measurement is ± 3 dB at 125 and 160 Hz, ± 2 dB for 200 and 250 Hz, and ± 1 dB from 315 to 4,000 Hz, according to ASTM E 90. The actual precision of the lab tests at low frequencies would appear to be well within that suggested by E 90 for the RAL data.

For the floors, both Impact sound transmission and airborne sound transmission loss were conducted at Geiger and Hamme, inc. (Ann Arbor, Mich.) during 1969 and 1970, in compliance with ASTM E 492 and ASTM E 90. No special test conditions were used. The floor area was 12 by 16 feet. The precision of the measurement is ± 2 dB at 100 Hz and ± 1 dB from 125 to 3,150 Hz according to ASTM E 492 (8).

The field tests for Wall A and Floors A and B were conducted in a development of two-story wood-frame apartments consisting of 11 buildings with 16 to 25 dwelling units per

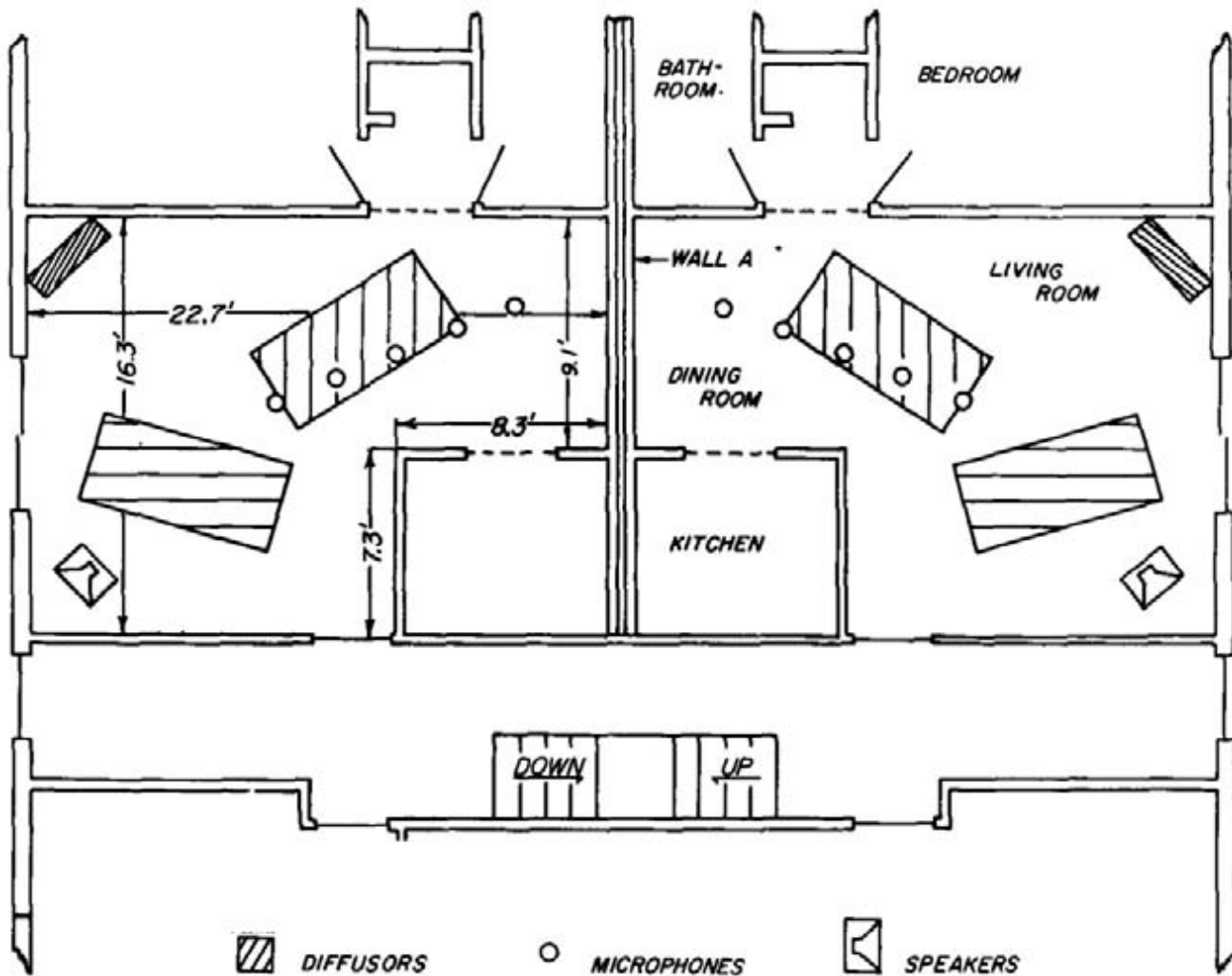


Figure 8.—A plan view of the apartment used for field tests of Wall A shows approximate locations of speakers, microphones, and diffusers.

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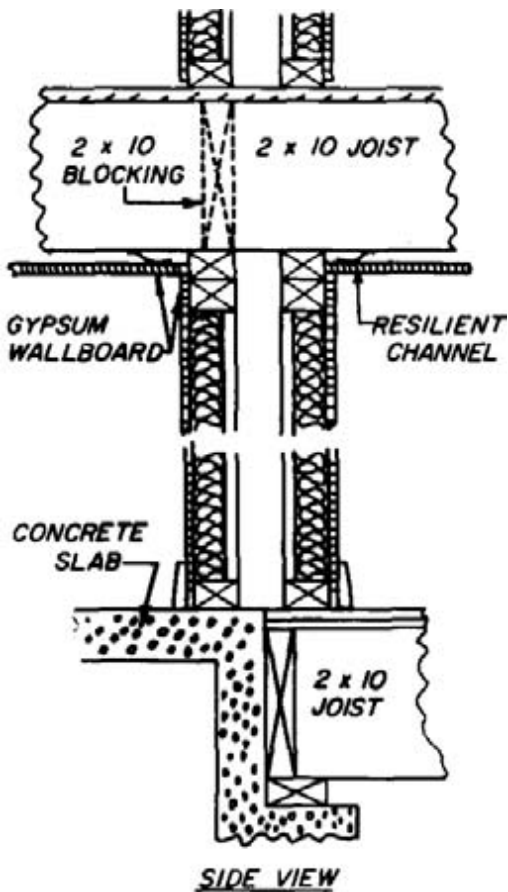


Figure 9.—Top and side views of a typical field installation of Wall A show some details of perimeter and bounding structures.
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building. There were about 200 dwelling units in all; 50 had two bedrooms (680 ft² total floor area), and the rest one bedroom (530 ft² floor area) (figs. 8 and 9).

ASTM E 336 (4) was used for transmission loss field testing. The FPL instrumentation is of laboratory quality and includes both visual and auditory means for monitoring the random (pink) noise source and microphone signal quality. (Procedural and instrumental details are included in Appendix II of reference (24). For floor impact tests a field procedure based on an E 492 standard impact hammer (tapping) machine was used. To minimize airborne transmission from the tapping machine, the case was removed and absorptive material, in addition to the carpet and pad, was added to the source room.

Two field test environments or room conditions were used. One is referred to as the "bare room condition" (fig. 6) in which three fixed diffusers of 1/2-inch plywood (42 to 48 by 92 in.) were used. The other is the "absorptive room condition" obtained with wall-to-wall carpet and pad as well as closed drapes across the sliding glass doors. In general the fixed diffusers were not used for the absorptive room condition. Reverberation time vs. frequency was recorded for the two conditions (fig. 10). The bare room condition more nearly simulates a laboratory test environment.

In order to estimate flanking sound transmission, temporary shields as required by E 336 were constructed in the field. The construction of these shields was similar to that described previously (18).

ANALYSIS OF RESULTS

Test wall references, generic descriptions, and STC and IIC values for the partitions evaluated are contained in figure 1 and tables 1 and 3. The detailed one-third-octave data for wall and floor lab tests are given in table 4. Lab and field data are shown graphically in figures 11 through 22. The data in these figures are for partitions that are sealed against airborne leaks or flanking. Structure-borne flanking will be discussed where it is thought to exist. The results of inadequately sealed walls and permissible leaks have been discussed (24).

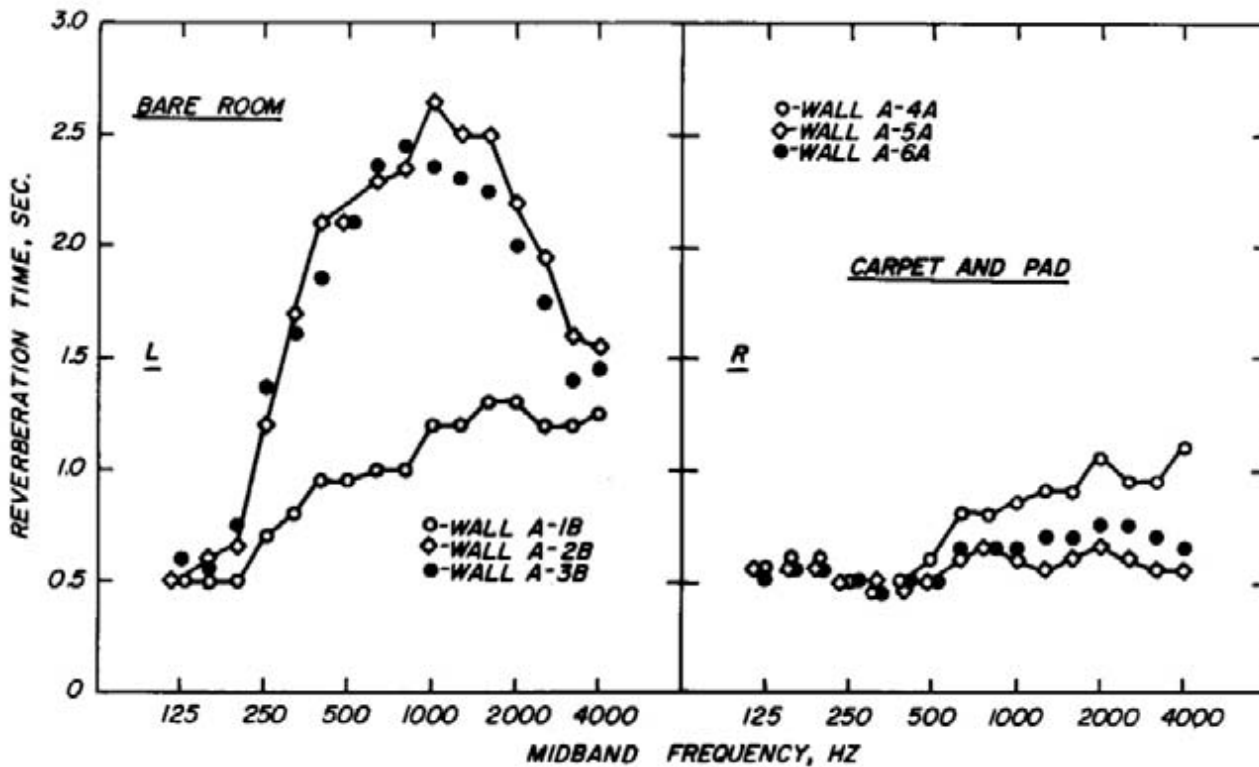


Figure 10.—Reverberation time vs. frequency for field tests under bare room (L) and carpet and pad (R) test environments. The bare room condition for Wall A-1B was obtained by placing sheets of 1/2-inch plywood over an installed carpet and pad.

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Double-Panel Walls

Lab TL was plotted against frequency for the double-row-of-stud Walls A, B, and C (fig. 11UL). As expected at the the of test, the TL values for Wall B (5/8-in. gypsum board and 2 x 4 studs) were generally a little higher than for Wall A (1/2-in. gypsum board and 2 x 3 studs), giving a 2-point STC improvement. Also, the additional layers of 5/8-inch gypsum board applied to Wall B to form Wall C gave a 6-point STC improvement. While the incremental STC increases seemed plausible, the actual values seemed generally higher than would at first be expected from some data (19,34) though more consistent with some other data (29).

In an attempt to justify the high STC data, the lab TL values were compared with the approximate TL theory (fig. 11UR, LL, and LR), in which lab TL and STC values would seem to be justified. In fact the lab TL data above 500 Hz would appear a little low, and the 6 dB/octave slope between 500 and 1,250 Hz would suggest some lab partition perimeter flanking.

The STC significance of this flanking depends on whether the lowered TL values contribute to the total deficiency count and any 8-point deficiencies. Of course the approximate theory suggests that any double-panel wall (without flanking, leaks, or bridging) should be 8-point-deficiency limited at 125 Hz by the initial TL slope of 18 dB/octave. Walls B and C are not 8-point-deficiency limited (fig. 11) and have some deficiency count due to flanking between 500 and 1,250 Hz. Thus Wall C would appear to have lab potential STC = 65. When the total surface weight of the construction (including studs) is used, a 15-point increase over theoretical mass law occurs (fig. 3).

For the combined panel weights (excluding studs), the STC values for Walls A, B, and C are 19 to 20 points higher than for theoretical mass law. These lab data and analyses give the double-panel light-frame construction a substantial STC advantage over single-panel masonry walls such as 8-inch

Table 4.—Laboratory transmission data for Walls A, B, and C, and Floors A and B.

Partition reference	STC or IIC	Third-octave bandwidth center frequencies, Hz																		
		100	125	160	200	250	315	400	500	630	800	1,000	1,250	1,600	2,000	2,500	3,150	4,000	5,000	
<u>Airborne transmission loss (ASTM E 90), dB</u>																				
Wall A (FPL/RAL 75-84)	55	28	31	35	40	46	49	52	54	57	59	61	63	64	64	62	59	61	63	
Wall B (FPL/RAL 75-83)	57	30	35	39	42	49	52	53	55	56	59	62	64	65	62	59	62	66	70	
Wall C (FPL/RAL 75-82)	63	39	41	46	50	55	58	59	61	62	64	67	69	70	67	66	68	69	70	
Floor A (PNW/G&H 3A) No carpet and pad	58	35	36	43	46	49	51	53	54	55	60	65	68	70	70	70	71	78	—	
Floor A (CCA/G&H 3MT) Vinyl-asbestos tile	57	37	42	43	48	49	50	49	51	53	56	61	64	68	66	65	70	76	83	
Floor A (CCA/G&H 2MT) Carpet and pad	58	37	41	42	47	49	50	50	54	54	59	62	68	76	70	72	83	91	95	
Floor B (PNW/G&H 2) No carpet and pad	55	34	36	36	42	48	49	52	52	54	53	58	62	64	64	63	66	76	—	
<u>Impact transmission (ASTM E 492), dB</u>																				
Floor A (PNW/G&H 3A) Carpet and pad	67	53	50	40	32	26	22	17	16	8										
Floor A (CCA/G&H 2MT) Carpet and pad	92	28	21	17	12	8	6	8	3	—										
Floor A (CCA/G&H 3MT) Vinyl-asbestos tile	51	52	52	50	49	51	50	56	56	53	53	52	49	49	51	52	46	39	37	

hollow concrete block (sealed). Of course, the use of light-frame auxiliary walls on masonry walls can substantially improve them (1,2).

This high TL performance under lab conditions suggests the possibility of flanking under field conditions. In a previous study (22), bounding structure flanking limits of FSTC = 50 were obtained for a duplex party wall location. If this were combined with an STC = 55 wall, the field FSTC would be about FSTC = 49

(using table 1 of reference (24)). Field tests run by FPL on replicate wall constructions for FPL/RAL A (STC = 55) did give comparably lower FSTC values (fig. 12L). While the replication for the three field tests was good, the average FSTC = 48 is 7 points lower than the lab value. This might have suggested substantial bounding structure flanking as predicted except that a temporary shield built next to Wall A-3B gave an FSTC = 55 (fig. 12R). Thus,

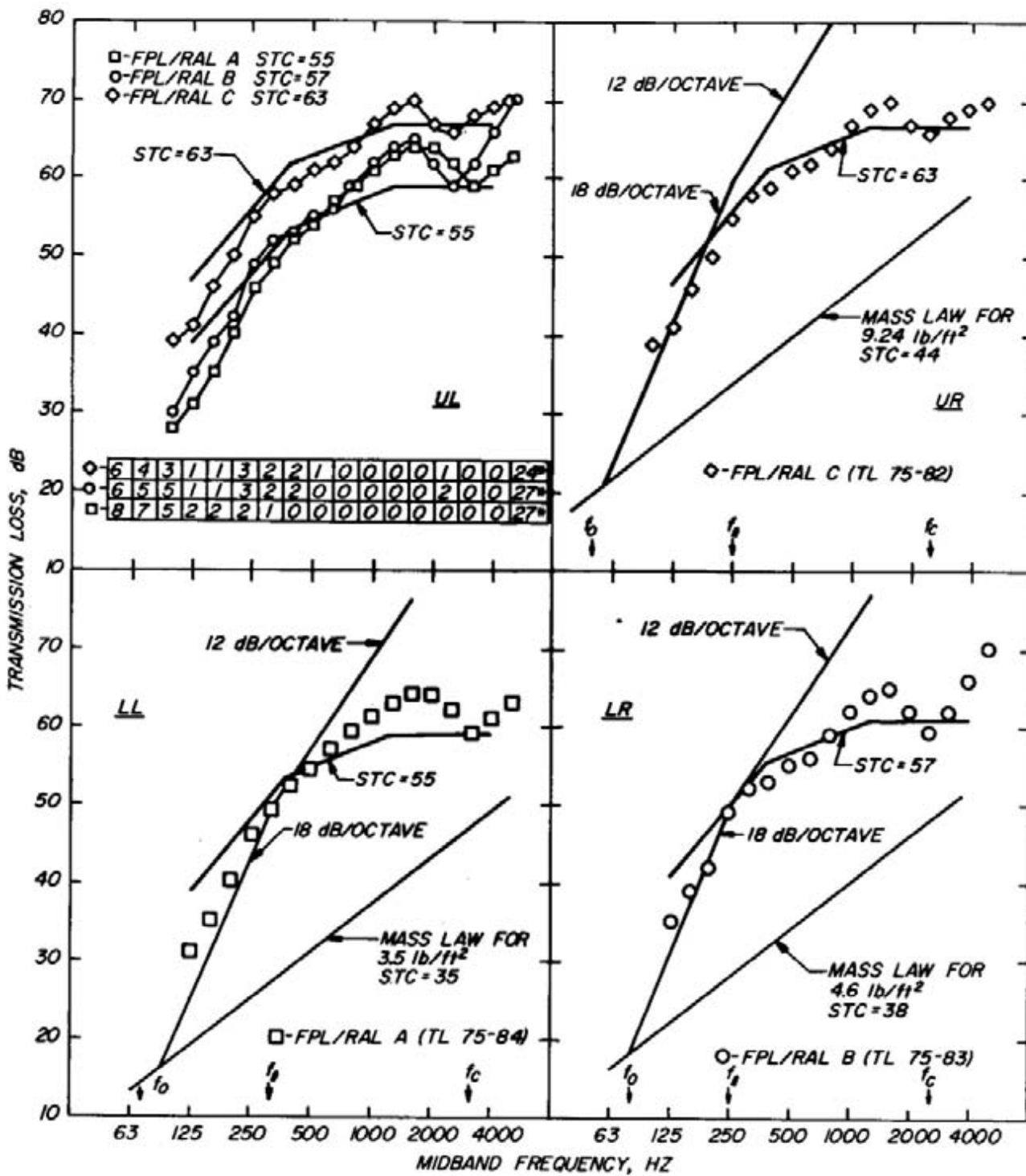


Figure 11.—Transmission loss vs. frequency for laboratory wall data, including a comparison of the FPL/RAL data for Walls A, B, and C (UL) and comparison of approximate theory and lab data for Walls A, B, and C (LL, LR, and UR, respectively). The deficiency points are shown in the boxes, with the total deficiencies, *, at the right.

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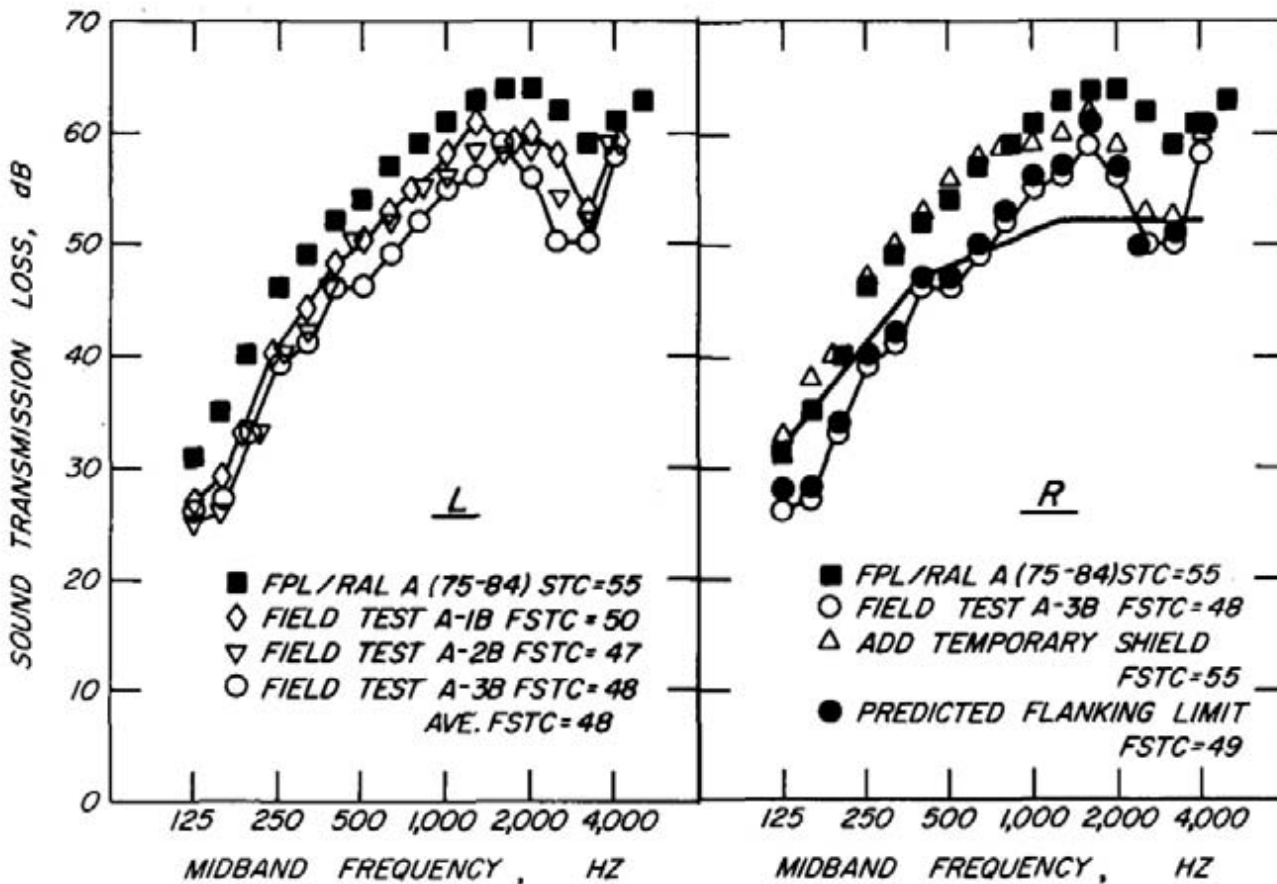


Figure 12.—Transmission loss (TL) vs. frequency data showing (L) the TL envelope for three field tests under bare room conditions compared with lab data for an identical construction, and (R) lab (FPL/RAL A) and field (A-3B) data compared with temporary shield TL data as well as a predicted flanking TL limit data. The disagreement between the flanking TL implied by the temporary shield and the predicted flanking TL suggests both wall perimeter and bounding structure flanking,

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it would appear that the flanking is either between the shield and the wall (or perhaps the shield changed the bounding structure flanking) or else some type of partition perimeter flanking exists. The continuous 2 x 10 joist over the top of the wall (fig. 9) suggests that all these possibilities exist.

Field data for similar constructions were also taken by FPL under absorptive room conditions (fig. 13). When a temporary shield was built for Wall A-5A, TL data (fig. 13R) were obtained. As with the bare room data (fig. 12), the flanking limit implied by the temporary shield differs from that obtained from the lab and field TL data. in this case, various com-

binations of wall perimeter and bounding structure flanking would seem to be suggested by the TL data. Due to construction schedules, the bare and absorptive room data are not for the same walls, so that comparisons of the bare and absorptive room data are less precise than in a previous study (22). Also, for Wall A-6A, the FSTC = 53 approaches the STC = 55 potential of the wall, suggesting a change in flanking as well as furnishings and this skews the "absorptive" average.

As a further check of the performance of double-row-of-stud walls, field data obtained by the Pacific Northwest Forest and Range Experiment Station (PNW) of the Forest Service

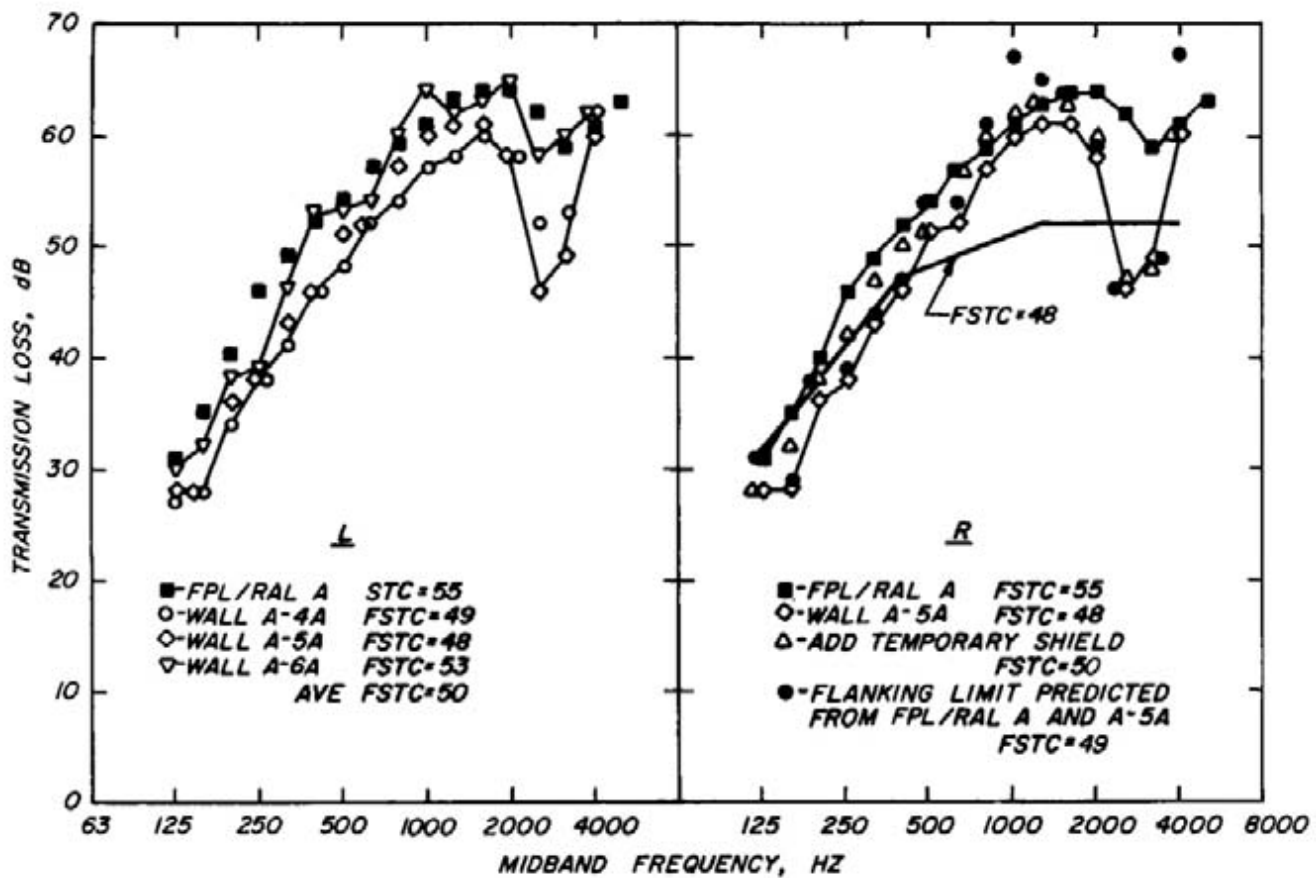


Figure 13.—Transmission loss (TL) vs. frequency data, showing (L) the TL envelope for three field tests under absorptive room conditions compared with lab data for an identical construction, and (R) lab (FPL/RAL A) and field (A-5A) data compared with temporary shield TL data as well as a predicted TL limit. The temporary shield and flanking limit TL values suggest various wall perimeter transmission and bounding structure flanking transmission.

(M 146 144)

were plotted (fig. 14). These walls are similar to wall FPL/RAL A in that they use 1/2-inch gypsum board and 3-1/2- to 4-1/2-inch absorption in the cavities. They differ in that 2 x 4 studs are used rather than 2 x 3 studs. The cavity depth is thus 8-1/4 inches for the PNW walls, similar to the 7-1/2 inches for FPL/RAL A so that the approximate theory would justify comparison of these lab and field data. The TL data (fig. 14) for the room conditions at the PNW would seem to support the conclusions drawn from figures 12 and 13, suggesting that double-row-of-stud FSTC performance averaging 6 points (range, 2 to 6 points) below lab performance is not limited to FPL or Midwest evaluations. Of course, all this depends on accepting the FPL/RAL A lab test

as valid and the approximate theory would seem to validate this position.

Double-row-of-stud walls have given STC values as low as 51 (19,34). These data were obtained in 1964 using one-half-octave-bandwidth noise sources and would at first seem entirely too low. However, the cavity depth was about 2 inches less than the current study and this, according to approximate theory, would reduce the STC by about two points. Only about one-half the absorption was used (2 vs. 4 in.) and this could provide another 2-point difference. Thus, under the design conditions of the present study, the STC = 51 might be more like STC = 55. However, it should also be noted that the STC = 51 value has been compared to field data for

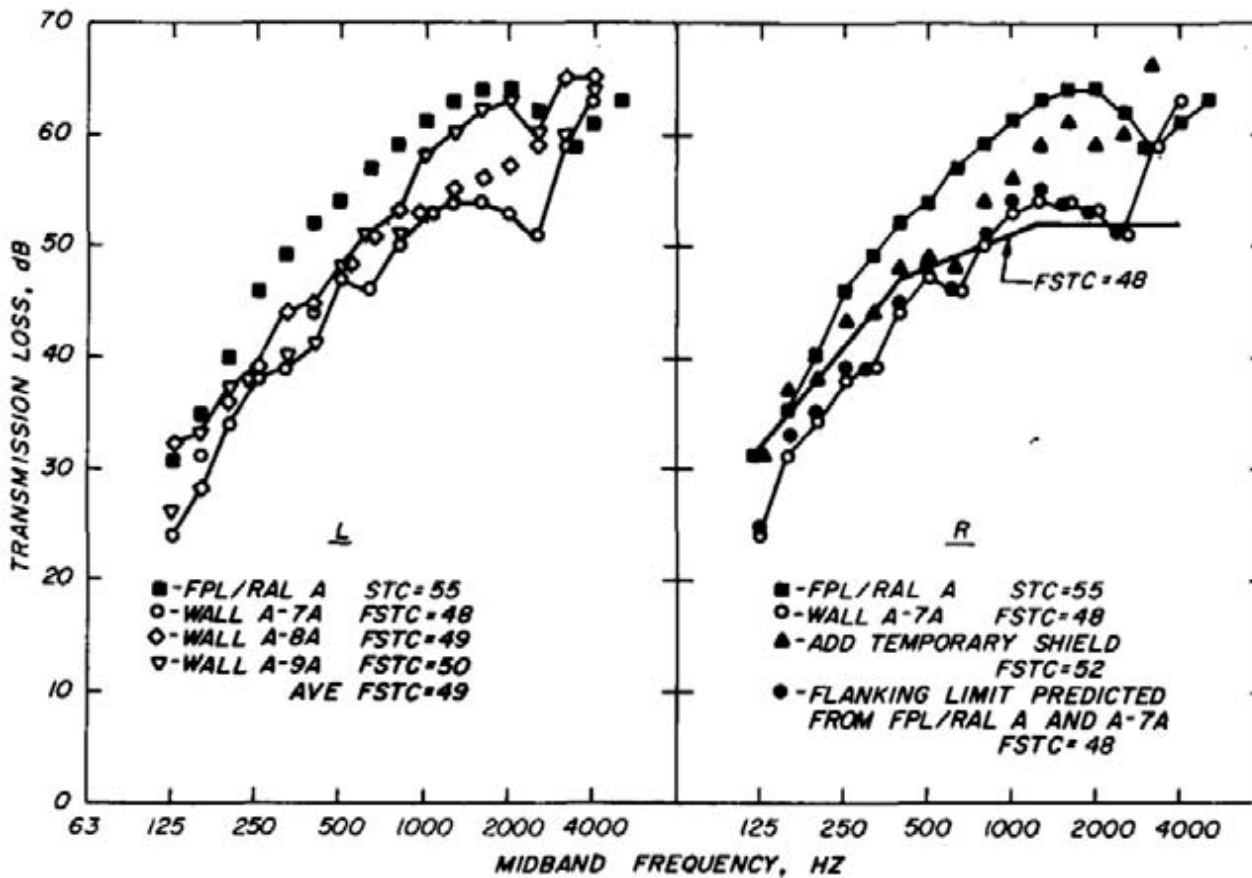


Figure 14.—Transmission loss (TL) vs. frequency data showing (L) the TL envelope for three field tests (79) under absorptive room conditions compared with lab data for a similar construction, and (R) lab (FPL/RAL A) and field (A-7A) data compared with temporary shield TL data as well as a predicted flanking TL limit. The temporary shield and flanking limit TL values suggest various wall perimeter transmission and bounding structure flanking transmission.

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double-row-of-stud constructions using 2 x 4 studs.

in summary, for the double-row-of-wood-stud designs for Walls A, B, and C, the lab data (fig. 11) would seem to indicate good potentials for providing high-performance sound insulation in light-frame constructions. However, field data (figs. 12-14) suggest that this is not generally achieved in typical field installations. This should encourage further research to determine what specific types of construction details are providing the bounding structure and perimeter flanking that limits the performance of these walls. These results also reinforce the need for rapid field testing to verify installed performance of walls, as field values can be more than the 5 dB below lab performance implied by some existing codes.

Walls with Septum Layer(s)

Triple-panel walls would not be expected to perform as well as double-panel walls of equivalent surface weight in the geometries typical of residential party walls (see appendix). Because this conclusion tends to run counter to builders' expectations, some examples of constructions found in the field with middle or septum layers were evaluated.

The septum layer(s) can be achieved by standing a panel material in the space between the double row of studs. The septum can also be nailed to the interior edge of the stud, though in this case the construction would not really be a triple-panel design, as will be noted subsequently. The septum material used in the partitions evaluated was 1/2-inch sound-

deadening board (SDB). Gypsum board has also been used as a septum material in residential constructions. The 1/2-inch SDB material is different from 1/2- or 5/8-inch gypsum board in that its surface weight is lower and its wood fiber construction provides some sound absorption due to its porosity, as well as transmission loss due to its mass. To characterize the 1/2-inch SDB, it was tested as an 8- by 10-foot party wall in a duplex living unit (24). The 1/2-inch SDB TL data obtained are compared (fig. 15L) with 5/8-inch gypsum board TL data obtained under identical field conditions. When the TL for the SDB are compared with theoretical mass law (fig. 15L), good agreement is obtained, though even better agreement would be obtained with equation (A5) in the appendix. When the receiving room reverberation times for the gypsum board and SDB are compared under bare room conditions (fig. 15R), the SDB values are significantly lower. However, the SDB reverberation times are higher at most frequencies than the 1/2 second (at all frequencies) that would nominally be obtained from the addition of carpet and pad.

The double-row-of-stud (1-1/2-in. plate separation) construction of Wall E included a double 1/2-inch SDB septum with a layer of SDB carefully attached to the inner face of each row of studs with 1-1/2-inch roofing nails, 8 inches on center (no additional absorption). In the field TL data for the three walls (fig. 18L) the FSTC values are controlled by low-frequency 6-point deficiencies (see table 1). The TL data for Wall E-18 (fig. 16R), along with temporary shield TL data, indicate mid- and high-frequency flanking.

The design of Wall E was by a builder who had been told that one septum layer was good, so he "reasoned" that two septum layers should be better. Because the layers are nailed to the studs, we really have two complete walls (gypsum board; stud; sound-deadening board) separated by a 1/2-inch air cavity. Thus, the theoretical curve in figure 16R was obtained (using the appendix) by treating each wall as a line-connected double-panel construction and then combining the two walls as two double-panel constructions. The 1/2-inch air space is "stiff" up to $f_0 = 200$ Hz, so that the low frequency performance is poor; the

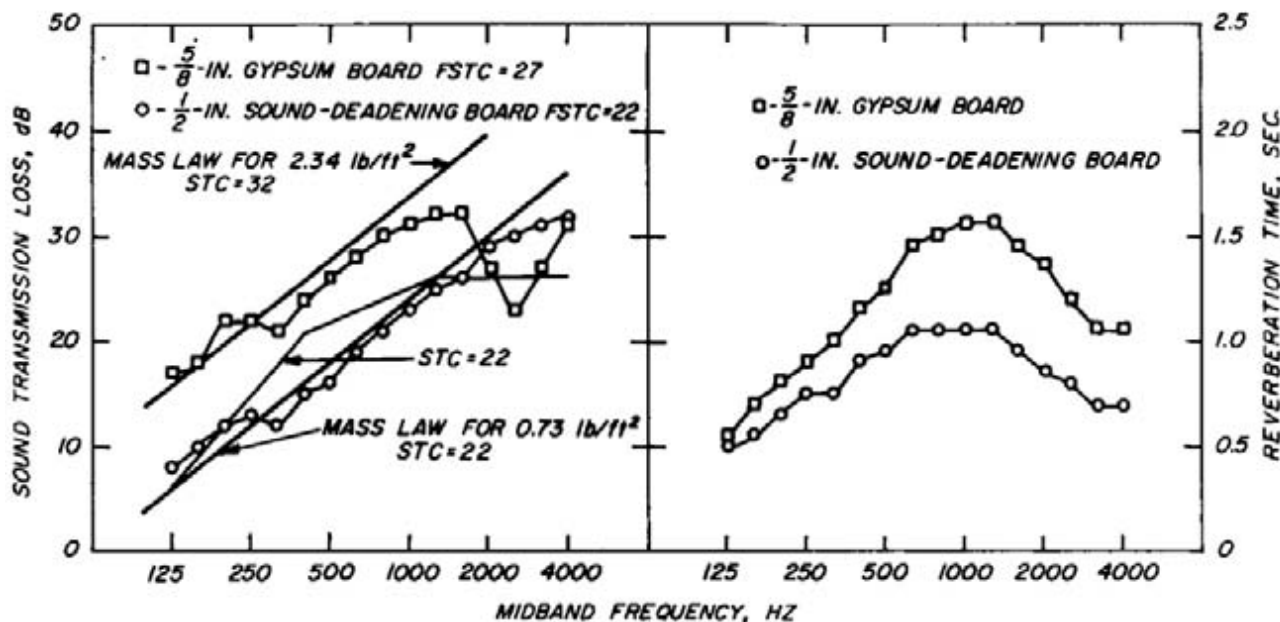


Figure 15.—Transmission loss and reverberation time vs. frequency for 5/8-inch gypsum board and 1/2-inch sound-deadening board, evaluated as an 8- by 10-foot single-panel partition under the bare room field conditions in the FPL rented duplex.

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theoretical TL rises rapidly above $f_0 = 200$ Hz. The approximate theory TL broadly supports the low TL values for Wall E (fig. 16R). While additional cavity absorption might have improved the TL somewhat, the high potential STC of double-row-of-stud wall design (with cavity insulation) such as Wall A was reduced 13 points by the use of two septum layers. If the double-panel potential of the wall had been realized, then bounding structure flanking would have limited the field performance.

Wall D is also an SDB septum construction (table 1) except that only one layer of 1/2-inch SDB is used and 2-1/4-inch fiberglass absorption is included in one row of stud cavities. The TL data for Wall D (av. FSTC = 47) (fig. 17) are better than for Wall E (av. FSTC = 42) and provides field performance equivalent to Wall

A (av. FSTC = 48) (fig. 12). This might at first seem to justify the design, but consideration of test environment factors and the approximate theory will suggest otherwise.

The TL data for Wall D (three separate walls) were obtained in a bedroom of 1,100 ft³, which does not satisfy the room volume requirements of ASTM E 336 for the TL data at 125 Hz. As noted (22), field test environments tend to give higher TL values at low frequencies (fig. 17). This is more likely for smaller rooms. In a larger room (or under lab conditions), the TL at 125 Hz for Wall D would be more like 20-22 dB, limiting the FSTC to 44-46. (In this respect the data for Walls E-1B and E-2B were obtained with room volumes of 2,570 ft³, whereas Wall E-3B had a volume of 1,148 ft³, accounting for the highest TL value at 125

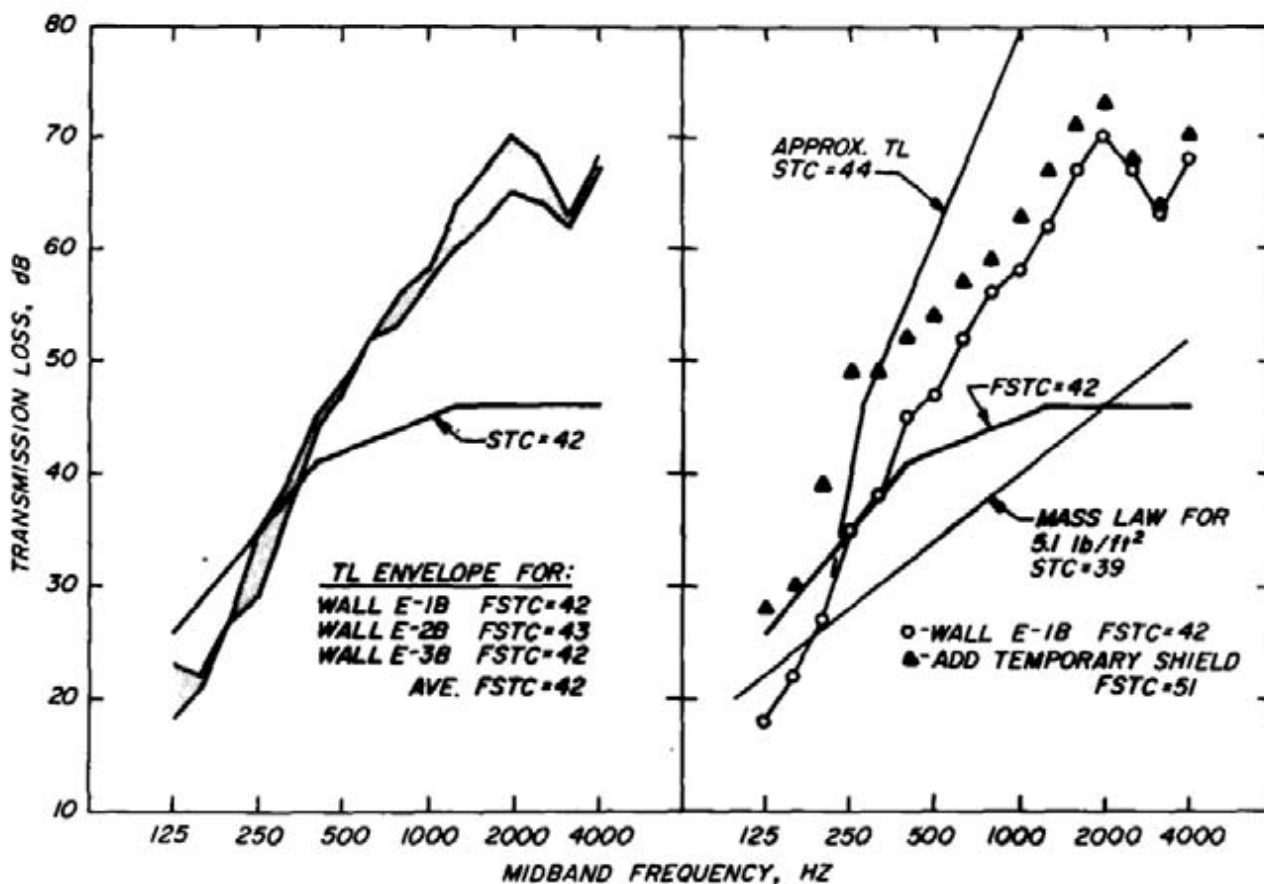


Figure 16.—Transmission loss (TL) vs. frequency data showing the TL envelope for field tests of three Wall E constructions (L) and field data for Wall E-1B compared with approximate theory and temporary shield data (R).

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Hz (fig. 16L).

The installation of the septum layer for Wall E was with only a few nails per 4- by 8-foot sheets so that the wall construction is more like a true triple-panel design. Thus, the approximate theory (fig. 17) is based on a triple-wall design, and broadly justifies the field performance of Wall D.

In summary, for septum-containing constructions, the approximate theory generally supports the poorer performance of these walls. While $FSTC \geq 45$ can be obtained under certain conditions of room size and added cavity absorption, such a design is neither acoustically efficient nor reliable compared to the simple double-row-of-stud designs of Walls A, B, and C.

Double-Panel Floors with Resilient Point Connections

The floors tested in the field for this study were known to have high sound-insulation potential on the basis of laboratory TL data. Further, experience with these designs demonstrated good impact performance at low frequencies below the frequency range of ASTM E 492. Thus, the main purpose of these tests was to compare lab and field data. An additional purpose was to compare the floor lab TL data with the approximate TL theory.

Laboratory TL data were recorded for Floors A (PNW/G&H 3A) and B (PNW/G&H 2) (16) with no carpet or pad (fig. 18L). For Floor A (3-1/2-in. absorption), the approximate TL

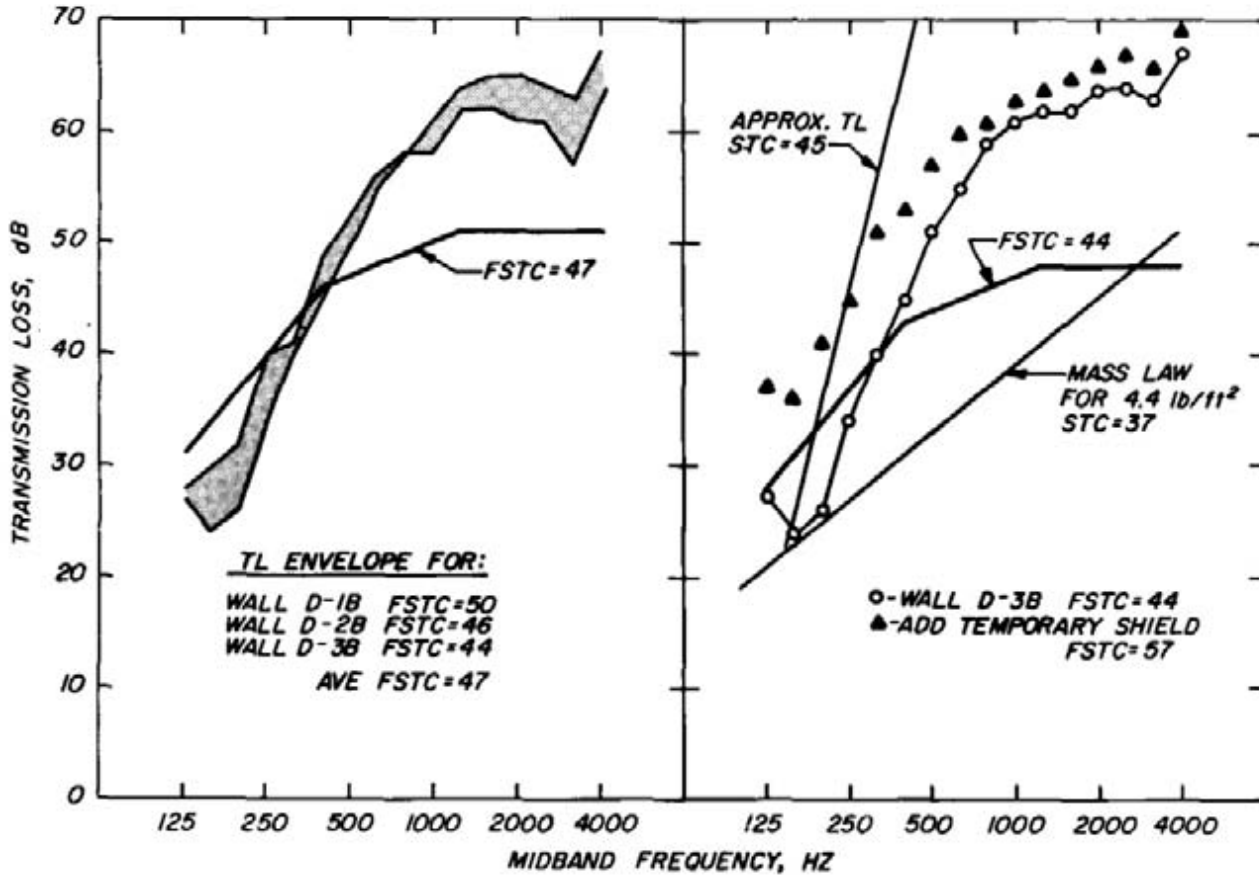


Figure 17.—Transmission loss (TL) vs. frequency, showing the TL envelope for field tests of three Wall D constructions (L), and TL data for D-3B compared with triple-panel approximate theory and temporary shield data (R).

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theory for point connection is applicable, and reasonably good agreement with theory is obtained above 125 Hz (fig. 18L). Floor B is identical to Floor A, except that the 3-1/2-inch fiberglass absorption is not included in the joist cavities. As might be expected, the TL for Floor B is generally lower than for Floor A, resulting in a 3-point decrease in the STC. The various dips in the TL curve are difficult to explain unambiguously due to the large number of resonant frequencies in this construction. For example, both the air cavity resonances ($f_1 = \frac{c}{2d}$ where c is velocity of sound and d is

cavity thickness) in the joist spaces and the estimated coincidence frequency for the lightweight concrete occur around 500 Hz. At about 2,500 Hz, the coincidence frequencies for both the 5/8-inch plywood subfloor and the 5/8-inch gypsum board are centered.

In laboratory TL data for Floor A (fig. 18R) good replication occurs, with the laboratory tests giving STC = 57, 58. Because many field situations involve carpet and pad as well as other furnishings, lab TL data for Floor A (CCA/G&H 2MT) with carpet and pad are compared with the bare room data of Floor A (CCA/G&H 3MT) (13). While STC increased by

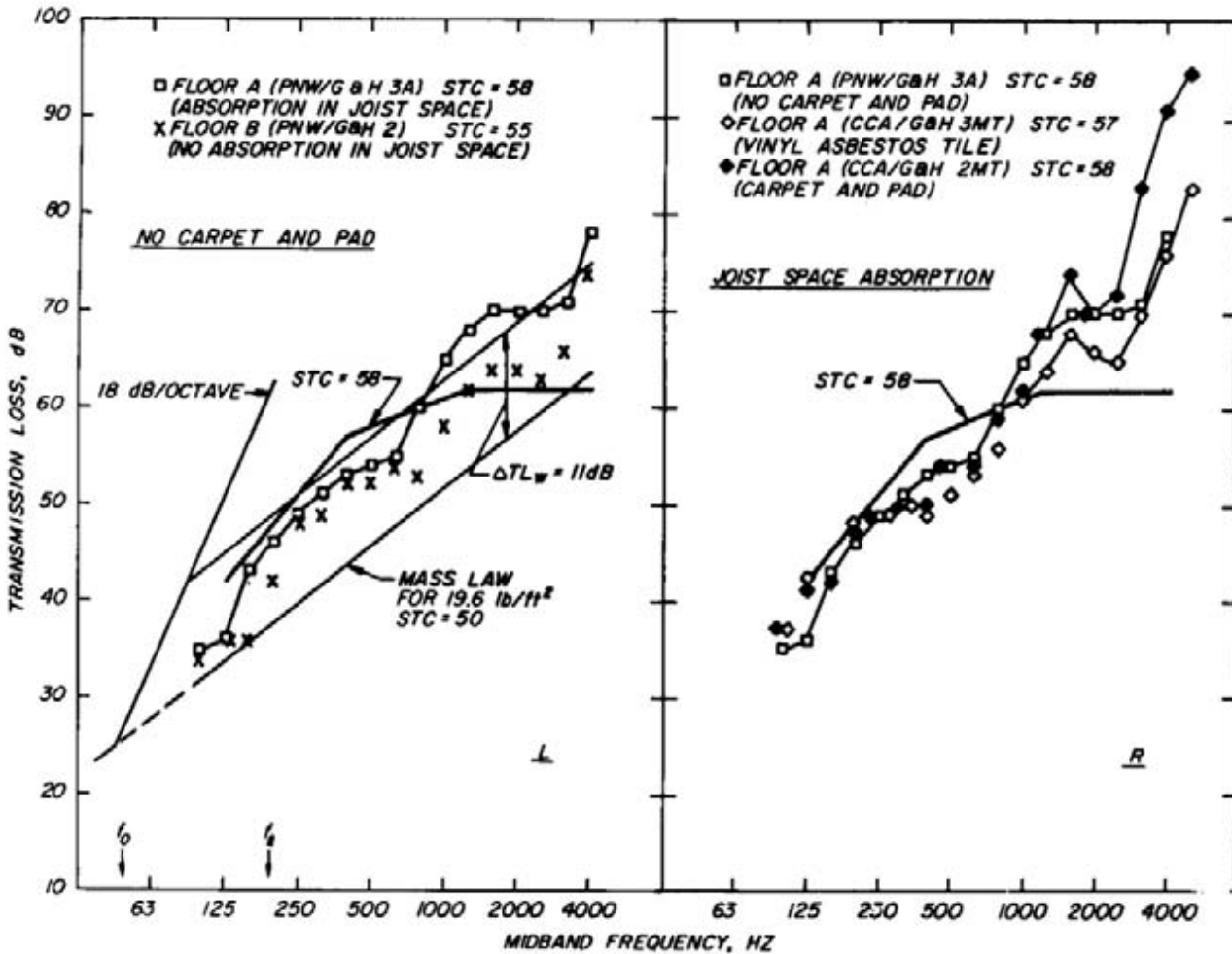


Figure 18.—Laboratory transmission loss (TL) vs. frequency for laboratory floor data, including a comparison of Floors A and B with approximate TL theory (L), and a comparison of data for Floor A from two different laboratories (R). The graph also shows the effect on the TL of the addition of a carpet and pad.

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only 1 point, TL increases from 5 to 10 dB occurred (31) at higher frequencies (above the STC rating curve). While the addition of carpet and pad and drapes can increase the field TL, especially at mid and higher frequencies (22,24), similar phenomena can occur under laboratory conditions. This, of course, complicates lab-field correlation statements for floors as previously noted for walls.

Because the field TL data for Floors A and B (fig. 19L) were obtained with carpet and pad, they are not directly comparable with the lab TL data (fig. 18L). However, the generally higher TL above 500 Hz (fig. 19L) for Floor A in the field test is similar to that for the lab test (fig. 18L) so the difference is assumed to be due to cavity absorption. Also the 2-point field increase in STC is comparable to the 3-point

lab increase. The increase for Floor A in the field TL with the addition of carpet and pad (fig. 19R) is similar to that for the lab TL (fig. 18R). As with the lab data, the TL increases are mostly above 500 Hz and above the STC rating curve so no change in STC occurs.

In comparisons of lab and field values (fig. 20) remarkable agreement between both (F)STC and TL values occurs using Floor A (PNW/G&H 3A) for the lab data. Lab and field data under bare and absorptive room conditions (fig. 21) can be compared using Floor A (CCA/G&H 3MT) lab data. The (F)STC agreement is less impressive. It is also interesting (fig. 21) that under absorptive room conditions, the field data FSTC = 60 for Floor A-2A is 2 points higher than comparable lab data and 3 points higher than bare room lab data.

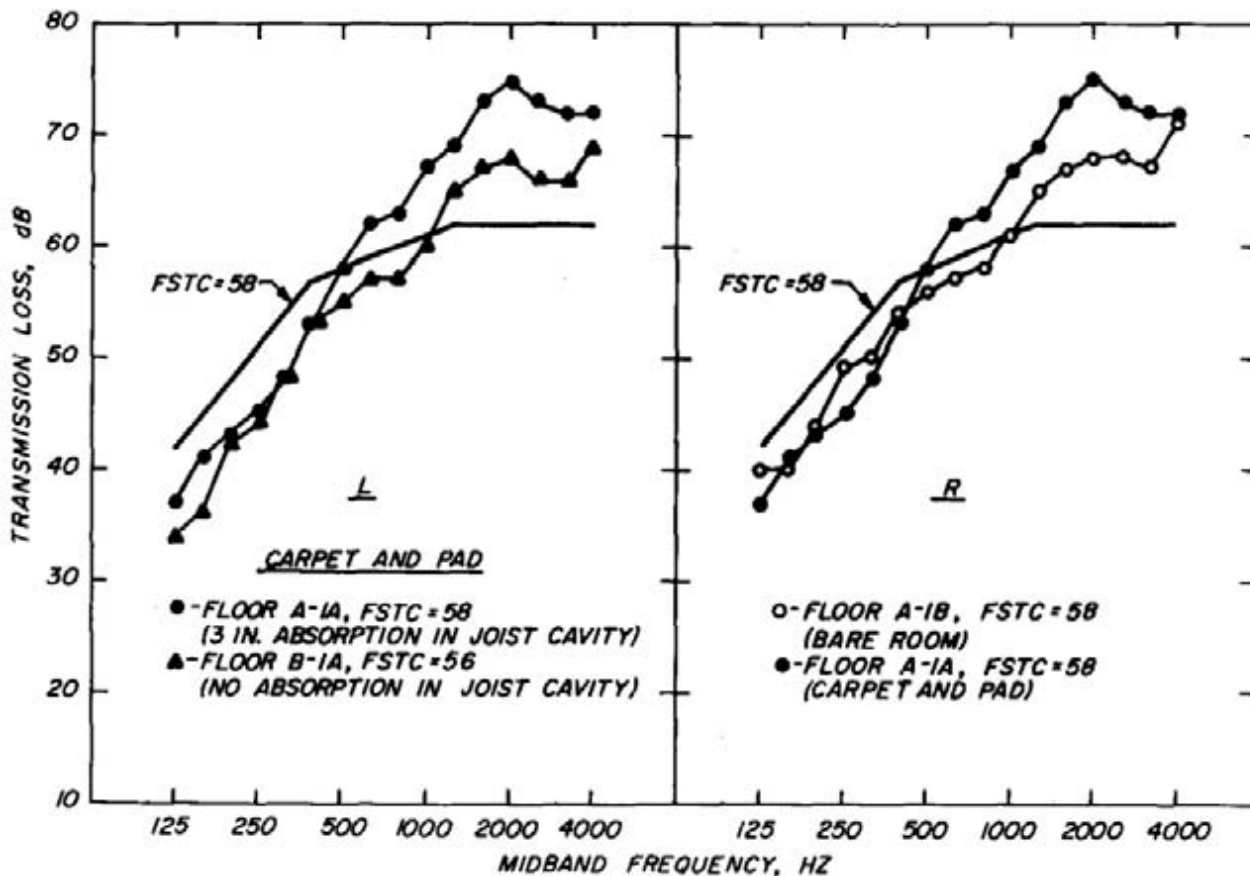


Figure 19.—Transmission loss (TL) vs. frequency for floor field data including a comparison of TL for two floors identical except for the inclusion of absorption in the joist cavity (L) and a comparison of the TL for a single floor with and without carpet and pad (R).

(M 146 150)

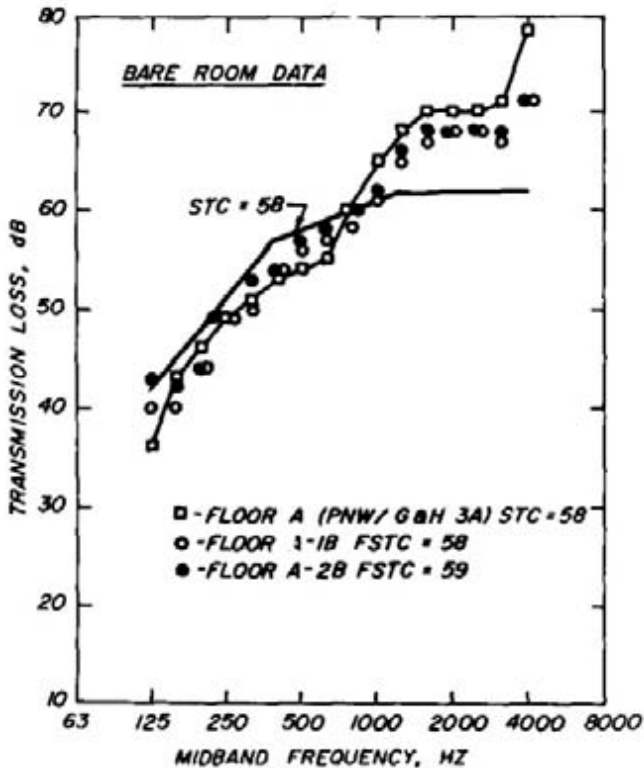


Figure 20.—Transmission loss (TL) vs. frequency comparing lab TL with field TL for two similar apartment floors.

(M 146 152)

This agreement shows that a light-frame construction has performed at $STC > 55$ without significant flanking. This at first appears to be quite an accomplishment when compared with the perimeter flanking for the double-row-of-stud walls (fig. 12). However, based on the weights of the panels (neglecting studs or joists), $\Delta TL_W \cong 10$ dB for the floor (fig. 18L) and $\Delta TL_W \cong 20$ dB above 250 Hz for the walls (fig. 11LL) (see appendix for definitions of ΔTL_W). Thus, the double-panel design for Wall A should be more susceptible

to perimeter flanking than the resilient-point-connection design of Floor A. Nevertheless, the $FSTC = 58$ suggests that the bounding structure flanking limit is about $FSTC = 65$. As was the case for some of the wall field data, the field TL values for 125 Hz are lower than the lab TL value. However, the STC rating for the point connection TL response does not emphasize low frequency deficiency points, so that these differences in lab and field TL values are not too significant.

The impact sound pressure level using an ASTM E 492 tapping machine varies widely from bare floor to carpet and pad floor coverings (fig. 22L). An attempt to obtain field impact data with carpet and pad was largely unsuccessful due to background noise interference (fig. 22R). However, the field results at $IIC = 77$ were apparently comparable to the carpet and pad lab data for Floor A (PNW/G&H 3A) at $IIC = 67$. The $IIC = 51$ for test (CCA/G&H 3MT) on vinyl-asbestos tile was a very good result in terms of exceeding $IIC \geq 50$ codes. However, other tests of replicate structures give $IIC = 46$, suggesting a range of values depending on the details of materials, assembly, and test procedures (the airborne TL data were similar).

In summary for the floor designs, both the lab and field data provided equivalently high performance for both airborne and impact noise sources. The airborne lab TL response for Floor A gave good agreement with approximate TL theory for a double-panel design with point connections. Even without joist cavity absorption an $STC = 55$ was obtained for Floor B, only 3 points lower than for Floor A⁴.

⁴Note that the $\Delta STC = 3$ applies to this particular floor construction and is not a rule of thumb for the inclusion of absorption. For example, the STC for Wall A would be reduced 8 points to $STC = 47$ (29) if all the absorption were removed.

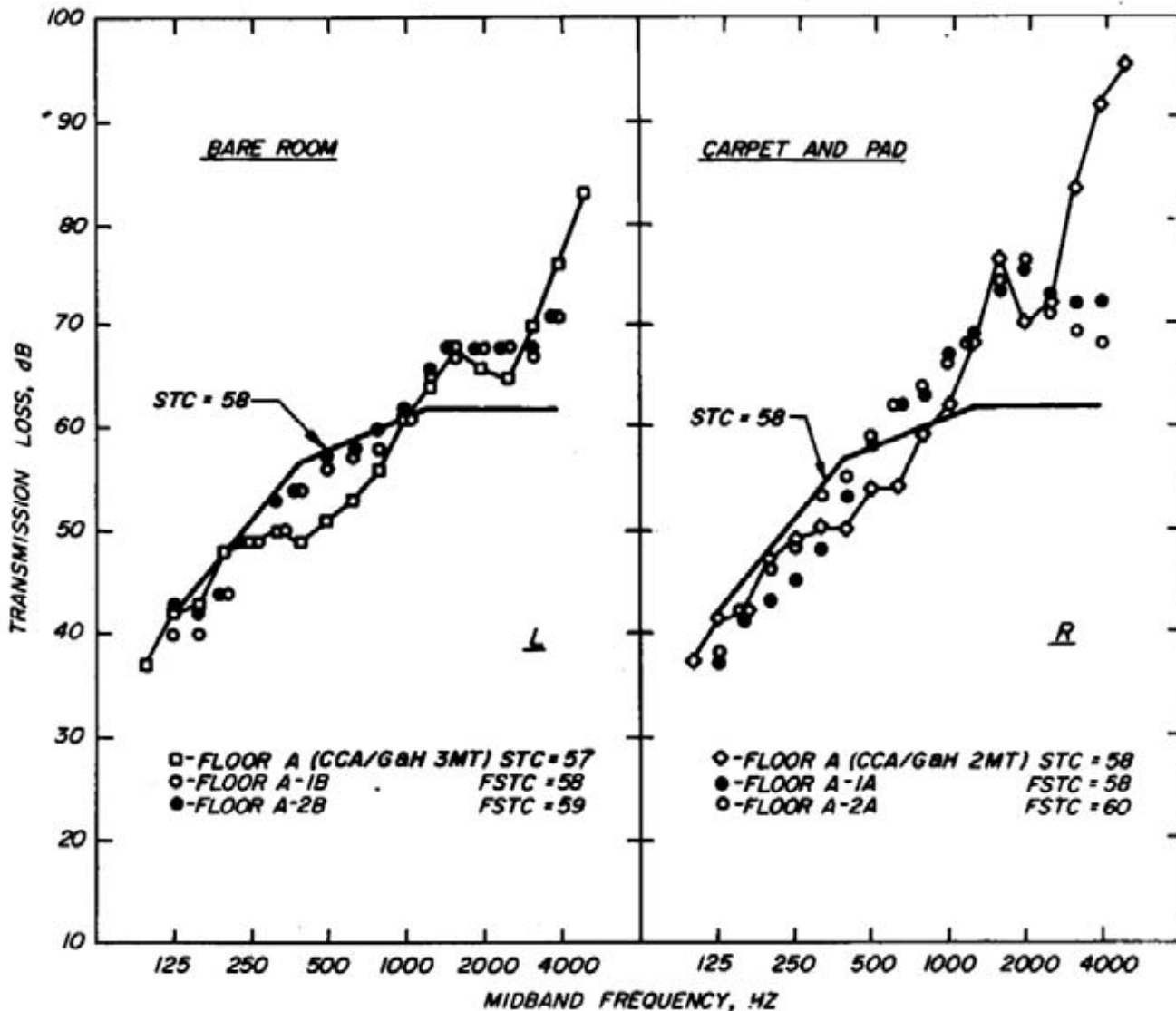


Figure 21.—Transmission loss (TL) vs. frequency, comparing lab and field TL for similar apartment floors under bare room (L) and absorptive room (R) conditions.

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SUMMARY OF LAB-FIELD TECHNOLOGIES

This summary brings together the various findings in this report on lab-field TL relationships so that they may be added to the developments already summarized in the introductory section on "Field Test Site Effects." The previous developments were derived from field data obtained in a rented duplex where considerable control could be maintained over the experimental test series. The field

data for this study were obtained at ongoing construction sites so that construction schedules prevented running some tests that would have permitted direct comparisons of, for example, the TL for bare and absorptive room conditions. However, the data were obtained under more typical field conditions. The wall laboratory data for this study were obtained at the same location as for the previous

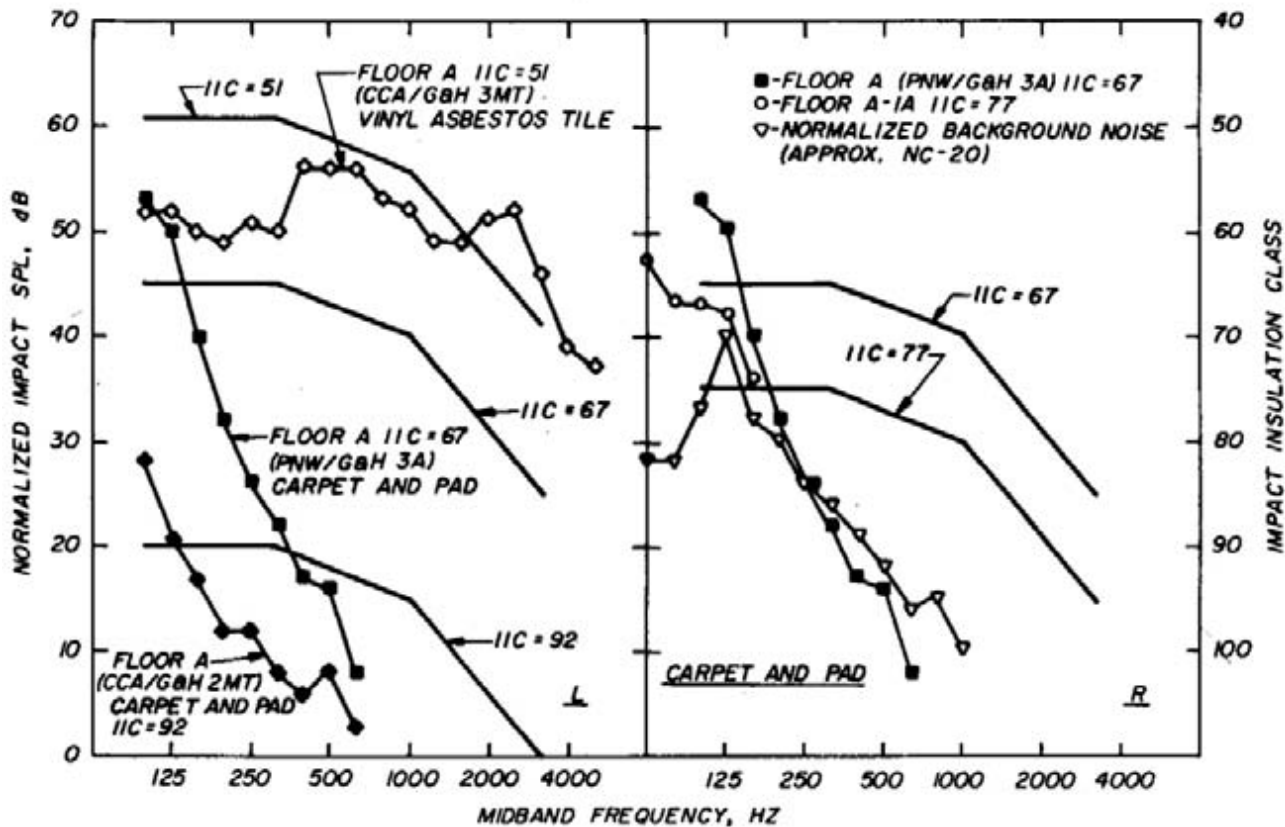


Figure 22.—Normalized impact Sound Pressure Level (SPL) vs. frequency data for Floor A includes a comparison of lab data for vinyl tile floor covering with lab data for carpet and pad (L), and a comparison of lab and field data for carpet and pad and an illustration of difficulty with background noise under field conditions (R).

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studies.

Two types of *flanking transmission* were noted. Under lab conditions, some type of "perimeter flanking" limited the TL response above 500 Hz for Walls A, B, and C. Under field conditions for these walls, both perimeter and "bounding structure" flanking were needed to account for the data. The actual field flanking limits for walls averaged about $FSTC \cong 49$, similar to previously reported bare room wall flanking limits (25). However, one wall at $FSTC=53$ would have an $FSTC \cong 57$ flanking limit. The flanking limit prediction (24) along with temporary shield data was helpful in separating the two kinds of flanking.

The apparent lack of flanking in the field for Floors A and B at $STC = 55$ to 58 suggests a field flanking limit $FSTC \cong 65$, a very high potential for a wood-frame construction. The lack of flanking was apparently due to both the floor design and the bounding structure fram-

ing. The resilient-point-connection design helped minimize perimeter flanking by limiting the DTL_{Wf} , and the platform framing appropriate to the floor construction minimized bounding structure flanking.

Test environment effects were found throughout the lab and field data similar to those described previously (22,24). The strongest effects tend to be at low frequencies (modal distribution) and at high frequencies (interaction of sound field diffuseness and coincidence phenomena) (fig. 7).

Low frequency modal distribution effects are easily identified by noting the TL slope at 125 to 200 Hz. Approximate theory suggests this slope should be $+18$ dB/octave above f_0 and $+6$ dB/octave below f_0 . It is also important that the first panel resonance, f_{11} , (23), be well below 100 Hz. For 5/8-inch gypsum board in 4-by 8-foot sheets, $f_{11} \cong 10$ Hz and is not a factor.

If some reflections occur at the line of attachment of the gypsum board to the studs, then a higher $f_{11} \cong 70$ can be obtained and the assumption of infinite panels would not be fully justified. Nevertheless, a TL slope that was nearly flat with frequency (or negative) is taken as evidence of test environment effects.

Examples of these low frequency effects can be found in the field data for Walls A-1B, A-2B, and A-3B (fig. 12L), Walls A-5A and A-6A (fig. 13L), and Wall A-8A (fig. 14L). Other field examples are Wall E-3B (fig. 16L) and Walls D-2B and D-3B (fig. 17L). Lab effects are not evident for walls (fig. 11) though there is some low TL slope floor data (fig. 18) which may be due to test environment effects.

Diffuseness-coincidence interactions at higher frequencies are not easily seen in the wall data. This is because of the extensive flanking interactions above 500 Hz and also because direct comparisons of bare and absorptive data were not made. However, for the floor data these comparisons were made for both field (fig. 19R) and lab (fig. 18R) tests. in

both cases the TL under absorptive conditions (carpet and pad added) are significantly higher than the bare room TL. This example is complicated by having different coincidence frequencies for the ceiling (5/8-in. gypsum board, $f_c = 2,500$ Hz) and the subfloor (5/8-in. plywood, $f_c = 1,140$ and $2,830$ Hz). When the absorptive surface is on the floor, the radiation of the floor is also affected (31). Nevertheless, some combination of these effects changing the test environment also changed the TL, though, for this design, the change was mostly above the STC rating curve.

Finally, lab-field correlations for these high-performance partitions must be considered. For the walls, the field performance was apparently dominated by flanking and was well below the lab potential performance. Any TL benefits for absorptive room conditions were largely obscured by the flanking effects. For the floors, little significant flanking occurred, and field results were about the same as lab with field absorptive room data being up to 2 points higher than lab.

CONCLUSIONS

1. Double-row-of-wood-stud party partitions with gypsum board faces and cavity absorption gave high lab performance of STC = 55 to 63 depending on the specific construction:

Wall A. Double row of 2 x 3 studs, 16 inches on center (o.c.) (2-1/2-in. plate spacing), with double 2-1/4-inch glass fiber stud cavity absorption and 1/2-inch gypsum board faces: STC = 55.

Wall B. Double row of 2 x 4 studs, 16 inches o.c. (1-in. plate spacing), with double 3-1/2-inch glass fiber stud cavity absorption and 5/8-inch gypsum board faces: STC = 57.

Wall C. Same as Wall B, except double 5/8-inch gypsum board on each face: STC=63.

2. The field performance of Wall A was found to average FSTC = 49 under bare and absorptive room conditions with a range from FSTC = 47 to 53. The reduced field performance was apparently due to combinations of bounding structure and partition perimeter flanking and suggests the need for further research to upgrade this field performance.

3. Field performance of double-row-of-wood-stud constructions with middle or septum layers gave field performances generally compatible with the lower lab potential performance of FSTC $\cong 45$ expected of these constructions on the basis of approximate theory:

Wall D. Double row of 2 x 3 studs, 16 inches o.c. (2-1/2-in. plate spacing), with single 2-1/4-inch glass fiber, single 1/2-inch sound-deadening-board septum, and single 1/2-inch gypsum board facings: FSTC = 50, 46, and 44 (average FSTC = 47). These FSTC values were apparently raised somewhat by the small room volume.

Wall E. Double row of 2 x 4 studs, 16 inches o.c. (1-1/2-in. plate spacing), with double 1/2-inch sound-deadening septum nailed to the inner faces of the studs: FSTC = 42, 43, 42.

4. The wood-joint floors with concrete toppings and resilient-channel-mounted gypsum board ceilings gave equivalently high lab and field airborne noise performance at (F)STC = 55 to 60, depending on the specific construction (and test environment) as follows:

Floor A. 2 x 10 joists, 16 inches o.c. (3-1/2-in. glass fiber in cavity), with 1-1/2-inch lightweight concrete over 5/8-inch subfloor, and 5/8-inch gypsum board mounted with metal resilient channels: FSTC = 58, 59 (non-absorptive floor covering): FSTC = 58, 60 (carpet and pad).

Floor B. Same as Floor A, minus joist cavity absorption: FSTC = 56 (nonabsorptive floor covering).

5. The field impact noise performance for Floor A with carpet and pad was about IIC = 77, apparently similar to lab data at IIC = 67, 92 depending on carpet and pad materials.

6. The approximate TL theories in combination with lab-field technologies were highly successful in explaining the performance and correlation of double-panel wall and floor constructions under both lab and field conditions.

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APPENDIX: CALCULATION OF TRANSMISSION LOSS FOR DOUBLE-PANEL PARTITIONS

In this abbreviated summary of improvements in approximate TL theories developed by Sharp (32), several errors in the original reference are corrected and some additional comments are included in the footnotes.

The effectiveness of an airborne sound insulator can be quantified by obtaining the transmission loss, TL, in decibels (dB) as described in ASTM E 90 (9) for laboratory tests and E 336 (4) for field tests. Experimentally, for diffuse sound fields, the transmission loss is normally obtained from⁵

$$TL = \bar{L}_1 - \bar{L}_2 + 10 \log \frac{S}{A_2} \quad (A1)$$

where

L_1 is average sound pressure level in the source room (dB),

L_2 is average sound pressure level in the receiving room (dB),

S is area of test partition (ft^2), and

A_2 is total absorption of the receiving room (fps Sabins).

The use of A_2 in the normalizing term $10 \log (S/A_2)$ is based on the assumption of a reverberant and diffuse sound field. It is usually obtained from

$$A_2 = \frac{0.049V_2}{T_2} \quad (A2)$$

where

V_2 is volume of receiving room (ft^3),

and

T_2 is reverberation time of receiving room (sec).

Equation (A1) provides the relationship between the gross property of the panel (i.e.,

TL) and the observable acoustic quantities (sound pressure level and absorption). We must, however, turn to detailed descriptions of the panel dynamics in order to provide a link between panel physical properties and TL.

Single-Panel Design

There are several available presentations for the TL of single-panel designs (e.g., 32, 35). The simplest case is for homogenous single-panel or integral-type partitions which, if they are "limp," can be represented by:⁶

$$TL \cong 10 \log \left[1 + \left(\frac{\omega \rho_s}{3.6 \rho c} \right)^2 \right] \quad (A3)$$

⁵All logarithms in this report are to base 10.

⁶Equation (A3) is given directly in reference (32), though this reference contains an error so that the derivation from reference (26) should have yielded.

$$TL \cong 10 \log \left[1 + \left(\frac{\omega \rho_s}{4.0 \rho c} \right)^2 \right]$$

(Based on private communication with Ted Schultz of Bolt, Beranek, and Newman, Cambridge, Mass.) Equation (A3) can be derived from (35)

$$TL \cong 10 \log \left[1 + \left(\frac{\omega \rho_s}{2 \rho c} \right)^2 \right] - 5$$

but the two expressions are not quite equivalent at low values of $\omega \rho_s$. The form of equations (A3) and (A4) is preferred for this analysis. The full justification for this preference will be the subject of a future report.

where

ω is angular frequency, $2\pi f$, where f is the frequency in cycles per second (Hz),

ρ_S is mass of panel per unit area,
 ρ is mass per unit volume of air,
 and

c is velocity of sound in air.

For $\omega\rho_S \gg 2\rho c$ the theoretical mass law can be written as:⁷

$$TL \cong 20 \log wf - 33.5 \quad (A4)$$

where

w is surface weight of panel (lb/ft²),

and

f is frequency (Hz).

For $TL = 10-15$ dB, equation (A3) is recommended, as differences in values between equations (A3) and (A4) can result through round-off to integer values.

Equation (A4) is known as the "field incidence limp-wall mass law" or more briefly as the mass law. In addition to noting that neither stiffness nor damping occurs (by assumption) in equation (A4), doubling the frequency or the panel surface weight results in a 6-decibel increase in TL. The mass of the panel interacting with its stiffness will always result in a resonant condition at some frequencies and can detract from its mass law performance. An example of this is in the text (fig.2) where a "resonant-like" condition known as the coincidence phenomenon has significantly lowered the transmission loss of 5/8-inch gypsum board above 1,800 Hz. There are several mass-stiffness conditions which are summarized ((23) and elsewhere) and include the finite size of the panel (especially first panel resonance), coincidence phenomenon, bending-shear wave crossover, and dilatational resonance. The frequency relationship of the coincidence phenomenon and the bending-shear wave crossover can be important to explaining the TL response for thicker panels such as doors, sandwich constructions, and concrete constructions. The dilatational resonance is likely to be important for sandwich constructions with porous cores such as foams and honeycombs. For the gypsum board facings used for the walls and ceiling, the mass law of equation (A4) will be adequate for the lower frequencies (text fig. 2) with the coincidence dip centering on a frequency obtained from:

$$f_c = \frac{c^2}{2\pi} \sqrt{\frac{\rho_S}{D}} \quad (A7)$$

where

D is bending stiffness per unit width (lb-in.²/in.)

This is the normal expression for the panel coincidence frequency and has the following physical meaning. Unlike compressional sound waves in air, which have a propagation velocity independent of frequency, the velocity of bending waves increases with increasing frequency. The critical frequency phenomenon occurs when the incident airborne sound energy has the same velocity as the bending waves: Energy transfer between the two types of waves is very efficient. The critical frequency, f_c , corresponds to the lowest frequency where the wave speeds are equal and occurs at lower angles of incidence to the panel. As the incident sound energy approaches normal incidence, there is a protected velocity of the incident sound energy for which coincidence occurs. Thus, the coincidence phenomenon occurs over a wide frequency range (text fig. 2) for 5/8-inch gypsum board. The depth of the coincidence dip is controlled by the internal

⁷ Equation (A4) is the approximate form of mass law recommended by Beranek (11) and is based on $rc = 83.1$ fps rays and the angle of incidence of the sound field integrated over 0 to 78°. There have been other mass law approximations such as that of Cremer and Heckl (15) and Josse and Lamure (26) which are based on an average angle of incidence = 60° (equivalent to integration from 0-82°) and give (using $\rho c = 86.0$ fps rays as specified in ASTM C 834 (σ)),

$$TL \cong 10 \log \left[1 + \left(\frac{\omega\rho_S}{4\rho c} \right)^2 \right] \cong 20 \log fw - 34.8 \quad (A5)$$

Some laboratories find that a mass law based on integration from 0-85° best fits their data, and this gives ($\rho c = 86.0$ fps rays)

$$\cong 10 \log \left[1 + \left(\frac{\omega\rho_S}{4.4\rho c} \right)^2 \right] \cong 20 \log fw - 35.6 \quad (A6)$$

While equation (A5) probably has a somewhat stronger theoretical justification, it is important to use the mass law appropriate to the laboratory or field data involved, especially if the double-panel approximate theory is used.

damping factor, η , of the panel. Methods for predicting the transmission loss-frequency response in the coincidence frequency range when η is known have been given (32,35).

Double-Panel Design

To provide quantification of the actual double-panel TL response, recent improvements in approximate theories by Sharp (32) founded on the works of Cremer and Heckl (15), London (27), and Vér and Holmer (35) can be used. The approximations include using infinite rather than finite panel theory, neglecting studs or joists and assuming about 2 inches of cavity absorption so that stud cavity resonances can be ignored. Assumptions regarding the angular distribution of sound energy at the panel faces are also made. Under these conditions, the TL response of a double-panel party wall can be divided into three frequency regions by the mass-air-mass cavity resonance, f_0 , and a limiting frequency, f_l (fig. A1). Then, for panels 1 and 2 (32),

$$f_0 = \frac{1}{2\pi} \left[\frac{3.6\rho c^2}{dw'} \right]^{1/2} = 320 \left[\frac{1}{dw'} \right]^{1/2} \quad (A8)$$

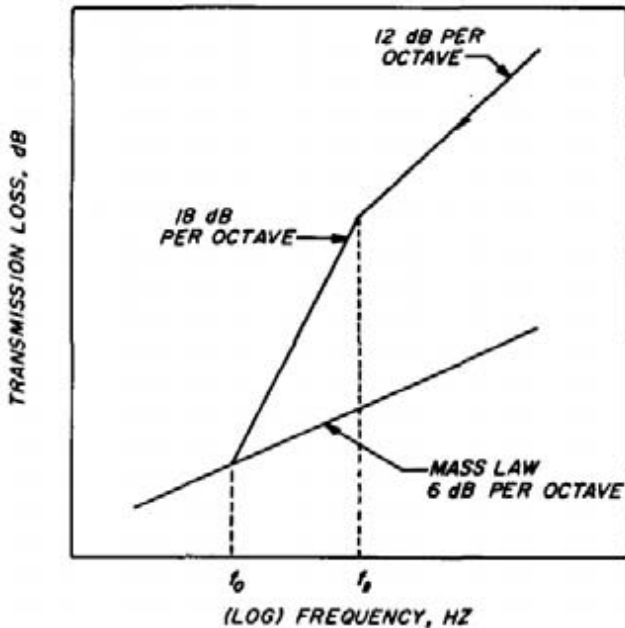


Figure A1.—General form of transmission loss vs. frequency for a double panel, showing the three frequency regions defined by f_0 and f_l .

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where

d is panel separation or cavity depth (in.), and

$$w' \text{ is } \frac{2w_1 w_2}{w_1 + w_2} \text{ where } w_1 \text{ and } w_2 \text{ are}$$

the surface weights of the panels (lb/ft^2).

Equation (A8) is valid for a double-panel construction where f_0 is well above the first panel resonance. In a double-panel wall design, f_0 is normally kept low by increasing d to prevent the rapid TL rise above f_0 from limiting the STC rating. The limiting frequency, f_l , is the frequency where the wavelength becomes comparable to the double-panel separation and is given by (32)

$$f_l = \frac{c}{2\pi d} \quad (A9)$$

The usual expression for f_0 (35) uses $2\rho c^2$ rather than $3.6\rho c^2$ as derived by Sharp, under the approximations already listed. The use of 3.6 assures (fig. A1) that f_0 comes at the intersection of the 18 dB/octave line with the 6dB/octave mass law line.⁸

Then under the assumptions already listed:

$$TL = 20 \log Wf - 33.5 \quad f < f_0 \quad (A10)$$

$$TL = TL_1 + TL_2 + 20 \log fd - 60.8 \quad f_0 < f < f_l \quad (A11)$$

$$TL = TL_1 + TL_2 + 6 \quad f > f_l \quad (A12)$$

⁸If mass law expressions different from equation (A4) are used, then corresponding adjustments in f_0 must also be made.

For example, equation (A5) would require

$$f_0' = \frac{1}{2\pi} \left[\frac{4.0\rho c^2}{d\rho_s} \right]^{1/2} = 340 \left[\frac{1}{dw} \right]^{1/2}$$

Equation (A6) would require

$$f_0 = \frac{1}{2\pi} \left[\frac{4.4\rho c^2}{d\rho_s} \right]^{1/2} = 360 \left[\frac{1}{dw} \right]^{1/2}$$

where

- W is the sum of panel surface weights, $w_1 + w_2$ (lb/ft²),
- TL_1 is transmission loss of Panel 1, which for a limp mass is $20 \log w_1 f - 33.5$.
- TL_2 is transmission loss of Panel 2, which for a limp mass is $20 \log w_2 f - 33.5$, and
- d is panel separation or cavity depth (in.).
- f is frequency (Hz)

In summary for equations (A10), (A11), and (A12): Below f_0 , the TL follows the mass law (6 dB/octave) based on the total surface weight of the panels: between f_0 and f_1 , the TL is the sum of the separate panel TL's plus a correction for cavity thickness (18 dB/octave); above f_1 , the TL is the sum of the separate panel TL's plus a constant (12dB/octave). The TL_1 and TL_2 may also be obtained experimentally for the separate leaves and then combined through equations (A10), (A11), and (A12) to predict the double-panel TL. An example of this is (fig. A2) for 5/8-inch gypsum board panels with a 4-inch cavity, cavity insulation, and no studs. Good agreement exists between

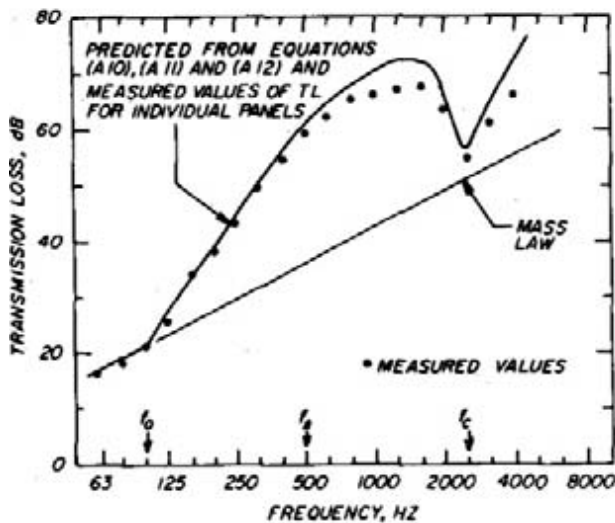


Figure A2.—Comparison of measured and calculated transmission loss (TL) for a double-panel wall using 5/8-inch gypsum board panels 4 inches apart with 2 inches of absorption in the cavity (32). See figure 2 in text.

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theory and experiment—even in the coincidence region (the use of the coincidence TL's may not always be valid). The disagreement in figure A2 between experiment and theory between 1,000 and 1,600 Hz may have been perimeter flanking, as it was necessary to seal the perimeter of the construction. Additional examples of double-panel predictions are given in the data analysis section. These predictions are effective up to about $(1/2) f_c$.

Triple-Panel Design

For a triple-panel design, an approximate theory similar to that for double-panel walls can be derived (32). For three panels w_1 , w_2 (center), and w_3 with d_1 = separation between w_1 and w_2 , and d_2 = separation between w_2 and w_3 , the TL response can again be divided into three frequency ranges by mass-air-mass cavity resonance, f_+ , and a limiting frequency, f_l (fig. A3). For a triple-panel wall with absorption equivalent to at least 2 inches of fiberglass batts in each cavity and no sound bridges:

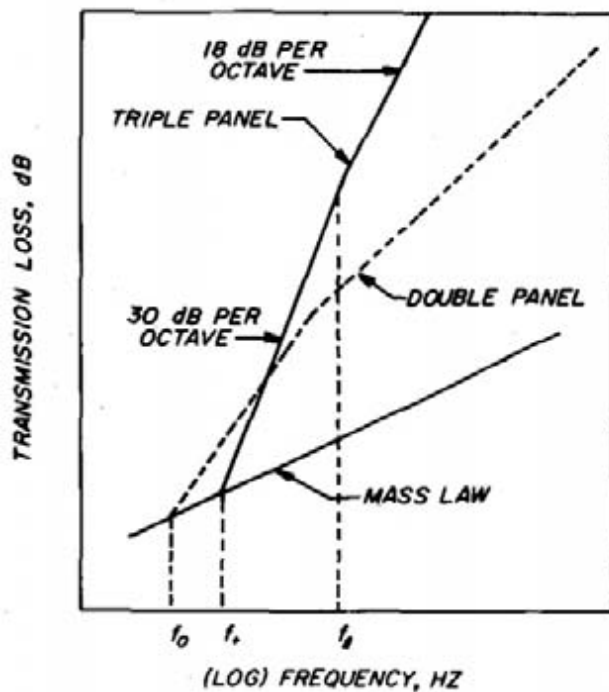


Figure A3.—A comparison of the transmission loss (TL) provided by double- and triple-panel constructions of equal total mass and overall thickness (32).

(M 146 156)

f_B , as for double-panel theory. Above f_B , the sound transmission is controlled by the point (or line) connections, and the TL increases at 6 dB/octave.

Because the bridged TL response is parallel to the mass law line above f_B , a convenient way of expressing the TL is in terms of ΔTL_W , the increase in the TL over the mass law based on total surface weight of the panels. For point connections (to one panel only):

$$\Delta TL_{WP} = 20 \log (ef_c) - 51, \text{ for } w_1 = w_2 \quad (\text{A18})$$

For line connections:

$$\Delta TL_{WL} = 10 \log (bf_c) - 29, \text{ for } w_1 = w_2 \quad (\text{A19})$$

where

- e is point lattice spacing (ft),
- e^2 is area associated with each point connection,
- b is line stud separation (ft), and
- f_c is critical frequency of panel supported by point connections or, in the case of line connections, the higher critical frequency of the two.

When ΔTL_W is known, f_B can be calculated from (32):

$$f_B = f_0 \text{ antilog } \frac{\Delta TL_W}{40} \quad (\text{A20})$$

For equation (A18), the panel with the highest f_c should be mounted on the side of the stud with the point connections. (Sharp noted experimentally that not much is gained by using point connections on both sides of wood studs.) It must be recognized, however, that equations (A18) and (A19) do not account for the effects of coincidence in either of the two panels. Thus the method of adding the quantity ΔTL_W to obtain the overall transmission loss of the bridged double panel is valid only up to about $(1/2)f_c$ of the point-attached panel.

The TL data for Wall B (25) exemplify a resilient-point connection (fig. A5). This construction consists of 2 x 4 studs, 16 inches on center (2-1/2-in. insulation in the study cavity) with 5/8-inch type-X gypsum board (2.34 lb/ft²) mounted directly to one side of the studs and over resilient channels (applied horizontally on 24-in. centers) on the other side. First, it may be noted that the predicted increases over mass law of the combined panels are close to experiment up to 1,250 Hz. Above this frequency the coincidence phenomenon, which is not included in the prediction, dominates. Second, the

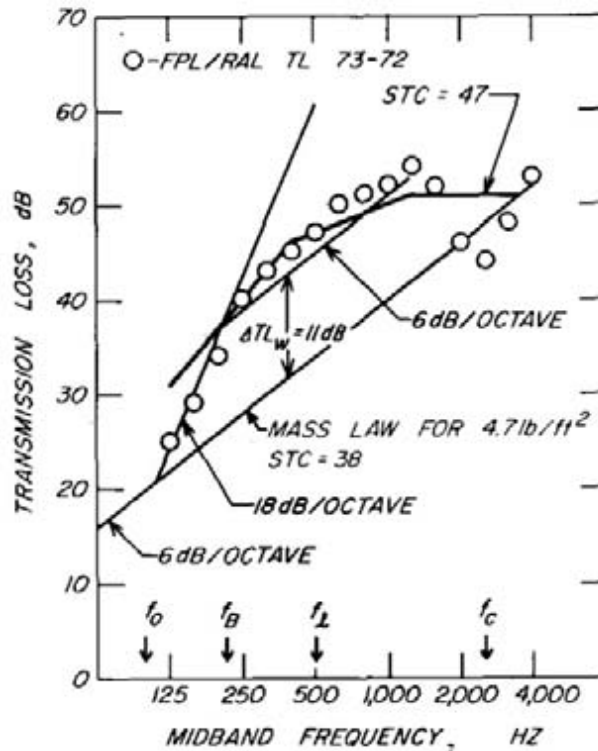


Figure A5.—Transmission loss vs. frequency data obtained in a laboratory for a single-row-of-wood-stud (16 in. o.c.) wall with a 2-1/4-inch fiberglass absorption in the stud cavities. The facings were 5/8-inch gypsum board with one side directly attached and the other side over resilient channels. The good correspondence between the data and approximate theory indicate that the resilient channels perform similar to, though a little better than, point connections.

(M 143 850)

“resilience” of the channels provides a small improvement over the rigid-point connections on which the theory is based.

In summary, for the approximate TL theory, a very useful analytical tool has been provided for explaining the TL for single-panel, double-panel, triple-panel, and single-row-of-stud partitions with point or line connections. The theory can be applied using theoretical mass law over the frequency range for which it applies to panels. The theory can also be applied using the TL data obtained for individual panels. In this case the theory may work for TL data in the coincidence frequency region, though this cannot be assumed in general. The theory cannot only be used to explain or make plausible existing partition TL responses, but it can also be used to study TL parameter interaction in wall and floor-ceiling design.
