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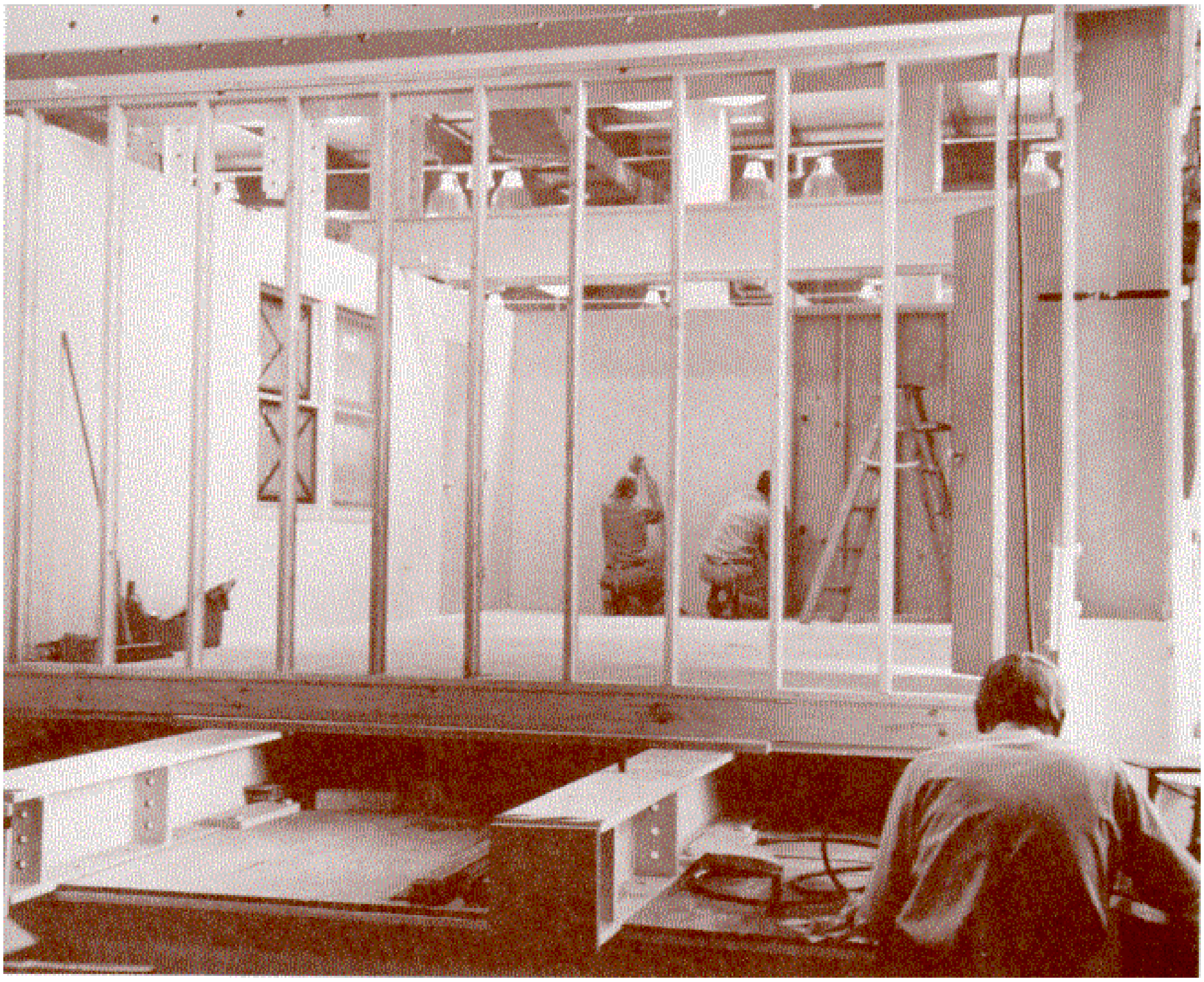
Light-Frame Wall and Floor Systems

Analysis and Performance

G. Sherwood
R. C. Moody



Abstract

This report describes methods of predicting the performance of light-frame wood structures with emphasis on floor and wall systems. Methods of predicting structural performance, fire safety, and environmental concerns including thermal, moisture, and acoustic performance are addressed in the three major sections.

Keywords: Light-frame, wood construction, walls, floors, structural performance, fire safety, thermal performance, moisture, noise control, acoustics

Acknowledgments

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Part 11, consisting of Chapters 5 and 6, was authored by Erwin L. Schaffer, Robert White, and John Brenden of the Forest Products Laboratory.

In Part III, Chapter 7 is a revision of a paper by Hans; Chapter 8, a revision of a paper by Labs and Watson; Chapter 9, a revision of a paper by Sherwood and TenWolde; and Chapter 10, a revision of a paper by Rudder and Jones.

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Abbreviations

The following organizations are frequently referred to in the text by their initial letters, as shown below.

American National Standards Institute . . . ANSI

American Plywood Association . . . . APA

American Society of Civil Engineers . . . . . ASCE

American Society of Heating, Refrigerating and Air-Conditioning Engineers . . . . ASHRAE

American Society for Testing and Materials . . . . ASTM

Associate Committee on the National Building Code . . . . AC-NBC

Building Officials and Code Administrators International, Inc. . . . . BOCA

Central Housing Committee on Research Design and Construction . . . . . . CHC

Federal Housing Administration . . . . FHA

Forest Products Research Society . . . . FPRS

International Conference of Building Officials . . . . ICBO

National Association of Home Builders . . . NAHB

NAHB Research Foundation . . . . NAHB-RF

National Bureau of Standards . . . . NBS

National Forest Products Association . . . . NFPA

Southern Building Code Congress . . . . SBCC

Timber Research and Development Association . . . . TRADA

Underwriters' Laboratories . . . . UL

U.S. Department of Agriculture, Forest Service, Forest Products Laboratory . . . . FPL

U.S. Department of Commerce, National Technical Information Service . . . . NTIS

U.S. Department of Energy . . . . DOE

U.S. Department of Housing and Urban Development . . . . HUD

Part I
Structural Performance

Structural adequacy is the fundamental requirement for light-frame buildings and, therefore, the first subject to be discussed in Part I of this report. Other subjects of primary importance are fire safety and the economy and comfort of the living environment, and these are discussed respectively in Part II and Part III. Each factor is considered together with methods of predicting the expected performance based on material properties and construction techniques.

Important items of safety and living environment depend on having a structurally adequate enclosure that resists the elements of rain, snow, and wind. Because appropriate materials are required to achieve an adequate enclosure, wood structural materials are considered in the first chapter, then the performance of structural systems (walls and floors) and methods of analyzing the response of these systems to imposed loads.

Floors must support occupancy loads while walls support a combination of loads caused by wind, occupants, and loads on the roof. For satisfactory behavior, each must support its loads without excessive deflections, deformations, or vibrations.

Part I
Structural Performance

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Chapter 1
Wood Structural Materials

Introduction

Wood structural materials for light-frame construction are classified as lumber or panel products. For these products, particular design values (allowable properties or stresses) are associated with specific species and grades. The increasing use of both lumber and panel products in manufactured components that involve engineering design has brought a growing awareness of the need for improved accuracy in assigning design values. Methods for achieving this accuracy for lumber are presented. Panel products are manufactured from reconstituted material, and properties can be controlled to a large extent in the fabrication process.

Lumber

Visually Graded Lumber

Visually graded lumber is commonly used for light-frame structures. The present system for assigning engineering design values to visually graded lumber has worked well when measured by the criteria of excellent performance in the full range of structure types from housing to highly engineered industrial or commercial buildings. Two ASTM standards are presently used to develop these design values. The first, D 2555 (ASTM 1984a), commonly called the "clear wood standard," provides average properties of clear material and a measure of their variability for all commercial species, both in the United States and Canada. In this standard, methods are also provided for the grouping of species and the determination of the strength and stiffness of clear, straight-grained unseasoned wood.

The other applicable standard, D 245 (ASTM 1984b), covers the basic principles for grading structural lumber visually and for establishing related design values. It also includes necessary procedures for the formulation of structural grades of the desired strength ratio (that is, the anticipated strength after allowance is made for the effect of maximum permitted knots, cross grain, and other strength-reducing characteristics occurring in a given grade). Strength ratios are expressed as a fraction of the strength of clear, straight-grained lumber. ASTM D 245 provides modifications for design use in response to variations of size and moisture content of lumber, duration of load, multiple-member systems, and the chosen safety factor. However, it is limited by the existence of some degree of uncertainty in all of the adjustment factors that are applied to convert the strength of small clear, straight-grained specimens to design values.

Specifying Visually Graded Lumber

Visually graded structural lumber should be specified to meet the requirements of the American Softwood Lumber Standard PS 20-70 (U.S. Department of Commerce, current issue) which standardizes methods of lumber grading and lumber sizes throughout the

United States. Several grading agencies (table 1-1) have prepared rules that follow PS 20 along with the previously noted ASTM standard, and each piece of lumber should be stamped with a recognized grade mark to assure that it is of the proper quality (fig. 1-1).

Softwood dimension lumber is categorized as follows:
Boards – lumber less than 2 inches in nominal thickness
Dimension – lumber from 2 inches to (but not including) 5 inches in nominal thickness
Timber – lumber 5 or more inches in thickness in the least dimension
Standard lumber sizes are given in table 1-2.

For light-frame construction, dimension lumber is the most commonly used. Part of PS 20–70 includes a national grading rule for dimension lumber between 2 and 4 inches in nominal thickness. Visual grades established according to this national grading rule are given in table 1-3. Descriptions of the grades are found in rule books available from the agencies given in table 1-1. Engineering design values for these grades of different species or species groups are also available from these agencies and are published in the National Design Specification (NFPA, latest issue). Before proceeding very far with the design process, the designer and/or builder should determine the availability of speciks and grades in the area.

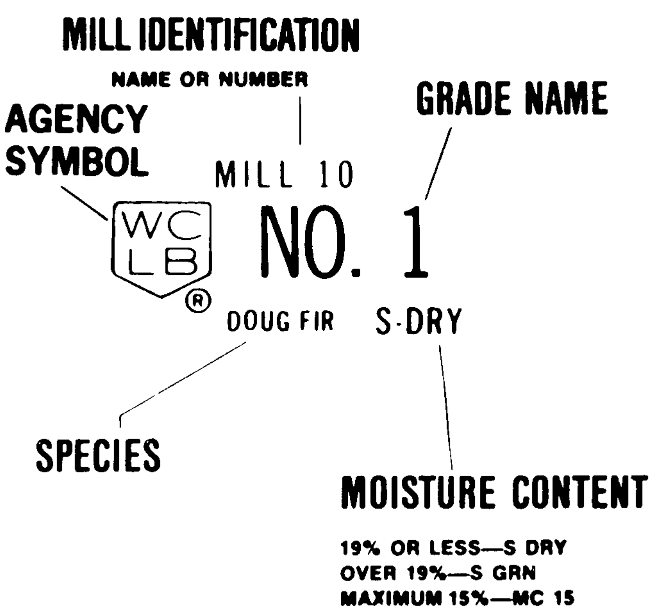

Figure 1-1 – Example of grade mark for lumber. (ML88 0001)

Machine Stress Rated Lumber

Machine stress rated (MSR) lumber utilizes a combination of visual and mechanical evaluations to grade pieces of lumber. Grade stamps on each piece indicate the species, moisture condition at time of manufacture, modulus of elasticity (E), and fiber stress in bending (F_b). Machine certification procedures involve the sampling and testing of material that (a) meets the visual requirements of the grade and (b) has been placed in that grade because of the stiffness (E) found by the machine. Each piece in the sample is physically tested for strength and stiffness to determine whether it fully meets not only the E but also the F_b requirements of the grade.

Table 1-1 – Organizations that publish stress-grade rules conforming to American Lumber Standard and provide grading services

Organization and Service	Mailing address
Stress-grade rules and grading services	
Northeastern Lumber Mfrs. Assoc.	272 Tuttle Road P.O. Box 87A Cumberland, ME 04021
Redwood Inspection Service	One Lombard Street San Francisco, CA 94111
Southern Pine Inspection Bureau	4709 Scenic Highway Pensacola, FL 32504
West Coast Lumber Inspection Bureau	Box 23145, 6980 S.W. Varns Road Portland, OR 97223
Western Wood Products Assoc.	522 SW 5th Avenue Portland, OR 97204-2122
National Lumber Grades Authority	1460-1055 W. Hastings St., Vancouver, BC Canada V6E 2G8
Grading services	
East Coast Lumber Inspection	P. O. Drawer 970 Perry, FL 32347
California Lumber Inspection Service	1190 Lincoln Avenue San Jose, CA 95125
Pacific Lumber Inspection Bureau, Inc.	1411 Fourth Avenue Building Suite 1130 Seattle, WA 98101
Timber Products Inspection and Testing Service, Inc.	P.O. Box 919 Conyers, GA 30207

Table 1–2 – American Standard lumber sizes for stress-graded lumber for construction[1]

Item	Thickness			Face width		
		Minimum dressed			Minimum dressed	
	Nominal	Dry	Green	Nominal	Dry	Green
	– – – – – – – –	– – – – – – – –	– – – – – – – –	-in – – – – – – – –	– – – – – – – –	– – – – – – – –
Dimension	2	1-1/2	1-9/16	2	1-1/2	1-9/16
	2-1/2	2	2-1/16	3	2-1/2	2-9/16
	3	2-1/2	2-9/16	4	3-1/2	3-9/16
	3-1/2	3	3-1/16	5	4-1/2	4-5/8
	4	3-1/2	3-9/16	6	5-1/2	5-5/8
	4-1/2	4	4-1/16	8	7-1/4	7-1/2
				10	9-1/4	9-1/2
				12	11-1/4	11-1/2
				14	13-1/4	13-1/2
				16	15-1/4	15-1/2
Timbers	5 and greater		1/2 less than nominal	5 and greater		1/2 less than nominal

[1]Nominal sizes in the table are used for convenience. No inference should be drawn that they represent actual sizes.

Table 1–3 – Visual grades described in the National Grading Rule[1]

Lumber classification	Grade names
Light framing (2 to 4 in thick, 2 to 4 in wide)[2]	Construction Standard Utility
Structural light framing (2 to 4 in thick, 2 to 4 in wide)	Select Structural 1 2 3
Studs (2 to 4 in thick, 2 to 6 in wide)	Stud
Structural joists and planks (2 to 4 in thick, 5 in and wider)	Select Structural 1 2 3
Appearance framing (2 to 4 in thick, 2 in wide or wider)	Appearance

[1]Sizes shown are nominal.
[2]For widths narrower than 4 in, contact rule-writing agencies (Table 1-1) for additional information.

Tensile values (F_t) are assigned to each E-F_b classification on the basis of previous tests of lumber (primarily of the 2 by 4 size) and are related to the F_b level. Design values for compression parallel to grain (F_c) are established on the basis of 80 percent of the assigned bending values. Design values for horizontal shear and compression perpendicular to grain are assigned the same as the design values for visually graded lumber because they are independent of grade.

During each shift of an MSR mill's operation, each MSR grade and size is sampled and tested to determine continued conformance to the E and F_b design values assigned to each grade, thus maintaining continuous monitoring of the output for these properties.

Proof Loading

Proof loading is a method for assessment of design values that has been advanced in recent years, a proof load being equivalent to the assigned design value multiplied by the appropriate duration of load adjustment and safety factor. If every piece of lumber could be subjected to the correct level of proof load for each property of interest, nearly 100 percent confidence could be placed in the performance of each piece. However, it would be extremely difficult and expensive to provide this level of confidence.

In the glued-laminated timber industry, some manufacturers are using bending procedures for proof-testing tension laminations for glued-laminated beams. Also, some truss manufacturers are using tension loading for tension chords. While this procedure is not likely to be utilized in the thousands of sawmills producing visual and machine-rated dimension lumber in this country, it has some definite applications to specialty products.

National In-Grade Lumber Testing Program

In 1977, the U.S. Department of Agriculture, Forest Service, Forest Products Laboratory and three agencies for writing lumber rules met to develop plans for the study of the performance of light-frame structures (Pinson 1983). This project was later expanded to include Canada. A research program resulted, caused indirectly by three factors: (1) Some new lumber results contradicted allowable values established by earlier research, (2) concepts of reliability based design had increasing importance, and (3) changes occurred in interpretation of product liability law.

The research program developed on the premise that light-frame structures perform well but that, if we are to describe this performance analytically, realistic design procedures and product performance data are needed (Galligan et al. 1980). The in-grade program investigated performance relating to mechanical and structural properties of light-frame construction, its original objectives being (a) to characterize properties of lumber furnished to the consumer, (b) to evaluate ASTM-based grading procedures, and (c) to characterize analytically how light-frame structures perform.

Part I of the in-grade program consisted of tests of 2 by 4 Stud grade and 2 by 8 No. 2 Douglas Fir and Southern Pine, and was limited to flexural properties. Results of the tests have been used to predict the structural performance of wall and floor systems built using this type of lumber (Polensek and Gromala 1984; Vanderbilt et al. 1983).

In Part 11, the tests evaluated flexural and also tension and compression properties of other grades and sizes of Douglas Fir and Southern Pine and a full array of grades and sizes of Hem-Fir. Part III included other species. A summary of the results is available (Green and Evans 1987).

Panel Products

Plywood was the basic structural panel for many years, and particleboard has been used in applications such as mobile home flooring. However, other types of structural panels are now on the market. The structural panel products referred to as structural flakeboards, introduced over the past 20 years, are of two basic types. The first, referred to under the generic heading of waferboard, was first introduced commercially in Canada in the mid-1960's, and production volume has recently grown considerably both in Canada and in the United States. The second type, usually discussed under the general label of oriented strandboard (OSB), is a newer product, first produced commercially in 1981. Changes in manufacturing technology are continually occurring and, in some instances, it may be difficult to differentiate between waferboard and OSB (O'Halloran and Youngquist 1984).

Although their appearance and properties differ to a considerable degree, plywood and the other panel products are marketed together as structural sheathing. These products can be used interchangeably to satisfy various structural requirements if it is specified that they conform to the American Plywood Association Performance Standard (APA 1982, O'Halloran 1982).

Plywood

Plywood is a glued wood panel made up of relatively thin layers or plies (or veneers), with the grain of adjacent layers at an angle, usually 90°. The usual construction has an odd number of plies, but even numbers of plies are also common. Often, with four-ply or six-ply panels, the inner two plies are laid with parallel grain, resulting in a rather thick central layer of wood.

Regardless of the number of plies, the outside plies are called faces or face and back plies, the inner plies are called cores or centers, and the plies immediately below the face and back are called crossbands. The core may be veneer, lumber, or particleboard, and, for most structural applications in light-frame construction, the total panel thickness varies from 1/4 inch to about 1-1/4 inch. The plies may vary as to number, thickness, species, and grade of wood.

As compared with solid wood, the chief advantages of plywood are that it has design values both for the length and width of the panel; it has greater resistance to splitting; it is available in large sheets, which permits many useful applications; and it is more dimensionally stable in the cross-panel direction. Use of plywood may result in improved utilization of wood; it covers large areas with minimal amounts of wood fiber, especially in applications using plywood that is thinner than sawn lumber.

The properties of plywood depend on the quality of the different layers of veneer, the order of layer placement in the panel, the glue used, and the control of gluing conditions in the gluing process. The grade of the panel depends upon the quality of the veneers used, particularly of the face and back. Face veneers and other plies may contain certain sizes and distributions of knots, splits, or growth characteristics that have a minimal effect on the strength properties required for specific uses. Such uses include structural applications such as sheathing for walls, roofs, or floors. The durability of the panel depends to a large extent upon the glue joint, particularly its water resistance.

Particleboard

Particleboard differ from the other structural panels in that the raw material is commonly the residue from systems for processing solid wood. The boards are manufactured from particles that tend to be small and result in lower structural performance than other panel products. Additional strength and stiffness can be obtained by increased resin content and/or additional thickness. In light-frame construction, the use of particleboard for primary structural purposes is limited. The most common secondary structural use is for floor underpayment.

Waferboard

Waferboard is a nonveneered, structural panel. In the past few years, waferboard production has experienced a tremendous expansion, with manufacturing firms taking advantage of the supplies of low-cost raw material from central and eastern Canada and upper Midwestern and northeastern United States.

Although it is manufactured under various trade names, waferboard is essentially a generic product with only minor differences from one manufacturer to the next. It is generally manufactured from low-density hardwoods (predominantly aspen), although at least one manufacturer utilizes spruce. Such species are ideal for two reasons: first, the low density facilitates material compaction which must take place during processing to achieve adequate panel properties; and second, the woods used are easily cut into the flakes required in manufacturing. Researchers have known for years the beneficial relationship between the geometry of flakes (large particles having large length-to-thickness ratios) and panel properties. Waferboard's construction is derived in part from using knowledge of this relationship.

Waferboard is composed of rather large, rectangular (2- by 2-in to 3- by 3-in), somewhat thick (0.030- to 0.035-in) chips (wafers) flaked from log segments and bonded together with a powdered phenolic resin. A typical waferboard product made from aspen is shown in figure 1-2. Marketed as a commodity sheathing panel, waferboard has enjoyed acceptance in several applications.

Oriented Strandboard

One drawback to waferboard is that it generally has lower structural bending stiffness and strength characteristics than plywood. Montrey (1983) states that a typical waferboard panel has approximately one-third of the E value in flexure of west coast Douglas Fir plywood in the panel direction. A perceived need for panel stiffness and strength greater than those of waferboard has spurred the evolution of technology — both product and process development – which has led to the introduction of OSB.

OSB is composed of three or five layers of aligned strands which are similar to wafers but possess length much greater than their width. In essence, strands are wafers that have been split along the wood grain so that they are much longer in the natural grain direction than across the grain. Strands in the panel top and bottom surface layers of OSB are aligned parallel to the panel direction, while strands in the core layer are aligned in the cross-panel direction. In essence, the OSB panel configuration is a mimic of plywood's construction. Strand alignment in the surface layers imparts panel stiffness and strength, analogous to the role of plywood face and back veneers. Cross alignment of strands in the core elevate cross-panel dimensional stability, as do core veneers in plywood.

Another significant difference exists between waferboard and OSB. Whereas in waferboard manufacture, powdered phenolic resin is generally used as the adhesive, OSB is currently bonded with phenolic resin that is applied in the liquid state during manufacture.

The properties of OSB panels are very nearly equal to those of plywood. A typical OSB panel made of aspen is pictured in figure 1-3. OSB's strand geometries are different from waferboard's wafer geometries, causing differing surface appearances; and the alignment of strands is quite noticeable on the surface.

Product and Performance Standards

Historically, plywood and particleboard have been manufactured according to national product standards such as ANSI A199.1 (formerly PS 1-83) for Construction and Industrial Plywood (ANSI 1983) or ANSI A208.1 for Mat-Formed Wood Particleboard (ANSI 1979). These standards are prescriptions for manufacturing an acceptable product, and the emphasis is placed on the manufacturing process. The user or code authority is left to determine the proper use.

Performance standards such as those promulgated by the American Plywood Association (APA 1982) are a recent development from a different approach. In such standards, the emphasis is placed on the end-use and the associated performance requirements. The objective of these performance standards is to assure that the product will satisfy the requirements of the application for which it was intended. Thus, performance standards must define performance criteria and test methods.

In the case of APA-rated sheathing, the panels are intended for roof, wall, and subfloor covering. Different products are span-rated for their particular end use. Floor and wall supports can range from 16 to 48 inches and wall studs between 16 and 24 inches for different products.

In order for a product to meet the performance standard, it must first pass a rigorous series of qualification tests which investigate properties in three major areas; structural adequacy, dimensional stability, and bond performance. Once a product has qualified for a specific series of span ratings, a mill specification is developed to describe both the process of its manufacture and its expected properties. A continuous quality assurance program must be followed to assure maintenance of an adequate level of product performance. The performance standard then requires that each panel must be stamped to certify that it is adequate for specific uses. An example of such a stamp is shown in figure 1-4.

Using the performance standard approach, a broader range of product types is available for any particular use, and the builder or consumer can select the most economical option.

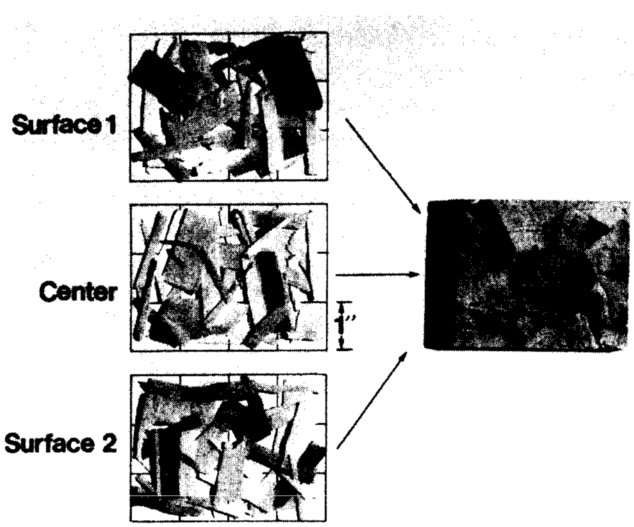

Figure 1–2 – Typical waferboard product showing type and orientation of flakes used throughout the thickness of the board.
(M 150 293)

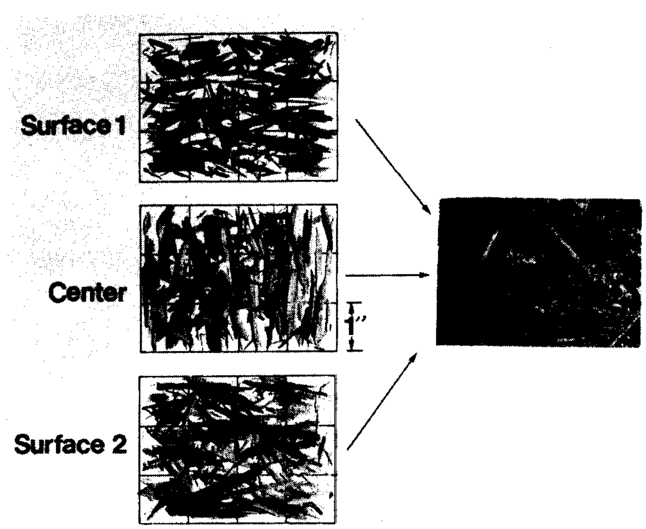

Figure 1–3 – Typical oriented strandboard product showing type and orientation of strands throughout the thickness of the board.
(M 150 294)

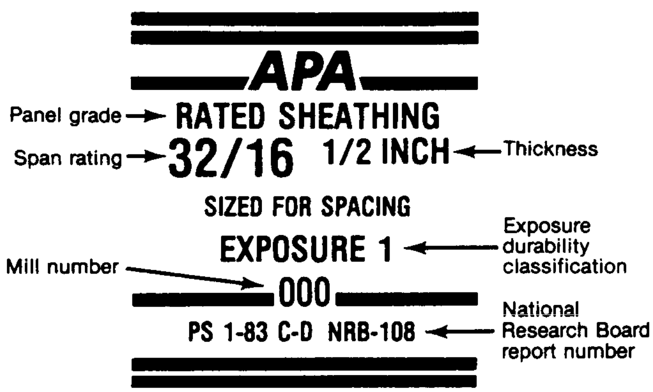

Figure 1–4 – Example of grade mark for panel products meeting the American Plywood Association performance standard. (ML88 0000).

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Chapter 2
Floors

Introduction

Light-frame floors contain multiple parallel joists as the main structural elements. For the first half of this century, board sheathing was used to distribute the vertical loads to the joists; but for the last 30 years, sheet products have almost completely replaced boards as the preferred sheathing.

Wood floor systems have long been designed by considering the joists to act as simple beams having similar properties and acting independently, both of each other and of the other materials composing the floor. It has been assumed that the sheathing's only function is to transfer loads to the joists.

These assumptions neglect many factors that affect the strength and stiffness of a floor. Moreover, the design procedure does not provide for improving methods of design to utilize modern materials and methods of construction.

Background

In a floor, the stiffness and strength of the joists alone are supplemented by interaction between the joists and the sheathing. Several researchers have investigated this interaction.

In tests performed at the Forest Products Laboratory (FPL) over 30 years ago (Heebink 1951), the additional stiffness resulting from diagonal board subflooring and hardwood finish floor was only about 10 percent. Russell (1954) concluded from this that "the traditional custom of neglecting the subfloor and finish floor, and designing on the basis of the joists alone, appears to be sound practice." However, later studies that investigated more modern construction materials and techniques revealed larger improvements in performance. Onysko (1970) provided an excellent summary of early floor research.

The National Association of Home Builders (1961) noted a 13 percent stiffness increase with a nailed plywood subfloor and a 38 percent increase when the plywood was nail-glued to the joists. Williston and Abner (1962) reported that complete floor systems deflected an average of 40 percent less than the joists alone and Hurst (1965) also reported substantial increases in stiffness resulting from composite action and other factors. Polensek et al. (1972) tested 44 floors and reported average stiffness increases of 15 to 104 percent. These studies and others (e.g. Corder and Jordan 1975; Vanderbilt et al. 1974) demonstrated that composite action can add significantly to a floor's performance.

The assumption that all joists have equal properties ignores the natural variability of wood building materials. Although the bridging effect of sheathing tends to minimize differences in joist deflections when floors are subjected to uniform loads (Polensek et al. 1972; Vanderbilt et al. 1974), the ability of sheathing to distribute loads, when variations in joist properties are large or loads are concentrated, is an important consideration in defining the actual performance of wood-joist floors.

Performance Factors

Codes and standards for floors generally state performance requirements as deflection limits and are not explicit about the length of time a load is applied. A deflection limit of 1/360 of the span is used in a majority of cases; however, 1/240 of the span is permitted by the Basic Building Code (BOCA 1975) where there is no plaster ceiling under the floor. The Southern Standard Building Code (SBCC 1979) does not state deflection limits, but states percent of recovery from deflection after the load is removed. The usual strength requirement is 2-1/2 times the design load. However, the Southern Standard Building Code (SBCC 1979) requires only double the design load.

The usual uniform load requirement for use in calculating deflections is 40 pounds per square foot (lb/ft^2) for first floor and 30 lb/ft^2 for second floor or bedrooms; however, the Uniform Building Code (ICBO 1979) requires 40 lb/ft^2 for all floors. There is no general agreement on maximal weight of concentrated loads to be applied or their area of application. Loads vary from 200 to 400 pounds and the area of application varies from a 5/8-inch diameter to a 3-inch diameter. None of the codes or standards directly address vibration of floors which appears to be a major criterion for acceptance.

The National Forest Products Association span tables for joists (NFPA 1977) are often cited for guidance in the selection of joists. These tables assume some load sharing by allowing a 15 percent increase for design stress in bending where repetitive members are no more than 24 inches apart. Joists are designed to carry assigned loads, and no consideration is given to sheathing.

The primary attributes of light-frame floors that cause them to behave differently from what simple beam theory predicts are:

(1) Composite Action – A floor joist does not act alone as a simple beam in carrying the imposed loads. The sheathing acts with the joist to form a composite T-beam. The joist acts as the web of the beam and the sheathing acts as the flange. This composite beam, however, cannot be analyzed by the simple equations defining the properties of most built-up sections. Because wood floors employ nonrigid connectors in fastening the sheathing to the joists, there is a slip plane between the two elements. Also, the presence of gaps in the sheathing disrupts the continuity of the flange and further complicates the analysis.

(2) Two-Way Action – The sheathing performs a second important function in distributing the load among the joists. The sheathing acts as a wide shallow beam that spans continuously over several joists. It reduces differences in individual joist deflections which would otherwise result from variability in the joist's properties. The stiffer the sheathing in the perpendicular-to-joist direction, the greater the two-way action and the less the variation in joist deflections.

Composite Action

The strength and stiffness added by composite action depend upon the axial stiffness of the flange (sheathing), the interlayer slip stiffness, and the presence or absence of gaps in the flange in the direction of the joist span. If the sheathing is rigidly fastened to the joist and there are no gaps, the behavior is fully composite and the T-beam's properties can be calculated by a simple analysis of the transformed area. If there is no connection between sheathing and joist, the two elements act as independent bending members in carrying the load; the contribution of the sheathing is usually negligible compared to that of the joist. Between these two extremes lies the case of most practical interest and greatest mathematical complexity.

When mechanical fasteners, such as nails or screws, are used to attach the sheathing to the joists, there is a certain amount of slip at the joist-sheathing interface. The degree to which the fasteners resist slip depends upon their lateral load/slip stiffness and the spacing between them. Although the relationship between lateral load and slip is nonlinear for most fasteners, most analyses assume a linear relationship. For such connectors, the interlayer stiffness, S, is equal to k/s, where k is the nail stiffness (i.e. load/slip ratio) and s is the spacing between individual connectors. For adhesives, S = Gb/t, where G is the shear modulus of the glue, and where b is the width and t the thickness of the glueline. The assumption of linearity is a reasonable simplification in the ranges of design load because the main load-carrying elements, the joists, do behave linearly and the overall behavior of the composite beam is very nearly linear.

Gaps in the sheathing can drastically reduce the amount of the composite action. For example, inserting a single gap at midspan in a previously continuous flange has the same effect as dividing the connector stiffness by four. Since sheathing manufacturers usually specify that gaps be left between individual sheets when their products are installed, analysis techniques must be able to account for the presence of gaps.

Figure 2-1 demonstrates how the interlayer stiffness, S, and the gap distance, L', affect the stiffness of a joist. The figure gives the midspan deflection for 2 x 6 joist supporting 40 lb/ft^2 over a 12-foot span as a function of the product SL'^2. For mechanical fasteners, S may be in the range 2,000 to 5,000 pounds per square inch (lb/in^2) and L' typically is 48 inches.

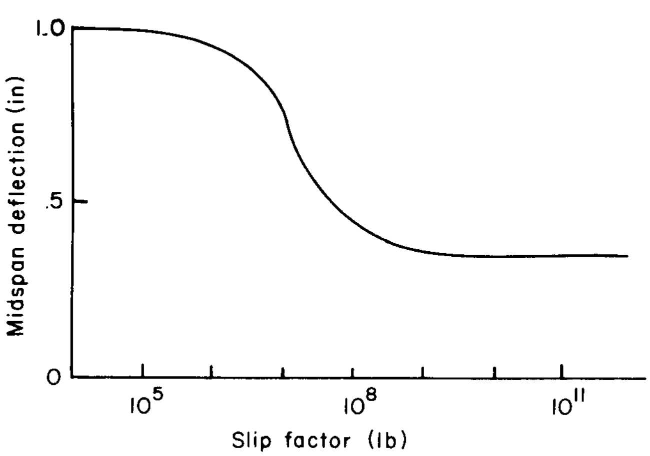

Figure 2–1 – Reduction in joist deflection resulting from composite action. (ML88 0002)

Two-Way Action

In the direction perpendicular to floor span, the sheathing acts as a continuous beam spanning over the supporting joists. It must have sufficient bending stiffness and strength to carry the imposed loads and transmit them to the supports (joists).

The sheathing properties in the direction perpendicular to the floor span also have an important effect on overall performance of the floor system. Joist properties vary with the natural variability of wood. If the joists (or composite T-beams) were to act independently of one another, considerable differences would occur in the deflection of individual members. In fact, the sheathing acts as a distribution element that directs higher portions of the total load to the stiffer (and usually stronger) joists and a lower share to the weaker ones. This phenomenon tends to average out the joist deflections and thereby reduces the maximum deflection, and the resulting joist deflections are less variable. This redistribution of load is also beneficial to the strength of the floor. Because the weakest joists often tend to be the least stiff ones, load is directed away from them to the stiffer, stronger ones.

Gaps in the sheathing can reduce its effectiveness as a distributor beam. However, because the sheathing usually spans over several joist spaces and because the gaps are normally staggered so they don't all occur over the same joist, gaps are normally not nearly as critical in reducing two-way action as they are in reducing composite action.

The effect of two-way action is illustrated in figure 2-2, which shows the performance of a floor with 2 by 8 joists and 3/4-inch sheathing subjected to uniform load. The joists have high variability in their bending stiffnesses. As the sheathing bending modulus, E_b, increases, the variation among joist deflections decreases.

Combined Composite and Two-Way Action

Composite and two-way action occur simultaneously in light-frame floor systems. In fact, the two are interdependent because they depend upon the same structural element, the sheathing.

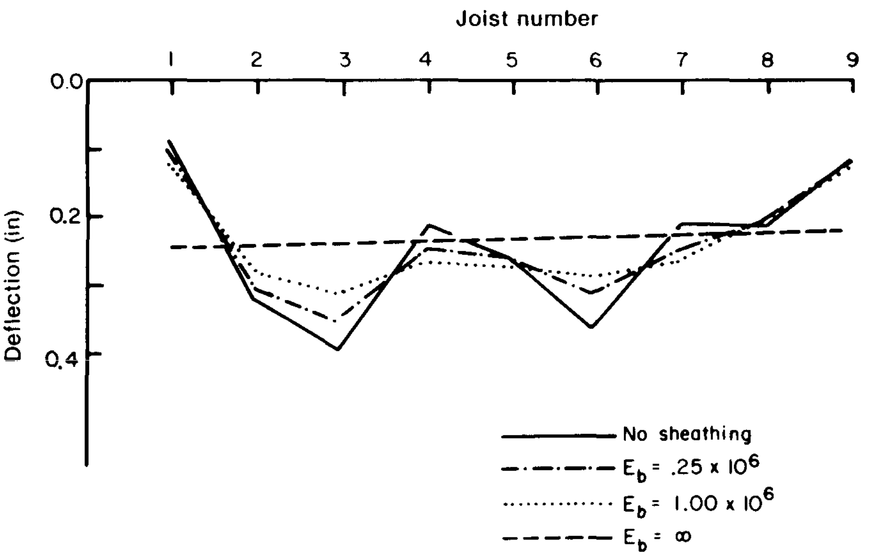

Figure 2–2 – Two-way action increases as sheathing stiffiness (E_b) increases, reducing joist deflection variability. (ML84 5837)

Composite action is maximized when the axial stiffness of the sheathing (flange) is high and the distance between gaps is great. With conventional orthotropic sheet materials, such as plywood, this dictates placing the sheathing with the long axis parallel to the joists.

Two-way action and load distribution are enhanced by increasing the bending stiffness of the sheathing across the joists (fig. 2-2). This dictates placing the sheathing with the long axis across the joists, as is common practice.

Thus, the dual aims of increasing stiffness (through composite action) and reducing variability (through two-way action) lead to conflicting demands. Designers will have to take this into account in specifying materials and considering new construction practices. Their work will be facilitated by the development and eventual adoption of new methods of floor analysis. Cunningham et al. (1982) studied the influence of sheathing properties on floor system performance and investigated a procedure for optimizing panel properties.

Experimental Evaluation of Floor Performance

Several researchers have determined the performance attributes of wood floors experimentally. Table 2-1 summarizes the results of recent studies which tested modern (i.e. panel sheathing rather than boards) single-span floors under uniform loads. The table includes data from 4 separate studies: 44 conventional nailed floors reported by Polensek et al. (1972), 2 nailed and 11 nail-glued floors by the National Association of Home Builders (1973), 4 nailed and 3 glued floors by McCutcheon (1977), and 15 nailed floors by Wheat et al. (1986). The conventional floors, which were tested at spans allowed by conventional design methods, all exceeded the traditional stiffness criterion of span/360 at 40 lb/ft^2,

Table 2-1 – Experimental floors tested under uniform load

Source[1]	Joists: Size	Joists: Species[2] and grade	Spacing	Sheathing: Type[3]	Sheathing: Connectors	Test span	Repli-cations	Performance at 40 lb/ft²: Deflection	Performance at 40 lb/ft²: Span ÷ deflection	Load at first joist break
	in		*in*			*ft-in*		*in*		*lb/ft²*
CONVENTIONAL FLOORS–NAILED SHEATHING–SPAN ≤ ALLOWABLE										
OSU	2 x 6	DF utility	16	1/2 in DF	Nails	9–0	5	0.213	510	*[4]
OSU	2 x 6	DF utility	16	1/2 in DF + 25/32 in. oak flooring	Nails	9–0	3	0.187	580	*
OSU	2 x 6	DF utility	16	1/2 in DF + 3/8 in. plywood flooring	Nails	9–0	3	0.158	685	*
OSU	2 x 6	WH utility	16	1/2 in DF	Nails	9–0	7	0.191	565	*
OSU	2 x 10	WH utility	16	1/2 in DF	Nails	15–4	5	0.337	545	*
OSU	2 x 10	DF utility	16	1/2 in DF	Nails	15–4	6	0.387	475	*
OSU	2 x 10	DF utility	16	1/2 in DF + 25/32 in. oak flooring	Nails	15–4	3	0.354	520	*
OSU	2 x 10	DF utility	16	1/2 in DF + 3/8 in. plywood flooring	Nails	15–4	2	0.427	430	*
OSU	2 x 10	DF utility	16	1/2 in DF	Nails	17–1	5	0.448	460	*
OSU	2 x 6	DF utility	16	1/2 in DF	Nails	10–0	5	0.248	485	*
NAHB	2 x 8	DF construction and standard	16	1/2 in underlayment	Nails	13–0	2	0.32	490	*
FPL	2 x 8	DF No. 2 and Better	16	5/8 in	8d nails at 6 and 8 in	12–0	4	0.267	540	145
UTA	2 x 8	SP No. 2 and Better	24	3/4 in SP (tongue and groove)	Nails	11–0	3	0.142	930	135
UTA	2 x 10	SP No. 2 and Better	24	3/4 in SP (tongue and groove)	Nails	14–4	3	0.320	540	132
UTA	2 x 10	DF No. 2 and Better	24	3/4 in SP (tongue and groove)	Nails	14–7	3	0.325	540	135
UTA	2 x 8	DF No. 2 and Better	16	23/32 in SP (tongue and groove)	Nails	13–1	3	0.243	645	176
UTA	2 x 8	SP No. 2 and Better	16	23/32 in SP (tongue and grove)	Nails	12–10	3	0.225	685	143
EXPERIMENTAL FLOORS–GLUED SHEATHING										
NAHB	2 x 6	WH 1.2E–1200f	16	1/2 in standard	Nails and elastomeric adhesives	12–0	1	0.53	270	95
NAHB	2 x 6	WH 1.8E–2100f	16	1/2 in standard	Nails and elastomeric adhesives	12–0	1	0.37	390	110
NAHB	2 x 6	WH 1.2E–1200f	16	1/2 in standard	Nails and elastomeric adhesives	12–0	1	0.43	335	100
NAHB	2 x 6	WH 1.8E–2100f	16	1/2 in standard	Nails and elastomeric adhesives	12–0	1	0.33	435	*
NAHB	2 x 12	WH 1.4E–1500f	16	1/2 in standard	Nails and elastomeric adhesives	22–6	1	0.77	350	85
NAHB	2 x 12	WH 1.8E–2100f	16	1/2 in standard	Nails and elastomeric adhesives	22–6	1	0.58	465	*
NAHB	2 x 12	WH 1.4E–1500f	16	1/2 in standard	Nails and elastomeric adhesives	22–6	1	0.65	415	100
NAHB	2 x 12	WH 1.8E–2100f	16	1/2 in standard	Nails and elastomeric adhesives	22–6	1	0.53	510	120
NAHB	2 x 6	WH 1.2E–1200f	12	1/2 in standard	Nails and elastomeric adhesives	10–0	1	0.20	600	205
NAHB	2 x 10	WH 1.8E–2100f	19.2	1/2 in standard	Nails and elastomeric adhesives	16–10	1	0.40	505	*
NAHB	2 x 12	WH 1.4E–1500f	14	1/2 in standard	Nails and elastomeric adhesives	18–0	1	0.35	615	135
FPL	2 x 8	DF No. 2 and Better	16	5/8 in	Nails and rigid adhesives	12–0	3	0.167	865	247

[1]FPL = Forest Products Laboratory (McCutcheon 1977); NAHB = National Association of Home Builders (1973); OSU = Oregon State University (Polensek et al. 1972); UTA = University of Texas at Austin (Wheat et al. 1985).
[2]DF = Douglas-fir; SP = southern pine; WH = western hemlock.
[3]All sheathing is plywood.
[4]* = first joist failure not reported.

Selection of Floor Joists From Tables

Most light-frame floors are designed by selecting joist properties and sizes from tables that have been developed based on various design loads and on stiffness and strength requirements. More sophisticated analysis is provided in models that consider the interaction of all materials in the floor system. While these models are readily available, they have not yet been generally accepted for use.

Proper sizes, species, and grades of lumber are necessary for adequate performance of light-frame floor systems. With a given design load and the proper design criteria from the local building code, the proper material can be selected through engineering design. This job has been simplified by charts prepared by the National Forest Products Association (NFPA 1977a) for floor systems with lumber-type joist. Information for roof systems with ceiling joists and rafters are also given. If trusses or other special components are planned, the manufacturer often provides similar information.

The Span Table for Joists and Rafters (NFPA 1977a) was prepared using various design loads and design criteria accepted by most building codes. The designer is responsible for determining the correct design load and assuring that the criteria are accepted by the building code. Then, the designer must select the proper material with appropriate allowable properties. This section demonstrates the use of tables to select a proper floor joist.

The two most important material properties for floor joists are the design stress in bending, called F_b, and the modulus of elasticity, called E. F_b is a measure of strength, and proper design is necessary to provide such a margin of safety that the load does not cause collapse. E is a measure of floor stiffness, and proper design provides assurance that the floor will not be too flexible or springy. An adequate joist must satisfy both criteria. First a joist is selected that has an adequate E value, then it is checked to be sure that F_b is adequate.

The floor plan and preliminary design may suggest the desired span of a floor system. For this example, we assume that the span in a residential building is 12 feet 9 inches between inside edges of supports and that the room will be a living (not sleeping) area. Joists are spaced 16 inches apart. The recommended design load for residential living areas is commonly 50 lb/ft^2 which includes 40 lb/ft^2 live load (occupants and furniture) and 10 lb/ft^2 dead load (lumber, sheathing, and floor covering). The criterion for stiffness is that the floor should not deflect more than 1/360 of the span under full live load.

Table 2-2 shows the allowable span of floor joists at 40 lb/ft^2 live load (NFPA 1977a). A grade of 2 by 8 having an E value of 1.6 million lb/in^2 and an F_b value of 1,250 lb/in^2 would span up to 12 feet 10 inches and thus satisfy both the strength and stiffness criteria. A 2 by 10 (not shown in table 2-2) having an E value of 0.8 million lb/in^2 and an F_b of 790 lb/in^2 would also satisfy the criteria. To complete the design, the proper species and grades must be selected in one of these sizes.

The designer must then determine what species of lumber is generally available. Design values for the many grades and species are given in the National Design Specification (NFPA 1986). Design values for joist and rafters are also given in Table W1 of another publication (NFPA 1977b). A sample portion of Table W1 is reproduced in table 2-3. Assume that the designer finds Southern Pine lumber is available from a number of local suppliers. From table 2-3, No. 2 Southern Pine (KD15), which means the lumber is kiln-dried to maximum of 15 percent moisture content, has an F_b of 1,500 lb/in^2 and E of 1.6 million lb/in^2, which exceeds the F_b and meets the E requirements for a 2 by 8. No. 2 (KD15) Southern Pine is a common grade and likely to be readily available if the supplier handles Southern Pine. A No. 2 Douglas Fir 2 by 8 also has properties that exceed design requirements. In addition, the designer should evaluate the economics of using a lower grade 2 by 10 material or a different species.

The National Design Specification (NFPA 1986) gives design values for over 40 species or species combinations. Considering species, species combinations, grades, and density classifications, there are several hundred sets of design properties for lumber. This multitude of possibilities sometimes makes it confusing for designers and fabricators of wood structures to choose sizes, grades, and species that are available in their area.

Table 2–2 – Allowable span of floor joists at 40 pounds per square foot live load (NFPA 1977a).[1] For each span, the required fiber stress in bending, F_b, is shown immediately below it.

Joist (2 x 8)	Modulus of elasticity (1,000,000 lb/in²)								
	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Spacing	Allowable span								
in	*ft-in*								
	12–10	13–2	13–6	13–10	14–2	14–5	14–8	15–0	15–3
12.0	940	990	1040	1090	1140	1190	1230	1280	1320
	12–3	12–7	12–11	13–3	13–6	13–10	14–1	14–4	14–7
13.7	980	1040	1090	1140	1190	1240	1290	1340	1380
	11–8	12–0	12–3	12–7	12–10	13–1	13–4	13–7	13–10
16.0	1040	1090	1150	1200	1250	1310	1360	1410	1460
	11–0	11–3	11–7	11–10	12–1	12–4	12–7	12–10	13–0
19.2	1100	1160	1220	1280	1330	1390	1440	1500	1550
	10–2	10–6	10–9	11–0	11–3	11–5	11–8	11–11	12–1
24.0	1190	1250	1310	1380	1440	1500	1550	1610	1670
	9–3	9–6	9–9	10–0	10–2	10–5	10–7	10–10	11–0
32.0	1300	1370	1450	1520	1570	1650	1700	1790	1840

[1]Spans are shown in feet and inches and are applicable to all areas except rooms used for sleeping and attic floors. Design criteria limit the deflection to the span divided by 360. The fiber stress values shown are required to satisfy the strength criteria at a live load of 40 lb/ft².

Table 2–3 – Design values for Southern Pine joists and rafters surfaced at 15 percent moisture content (KD) – visual grading (NFPA 1977b)[1]

Species and grade	Size	Allowable unit stress in bending F_b			Modulus of elasticity E	Grading rules agency
		Normal duration	Snow loading	7-day loading		
		lb/in²				
SOUTHERN PINE (Surfaced at 15 percent moisture content-KD)						
Select Structural		2150	2470	2690	1,800,000	
Dense Select Structural		2500	2880	3120	1,900,000	
No. 1		1850	2130	2310	1,800,000	
No. 1 Dense	2 x 5	2150	2470	2690	1,900,000	Southern
	and					Pine
No. 2	wider	1500	1720	1850	1,600,000	Inspection
No. 2 Dense		1750	2010	2190	1,700,000	Bureau
No. 3		875	1010	1090	1,500,000	
No. 3 Dense		1000	1150	1250	1,500,000	
Stud		900	1040	1120	1,500,000	

[1]These F_b values are for use where repetitive members are spaced not more than 24 inches. For wider spacing, the F_b values should be reduced 13 pct. Values for surfaced dry or surfaced green lumber apply at 19 pct maximum moisture content in use.

As noted in chapter 1, the lumber industry is now involved in extensive evaluations of the engineering properties of different grades and species of lumber. Careful consideration is being given to methods for combining species and reducing the number of possibilities from which choices must be made. Also, new evaluation techniques for design value assessment are now in use to varying degrees. As previously discussed, they include machine stress rating (MSR) of lumber, proof loading, and in-grade testing.

Modeling Floor Performance

A number of researchers have investigated the performance of wood floors and developed computer and mathematical models to account for composite and two-way action.

Goodman and Popov (1968) presented an early theoretical approach to the analysis of layered wood systems. From this work, researchers at Colorado State University have developed a comprehensive finite element computer program for modeling floor performance (Thompson et al. 1977). The program employs a crossing-beam analysis in which T-beam elements in the span direction intersect with sheathing strip elements in the transverse direction. Properties can be varied from element to element and it is thus possible to model the effects of variability in all material properties. The program can accommodate multiple layers of sheathing and flexible gaps. (A flexible gap represents a partial discontinuity that occurs when sheathing is tightly butted or when the sheets have tongue-and-groove edges.) The program assumes linear connector load/slip and has been used in a variety of theoretical studies into floor performance. Schaefer and Vanderbilt (1983) have provided a summary of the method of analysis and of the many studies conducted at Colorado State University.

Recently, Wheat et al. (1983) modified the program to consider nonlinear connector properties. A study of wood-joist floor strengths (Wheat and Moody 1984) concluded that strength predictions from the nonlinear model are about 10 percent lower than those from the linear model.

Foschi (1982) of Forintek Canada has also developed a finite element model for floor behavior. His approach includes consideration of lateral and torsional joist deflections as degrees of freedom and plate action in the sheathing, which are not considered in other analysis programs.

At Washington State University, much research has been conducted on the properties of composite beams bonded with elastomeric adhesives (Bessette and Hoyle 1985; Hoyle 1973; Itani et al. 1981; McGee and Hoyle 1974).

At FPL, research has concentrated on the development of simple analysis techniques that may be implemented with hand-held calculators or desk-top computers. McCutcheon (1977) presented an analytical method for computing the stiffness of floor joists with partial composite action. Based on a T-beam analysis, the method accounts for an interlayer slip plane and open gaps in the sheathing flange. A cooperative project between Forest Products Laboratory and Colorado State University (McCutcheon et al. 1981) showed that this simple model predicted average deflections under uniform loads that agree closely with those predicted by the finite element program. McCutcheon (1984) has extended the model to include two-way action and thereby to compute individual joist deflections; again, results compare very closely to those from the large-scale computer program. Most recently (McCutcheon 1986) the T-beam model has been simplified and expanded to an I-beam model that considers a layer of sheathing on both edges of the joist. The method modifies the axial stiffness of each flange, EA, to yield a reduced stiffness, $\overline{EA}$, which is then used in a simple transformed area analysis to compute the composite bending stiffness of the joist. The equation for the reduced flange stiffness is:

$$\overline{EA} = \frac{EA}{1 + 10\,\dfrac{EA}{SL'^2}}$$

where

EA is the physical axial stiffness of the flange;
S is the stiffness of the slip plane;
L' is the distance between gaps, along the joist;
EA is the reduced stiffness of an equivalent rigidly fastened flange.

The previous equation yields very good estimates for the composite stiffness of joists with one or two sheathing flanges nonrigidly attached. The application of simplified methods requires the use of estimates of stiffness of individual joists and panels in the system. Examples of the effect of varying the properties of the sheathing and connection are given by Moody and McCutcheon (1984).

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Chapter 3
Wall Systems Under Axial and Bending Loads

Introduction

Wall systems involve combined axial and bending loads and their analysis is complicated by the variety of possible combinations of materials and interactions of materials.

In this chapter, data on the performance of walls under axial and bending loads are presented, together with a technique for predicting this performance. Also, the influence of construction variables on performance is reviewed.

Background

Present light-frame wall systems in conventional structures are not engineered to take full advantage of the way they perform. Design techniques are based on calculating allowable stress from expected vertical and horizontal loads. Load sharing and composite action are ignored.

The model building codes (BOCA 1975, ICBO 1979, SBCC 1979) and the HUD Minimum Property Standards (U.S. Department of Housing and Urban Development 1973) provide prescriptive requirements that specify stud size and spacing for various applications. Local wind loads are used for horizontal load and a combination of dead and live load is used for vertical load. Design procedures accepted by the codes for walls to support bearing loads are usually quite direct and the performance requirement is simply support of the load without failure of the structural materials used. Two codes do include additional performance requirements. For bending, the Basic Building Code (BOCA 1975) requires that the wall support 2-1/2 times the design load, while the Southern Standard Building Code (SBCC 1979) requires a 75 percent recovery from maximum deflection resulting from twice the design load.

Performance Factors

The performance of wall systems has been determined by tests conducted both on complete structures and on individual wall sections. These tests have provided basic information on the structural behavior of walls including strength and deflections of studs and sheathings.

House Tests

The ideal way to determine the performance of light-frame wall systems is to test a complete structure. Although full-scale structural testing is extremely expensive and complex, several such tests have been performed, generally with low levels of axial load and the primary loading in bending. A review of these tests, for which no standard procedures are available, is helpful in illustrating that conventional wall systems are significantly stronger than design requirements.

Dorey and Schriever (1957) subjected a wood frame house to loads equivalent to a 120-mph wind without significant structural distress. Their test house, which contained interior partitions and bearing walls, exhibited midheight wall deflections of less than 0.2 inch. Hurst (1965) tested a house at various stages of construction to illustrate the magnitude of interactions in the completed structure. Although Hurst's loadings were actually a combination of bending and racking, they show that a conventional wall retains its structural integrity after cycles of lateral loading to 12 lb/ft^2 (equivalent to winds of about 70 mph). Tuomi and McCutcheon (1974) conducted a similar test, with one wall subjected to pure bending under a uniform (air bag) load. This wall exhibited deflections of up to 0.9 inch at 60 lb/ft^2, and one stud failed at an estimated 70 lb/ft^2. These pressures represent wind loads far in excess of 100 mph.

Based on these tests, walls in actual structures are obviously capable of withstanding bending loads far beyond what they are likely to experience in service.

Wall Tests

A number of wall sections have been evaluated under combined axial and bending loads. No standard procedures are available but those evaluated at NAHB Research Foundation (1974a, 1974b), Oregon State University (Polensek 1976a, Polensek and Atherton 1976), and Forest Products Laboratory (Gromala 1983) followed similar procedures. Axial loads representing a second story (floor + roof) design load were applied to each stud and the walls loaded to failure under uniform lateral load. A summary of results is given in table 3-1.

The tests indicated that nonlinear behavior of both studs and nailed joints was significant enough to influence performance. Results also indicated that, for typical wall configurations, the ultimate capacity can be much higher than the load at first stud failure.

Four tests on walls constructed with utility-grade studs representing minimal quality construction failed at 85 lb/ft^2 for studs 16 inches apart and 55 lb/ft^2 with studs 24 inches apart. Tests on exterior walls representing average construction (plywood exterior sheathing and gypsum interior) failed at loads near 120 lb/ft^2. Walls with gypsum board on both sides, which represent typical interior walls, had failure loads between 60 and 80 lb/ft^2. Strength and stiffness for these and other types of construction are given in table 3-1.

Table 3-1 – Summary of wall performance tests under axial and bending loads[1]

Source of data[2]	Framing			Sheathing		Number of tests	Axial load	Bending performance	
	Size	Grade	Species	Exterior	Interior			Average wall flexibility[3]	Average load at failure
	in			*- - - - - - - - in - - - - - - - -*			*lb/ft*	*in/10 lb/ft²*	*lb/ft²*
				16-INCH STUD SPACING					
NAHB-RF	2 x 3	C/S[4]	Douglas-fir	1/2 Fiberboard	3/8 Gypsum	3	600	0.30	50
NAHB-RF	2 x 3	C/S	Douglas-fir	5/8 Bevel siding	3/8 Gypsum	3	600	0.35	60
NAHB-RF	2 x 3	C/S	Douglas-fir	1/2 Gypsum	3/8 Gypsum	3	600	0.32	60
NAHB-RF	2 x 3	C/S	Douglas-fir	3/8 Gypsum	None	3	600	0.32	50
FPL	2 x 4	Stud	Douglas-fir	5/8 T-111 plywood	1/2 Gypsum	3	900	0.14	120
FPL	2 x 4	Stud	Douglas-fir	1/2 CDX plywood	1/2 Gypsum	3	900	0.08	120
NAHB-RF	2 x 4	Stud	Subalpine-fir	1/2 Fiberboard	1/2 Gypsum	2	1,000	0.30	40
NAHB-RF	2 x 4	Stud	Subalpine-fir	3/8 Plywood	1/2 Gypsum	2	1,000	0.21	50
NAHB-RF	2 x 4	Stud	Subalpine-fir	7/16 Lauan siding	1/2 Gypsum	2	1,000	0.23	55
NAHB-RF	2 x 4	Stud	Subalpine-fir	7/16 Hardboard siding	1/2 Gypsum	2	1,000	0.23	50
OSU	2 x 4	Utility	Englemann spruce	5/8 Lapped bevel	3/8 Gypsum	2	1,000	0.20	85
OSU	2 x 4	Stud	Douglas-fir	3/8 CDX plywood	1/2 Gypsum	3	1,500	0.16	115
				24-INCH STUD SPACING					
NAHB-RF	2 x 4	Stud	Douglas-fir	3/8 CD plywood	1/2 Gypsum	2	1,000	0.1 (est.)	120
NAHB-RF	2 x 4	Stud	Douglas-fir	1/2 Gypsum	1/2 Gypsum	1	1,000	0.25(est.)	80
FPL	2 x 4	Stud	Douglas-fir	5/8 T-111 plywood	1/2 Gypsum	2	600	0.14	100
FPL	2 x 4	Stud	Douglas-fir	1/2 CDX plywood	1/2 Gypsum	2	600	0.14	100
OSU	2 x 4	Utility	Englemann spruce	5/8 Lapped bevel	3/8 Gypsum	2	1,000	0.24	55

[1]Walls were 8 feet high and between 8 and 18 feet long with no openings. Axial load was first applied and walls loaded to failure under uniform lateral pressure.
[2]NAHB-RF = National Association of Home Builders Research Foundation; FPL = Forest Products Laboratory, U.S. Department of Agriculture, Forest Service; OSU = Oregon State University.
[3]Average slope of load vs. deflection curve for middle portion of wall up to lateral load of 40 lb/ft² given in terms of deflection per 10 lb/ft² of load. At a common design load of 20 lb/ft², deflections would be somewhat less than double the values given because of some slight nonlinearities.
[4]C/S = mixture of Construction and Standard grades.

Analysis Methods

A conventional wall is composed of a series of vertical framing members covered inside and out by one of the various types of board or sheet materials. Under axial and bending load, the framing members, or studs, are the primary load-carrying members in the system. As most building codes specify framing but not sheathing requirements for resisting axial and bending loads, the framing is assumed to be the only load-carrying member in many wall systems. This assumption produces conservative estimates of the true strength and stiffness of light-frame walls. The conservatism arises from neglecting lateral load distribution and composite action. Lateral distribution, commonly called load sharing, is present in all sheathed walls. It occurs by a bridging effect of the sheathing over the less stiff studs. Composite action makes the wall behave like a series of I-beams rather than rectangular studs. This type of load transfer results from stretching or compressing the sheathings as the stud bends.

Wall Model

Polensek (1976a) has developed a computer program for estimating light-frame wall performance. Program FINWALL is capable of linear or nonlinear analysis of walls under constant axial and increasing lateral loads.

The program combines the finite element method of analysis with a linear step-by-step procedure to calculate wall performance. The finite element mesh can be relatively coarse in this analysis (fig. 3-1) as stud and joint properties are assumed constant along the full height of a given stud and symmetrical about wall midheight.

Stiffness of the I-beam column elements is calculated by analyzing the partial composite action of the studs and sheathings using methods similar to those derived by Amana and Booth (1968). After calculation of I-beam column stiffness, the contributions of the two sheathings are analytically lumped into a single plate (fig. 3-2) for the remaining calculations.

A brief description of the program organization is included here in order to give the reader a feel for the relative simplicity and flexibility of the program.

FINWALL is broken into various subprograms, each of which has an easily described purpose: The main program is used to input parameters that will govern the computer run. Examples are number, length, and spacing of wall studs, choice of linear or nonlinear analysis, and identification of the number and types of loads to be applied. Subroutines requiring no user interaction for a given wall size and configuration are used to input matrix constants and define the node numbering in the wall. To describe the remaining input completely, the user prescribes the load magnitudes and points of application and physical dimensions and elastic properties of the respective components.

At this point the wall parameters are completely defined. During the program execution, the effective flange width of the sheathings and the stiffness of each partially composite I-beam are calculated (Amana and Booth 1968). This information is used by a matrix analysis subroutine that calculates stresses and deflections in the wall. Secondary moments induced by the axial loads (fig. 3-3) are calculated by an iterative procedure (Polensek 1976a).

Failure of an individual stud is computed when the midheight deflection of the stud exceeds the value input as its failure deflection. In the subsequent updating of the stiffness matrix the failed stud is assigned a near-zero stiffness. The wall is considered to be failed when two adjacent studs fail.

Predictability of test results – The agreement between deflections predicted from FINWALL and actual stud deflections is generally very good (Gromala 1983, Polensek 1976a); predicted failure loads approximate actual failure loads, but predictability of deflections beyond first stud failure is less accurate because of failure modes that cannot be predicted by the model.

The model assumes that wall failure is governed by bending strength of the studs and that stud failures are complete. Based on the tests, model accuracy can be expected in the range of less than 10 percent error at first stud failure and up to about 20 percent error at wall failure. This level of predictability at load levels three to five times greater than design requirements is excellent.

Program input – To predict wall performance accurately, data on the following are necessary:

(1) Geometry of the wall.
(2) Nonlinear load versus deflection data from the individual studs.

(3) Stiffness of the sheathing.
(4) Nonlinear load versus slip behavior of the connectors between studs and sheathing.

Because the load versus deformation behavior to failure is not available for each stud, estimates of this behavior are necessary in order to predict the ultimate strength of the walls. Such information is being developed as part of a national testing program. Sheathing stiffness data may be available from the manufacturer and can be obtained by ASTM test procedures. Load-slip behavior of the connections, such as is shown in figure 3-4, has been determined following a procedure given in figure 3-5 (Polensek 1976b, Polensek 1980).

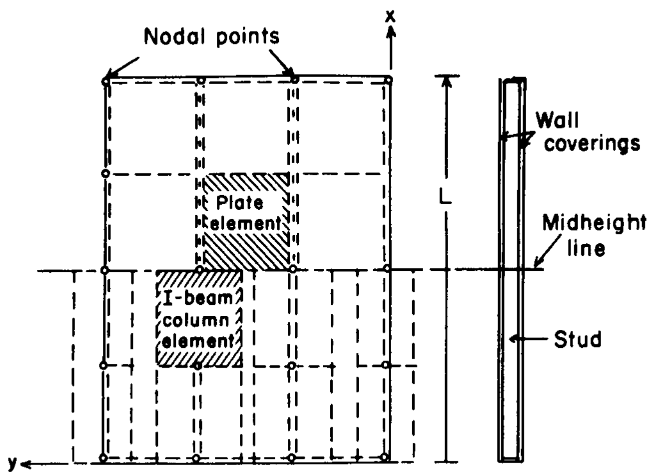

Figure 3-1 –Finite element mesh for Program FINWALL. (ML88 0003)

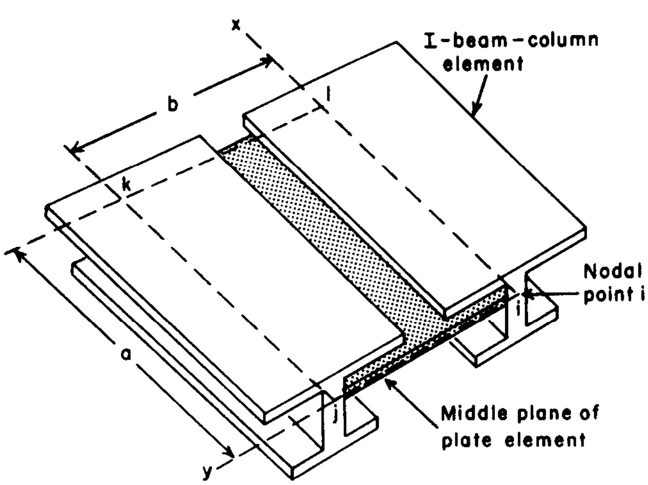

Figure 3-2–Assembly of I-beam column and plate elements. (ML88 0004)

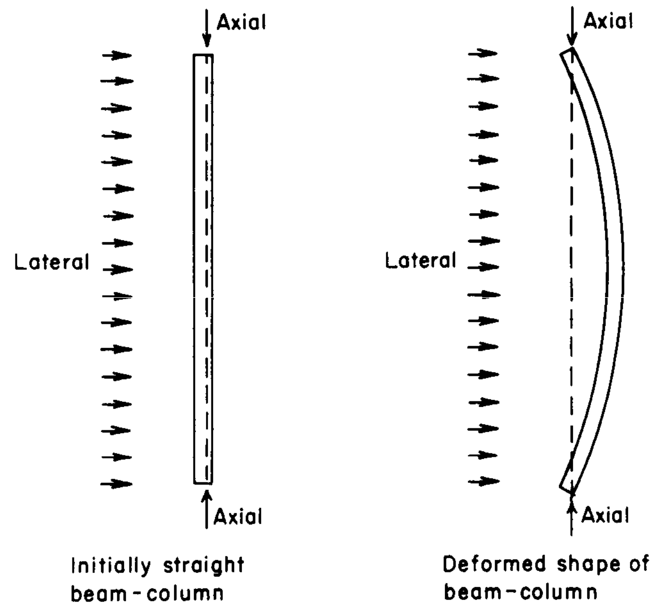

Figure 3-3 –As an initially straight beam-column defficts, the axial load induces secondary moments proportional to the load level and midspan deflection. (ML88 0005)

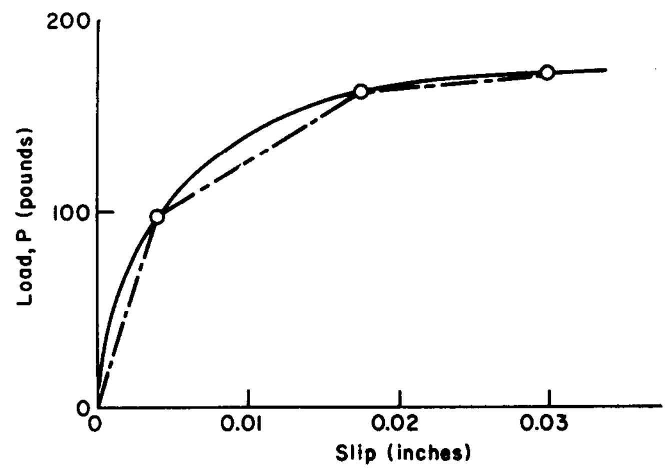

Figure 3-4–Load-slip curve for nailed joint and trilinear approximation. (M151 1502)

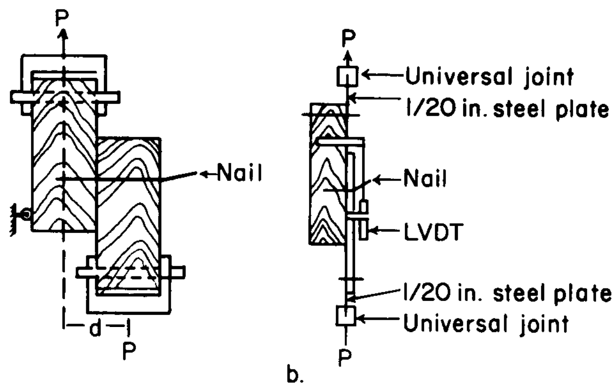

Figure 3-5 –Lateral nail test procedure:
(a) ASTM D 1761, (b) modified. (ML88 0006)

Sensitivity Studies

As previously noted, the major performance factors for wall systems are the properties of studs and sheathings, and the performance of fasteners. Performance factors are demonstrated by applying a variety of materials and construction to the model FINWALL.

Program FINWALL models nonlinear wall performance by using multilineal load-deflection relationships as input for the stud and fastener properties. Nonlinear analysis techniques and the introduction of variable material properties add considerable complexity to the model.

An initial sensitivity study was performed to determine the precision necessary in inputting various material properties. Material properties were changed one at a time to determine their individual effects on overall wall performance (Polensek 1980). The conclusion was that stud modulus of elasticity and fastener slip modulus have significant effects on predicted strength and stiffness, whereas effects of other properties such as sheathing stiffness are slight. Results indicated that additional material property research would be best directed at stud and nail properties.

A separate study, characterizing stud and fastener stiffness by multi-linear load-deflection relations, showed that these relations must be at least bilinear to provide acceptable accuracy (Polensek 1976b).

Approximately 75 walls were analyzed by computer to illustrate the effects of various parameters (load levels and material properties) on wall behavior. All walls consisted of 10 studs and were analyzed under constant axial and an increasing uniform lateral load. For most parameters, analyses were conducted at three levels; artificially low values, “best estimates, ” and artificially high values of each variable. It was anticipated that this procedure would best illustrate the potential influence of each variable on overall wall performance.

All comparisons were made to a type of wall that is relatively common and exhibits many of the nonlinearities and interactions discussed previously. The wall consists of 10 studs spaced 16 inches on center with plywood siding applied directly to the studs on the exterior and gypsum wallboard on the interior. Sheathings are fastened according to recommended nailing schedules. Axial load corresponds to the design load carried by the first-story wall in a two-story house in a region with moderate-to-high snow load.

Stud properties for the wall used as a standard for comparison were based on actual test data, the specific lot of ten studs being chosen because every stud exhibited a nonlinear load-deflection curve.

Program FINWALL predicts that the standard wall behaves linearly up to a lateral load level of 11 lb/ft^2. At this point the nail stiffness modulus at one of the studs changes. At 20 lb/ft^2, an average design wind load, the average stud deflection is 0.16 inch. The first predicted stud nonlinearity occurs at 83 lb/ft^2 and the first stud failure at 130 lb/ft^2. Response can be erratic after the first stud failure; in predictions for this wall, an additional nonadjacent stud fails at 132 lb/ft^2, and two adjacent studs fail at 139 lb/ft^2, defining wall failure. Average predicted deflection at maximum wall load is 2.4 inches. For clarity all parameter comparisons are presented relative to this standard wall.

Studs

As mentioned previously, stud behavior has the greatest influence on wall performance. The input data for the standard wall consist of a separate trilinear load-deflection relation for each stud. Six variations of the actual stud data were created to examine the effects of simplification of stud input data on predicted wall strength and stiffness. Table 3-2 shows the influence on wall behavior of idealizations of individual stud curves. Load-deflection curves were converted into individual linear relations or lumped into a representative piece to use for all 10 studs in the lot.

Table 3-2 – Performance of walls with six hypothetical lots of studs

Description of stud property	Computed performance (relative to standard wall)		
	Apparent bending stiffness at 20 pounds per square foot[1]	Load at first stud break	Load at failure
	- - - - - - - - - - -	*pct*	- - - - - - - - - - -
Variable studs[2]			
MOE = tangent modulus	108	288	278
MOE = secant modulus	68	191	183
Identical studs[3]			
All = lot average	99	161	150
All = weakest piece[4]	108	97	92
All = second weakest	83	85	81
All = third weakest	103	112	106

[1]Apparent stiffness calculated as the inverse of the average deflection.
[2]Linear MOE; different for each stud.
[3]Multilinear MOE; identical for each stud.
[4]Ranking of weakest pieces by their failure sequence in the standard wall.

The table shows that when each stud is replaced by a piece that has equal initial stiffness (tangent modulus) but deflects linearly to failure, initial stiffness is predicted adequately, but wall loads at first stud break and at failure are significantly overestimated. Replacement of each stud by an equivalent piece with stiffness equal to the secant modulus of the stud (fig. 3-6) gives only a slightly better estimate of maximum wall load and greatly underestimates initial wall stiffness.

Substitution of various combinations of 10 identical studs leads to similar inaccuracies. For a wall with 10 identical studs with averaged trilinear properties, prediction of initial stiffness is almost exact and failure is overestimated as expected. Creation of lots with properties of all studs equal to those of the studs that failed first, second, and third in the example wall illustrates some of the interactions occurring in the wall. The wall with every stud identical to the weakest piece in the example wall is actually stronger and stiffer than the wall with every stud identical to the second weakest piece. This is because the weakest piece in the example wall did not have the lowest single member bending strength in the group. As it was stiffer than its neighbors, however, it attracted more than its share of load and failed first.

In spite of the lack of an acceptable predictor for the examples shown, examination of the entire table with all six hypothetical lots gives the impression that some combinations of lot idealizations may be useful at least in determining upper and lower bounds for true wall performance. Until useful combinations are identified, however, complete nonlinear load-deflection properties of individual studs appear to be necessary for accurate prediction of both wall strength and wall stiffness. As will be discussed later, precise prediction of failure loads, which may be many times higher than expected maximum loads, may not be necessary.

Sheathing

The effect of sheathing properties on wall performance is relatively easy to model analytically. The contributions of load sharing and composite action to wall performance were discussed earlier. The magnitude of each contribution is directly related to stud stiffnesses and to the stiffness of the sheathing in a

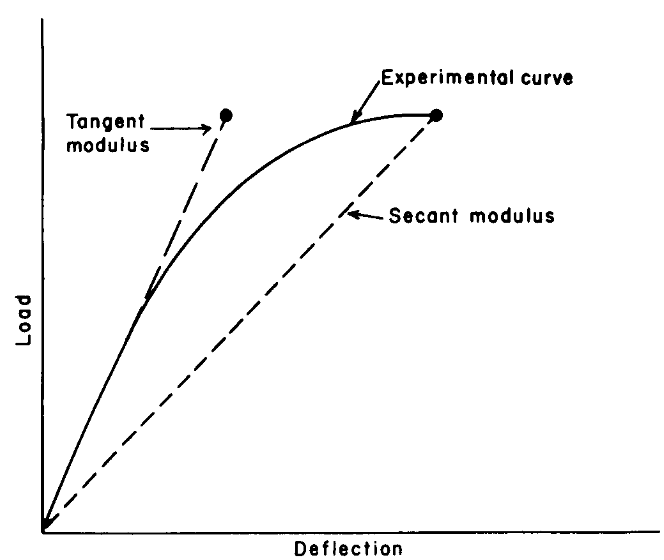

Figure 3-6– Definition of tangent and secant moduli. (ML88 0007)

specific principal direction. Hypothetical values can be input to the computer program to determine the effects on wall performance of varying the sheathing stiffness.

Identical sheathings on both sides of the studs were assumed to have various combinations of high stiffness, roughly equal to a stiff plywood, and low (near zero) stiffness in their principal directions. A sheathing with high stiffness in both directions is as rigid as can be postulated for a wood-based panel. When high stiffness is assigned perpendicular to stud and low stiffness parallel to stud, the result is predominantly a load-sharing system. Reversing these stiffnesses produces high composite action with little load sharing. At the low extreme is a sheathing with negligible stiffness in both directions. Note that the studs chosen for this group of simulations were of relatively good quality. As no single stud was exceptionally weaker than the rest, the effects of load sharing are less than could be expected for lower quality studs.

Table 3-3 presents the wide range of wall strengths and stiffnesses attained with various hypothetical sheathings. The first sheathing, extremely stiff across the studs but flexible parallel to the studs, could represent a horizontal board sheathing. This sheathing provides lateral load sharing but virtually no composite action. As indicated in the table, such a sheathing provides performance significantly inferior to the standard wall.

The composite-action sheathing, with stiffness parallel to the studs slightly greater than normal plywood, adds 26 percent to the wall's initial stiffness. However, at higher loads the nonlinear nail stiffness is much lower, decreasing the contribution of the sheathing. Thus the first break load and maximum wall load are barely higher than for the standard wall. The rigid sheathing, on the other hand, is predicted to result in a load 25 percent higher at first stud break and 27 percent higher at wall failure. The difference between performance of these two sheathings at higher loads can be attributed largely to the added load sharing by the rigid sheathing.

Other simulations show that sheathings contribute relatively more to overall performance when lower quality stud material is used. Both primary load-transfer mechanisms increase for low quality studs. Such studs normally exhibit higher variability in stiffness, promoting increased load sharing, and often have lower average properties, inducing a higher percentage of composite action.

Table 3-3 – Performance of walls with four hypothetical sheathings

Description of sheathing property	Computed performance (relative to standard wall): Apparent bending stiffness at 20 pounds per square foot[1]	Load at first stud break	Load at failure
	pct	*pct*	*pct*
Load sharing Ex[2] = 1,000 lb/in^2 Ey[3] = 2 million lb/in^2	64	66	68
Flexible plate Ex = 100 lb/in^2 Ey = 100 lb/in^2	63	58	56
Composite action Ex = 2 million lb/in^2 Ey = 100 lb/in^2	126	101	104
Rigid plate Ex = 2 million lb/in^2 Ey = 2 million lb/in^2	130	125	127

[1]Apparent stiffness calculated as the inverse of the average deflection.
[2]Ex = stiffness parallel to studs, approximately 1.7×10^6 lb/in^2 (plywood), 0.4×10^6 lb/in^2 (gypsum).
[3]Ey = stiffness perpendicular to studs, approximately 0.3×10^6 lb/in^2 (plywood), 0.2×10^6 lb/in^2 (gypsum).

Fasteners

Partial composite action results from the transferor bending stresses in the stud into axial tension and compression in the sheathings. If the connections between studs and sheathing were rigid, calculation of the strength and stiffness of the resulting I-beams (or stressed-skin panels) would be elementary. Nail connections, however, are nonrigid, and they transfer stresses nonlinearly as they slip. To illustrate the influence of fasteners on predicted wall behavior, connector moduli were varied from near zero (10 lb/in) to extremely stiff (100,000 lb/in). As shown in table 3-4, these cases were studied along with a third case in which the initial connector moduli were set equal to test values, approximately 4,000 lb/in for plywood and 9,000 lb/in for gypsum. In this case, however, the moduli were assumed to be linear to wall failure rather than decreasing to zero as in the standard wall.

Compared to the standard wall, strength and stiffness are about 30 percent lower for the flexible nail wall and 100 percent higher when rigid fasteners are used. Note that this calculation assumes that the sheathings are strong enough to force system failure in the studs, which is an invalid assumption at the extremely high load levels induced by theoretically rigid fasteners.

The last entry in table 3-4, a tangent modulus approximation to the nail load-slip curves, predicts performance to be within 20 percent of that for the standard wall.

Axial Load Level and Stud Spacing

The effects of axial load level and stud spacing were examined briefly and are summarized in table 3-5. The table shows that walls are not significantly stronger under light axial loads than under full two-story design loads for a typical house. The apparent anomaly in the table that predicts walls to be stiffer under greater axial load is caused by differences in initial deflection. Initial reverse curvature is induced by the slight eccentricity toward the interior sheathing in the application of axial load in the model, as suggested in ASTM E72 (ASTM 1977).

The simulation results for various axial load levels indicate that design levels of axial load in a two-story structure are not high enough to significantly change the wall's lateral load-carrying capacity. At higher axial loads, it is anticipated that secondary moments may significantly decrease wall capacity. Current design specifications (NFPA 1986) quantify this decrease only for individual members on an allowable stress basis. In some instances, this decrease is offset by an actual increase in wall strength caused by added compressive stresses on the studs that generally fail in a tension-bending mode. Research by Zahn (1982) has shown this effect for lumber, but it is not yet considered in any design procedures.

As expected, walls with studs spaced 24 inches apart are substantially weaker than the standard wall with 16-inch spacing. The decrease in strength is roughly proportional to the decrease in the number of studs per

Table 3-4 – Performance of walls with three hypothetical nail joint moduli (K)

Description of nail property	Computed performance (relative to standard wall)		
	Apparent bending stiffness at 20 pounds per square foot[1]	Load at first stud break	Load at failure
	pct		
Flexible nails K = 10 lb/in	65	70	70
Rigid nails K = 100,000 lb/in	195	191	213
Linear nails[2] $K = K_1$ from tests	84	88	91

[1]Apparent stiffness calculated as the inverse of the average deflection.
[2]K_1 = 4,000 lb/in (plywood), K_1 = 9,000 lb/in (gypsum).

unit length of wall. Yet the predicted strength of these walls with 24-inch stud spacings (the weakest configurations analyzed) far exceeds the maximum wind loadings that light-frame walls are expected to experience.

Simulations Using In-Grade Lumber

Analytical models such as FINWALL are not envisioned as tools for individual design cases. The model is too complex, and predictive techniques for nonlinear stud properties on an individual, nondestructive basis are not adequate for such application.

The major application of computer-based analysis at this time is in estimating performance for entire populations of walls. Such estimates can be useful in calibrating new reliability-based design procedures (Zahn 1977) against current construction. Calibration here means establishing acceptable performance levels as predicted by new methods based on performance of time-tested traditional systems.

The primary use of program FINWALL at this time is the development of probability distributions of wall performance based on data from tests of lumber collected at mill sites. The program provides statistically valid estimates of the bending strength and stiffness of Douglas-fir and southern pine dimension lumber (Galligan et al. 1980). Based on actual load-deflection plots of stud-grade lumber and laboratory tests on nailed joints, multilineal stiffness relations are derived, and for each lot of lumber tested (a lot consisting of 10 pieces sampled sequentially), a wall's performance can be analyzed. From the population of these lots of lumber, a distribution of wall strengths or stiffnesses can be assembled for any given wall configuration.

Extensive simulations using in-grade lumber of stud-grade Douglas-fir or southern pine have been conducted (Polensek and Gromala 1984). Various types of sheathing and siding were examined. Walls with plywood siding were about 11 percent stronger than those with bevel siding. As expected, walls with studs spaced 24 inches on center were lower in strength than those with studs 16 inches on center. In all instances, the calculated strength of the walls at failure was higher than the recommended wind design (50-year recurrence) load at all places in the United States.

The development of distributions of component properties is the first step in a reliability-based analysis. From the distributions of predicted performance and a consideration of anticipated loading, the code and regulatory agencies along with the design specification groups can define acceptable performance levels based on calibration to existing acceptable constructions.

Table 3-5 – Performance of walls as a function of axial load level and stud spacing

Description of wall configuration	Computed performance (relative to standard wall)		
	Apparent bending stiffness at 20 pounds per square foot[1]	Load at first stud break	Load at failure
	------------ *pct* ------------		
Two-story structure (900 lb/ft)			
16-inch spacing	100	100	100
24-inch spacing	64	65	65
One-story structure (540 lb/ft)			
16-inch spacing	85	102	96
24-inch spacing	57	68	71
Minimal axial load (300 lb/ft)			
16-inch spacing	77	104	107

[1]Apparent stiffness calculated as the inverse of the average deflection.

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Chapter 4
Wall Systems Under Shear Loads

Introduction

Wind and seismic forces are resisted by racking or shear walls in light-frame structures. These walls are also referred to as diaphragms. Properly designed and built, these racking walls transmit in-place shear forces to the foundation. They are normally constructed by fastening sheathing to both faces of framing materials with mechanical fasteners. In some instances, special bracing is added to resist the forces. These walls must have both adequate strength and rigidity. Obviously, strength is important to prevent collapse. Adequate stiffness is important to limit the distortions or deformation that can cause vibrations or, in extreme cases, can cause doors and windows to bind.

There are two general methods to quantify wall-racking behavior. The first is to perform wall-racking tests and relate the results to construction that has been historically acceptable. The second is rationally or empirically to correlate racking strength with lateral nail strength that represents the interaction between the framing and sheathing materials.

In this chapter, data on the performance of walls subjected to shear loading will be presented, together with techniques for predicting this behavior. The influence of construction variables will also be reviewed.

Background

Historically, the performance of racking walls has been judged by observed behavior or standard laboratory test performance. Prior to World War II, board sheathing and corner diagonal bracing were commonly used in light-frame construction. They provided adequate performance and thus became the bench mark of acceptance for later construction. Tests conducted on walls of this construction in the late 1930’s and early 1940’s formed the basis for the acceptance standards of the FHA (Anderson 1965) and HUD (1979).

Codes and standards for racking resistance are generally based on the results of the standard ASTM E 72 test (ASTM 1986). The HUD Minimum Property Standards (U.S. Department of Housing and Urban Development 1979) required that an 8- by 8-foot wall section, tested according to ASTM E 72 (table 4-l), meet or exceed an ultimate load of 5,200 pounds in order to be approved for shear wall application. Additionally, there were deformation limitations at lower loads (table 4-2).

The ASTM E 72 standard is intended to provide a common basis for comparison of sheathing materials. There has been some debate over its use in the certification of wall performance. Another ASTM standard for measuring the shear resistance of framed walls is ASTM E 564 (ASTM 1976). Although this standard has received limited recognition, it is intended for the evaluation of wall performance rather than performance of the sheathing and permits variations in the holddown mechanism and wall configuration which closely approximate actual wall performance.

Care must be used in interpreting test results. The holddown mechanism specified by ASTM E 72 and the vertical load applied may influence test results. Recent indications are that modifications of the holddown device may significantly change results. Thus, wall performance in a light-frame structure may be different from that in the E 72 test.

Framing requirements of the E 72 test include species and stud spacing that may differ from those used in actual construction. For example, E 72 specifies No. 1 Douglas-fir or southern pine. Both have average specific gravities near or above 0.5. Spruce-pine-fir, with specific gravity of about 0.35, is a common species group used for studs and wall framing, Similarly, E 72 specifies 16-inch stud spacing, but 24-inch spacing is an alternative. There is only a slight decrease in shear strength when studs are spaced 24 inches apart, because most of the load is carried by the perimeter fasteners in panel sheathing. In summary, the standard laboratory qualification tests may not accurately represent what is being built in the field.

Table 4-1 – Applicable standards

Reference	Title
ASTM E 72 (1987b)	Conducting Strength Tests of Panels for Building Construction
ASTM E 564 (1987a)	Static Load Test for Shear Resistance of Framed Walls for Buildings
ASTM D 1037 (1986a)	Evaluating the Properties of Wood-Base Fiber and Particle Panel Materials
ASTM D 1761 (1986b)	Testing Mechanical Fasteners in Wood

Houses are rarely built solely with 8-foot-long walls having no openings. There have been some indications that wall strength increases linearly with length, and that sections containing openings may not contribute to racking performance. Therefore, current practice is to subtract the length of openings from gross wall length and multiply by a strength per unit length to estimate allowable load.

Component interactions also play a major role in distributing loads to and from shear walls. The interactions depend upon component stiffness and connector efficiency. These contributions are currently ignored because little information is available for their evaluation.

Many walls sheathed with various panel materials have been evaluated using the E 72 procedure. Most of the racking tests indicate nonlinear load-deflection behavior dependent on the wall sheathing, framing, and fasteners. A typical load-deformation curve (in this case for an 8- by 8-foot panel with regular density fiberboard sheathing) is shown in figure 4-1. Ultimate strength values for various combinations of sheathing, framing, and fasteners for 8- by 8-foot panels are given in table 4-3. Extensive work by others could not be included because they used specimens of a different size (Sugiyama and Suzuki 1975; Suzuki et al. 1978).

Table 4-2 – HUD minimum property standards for wallracking performance based on E 72 standard test procedures (FHA 1949)

	1,200 pounds		2,400 pounds		
	Maximum deformation	Maximum residual deformation	Maximum deformation	Maximum residual deformation	Maximum load
	in				*lb*
Dry test	0.20	0.10	0.60	0.30	5,200
Wet test	0.28	0.14	0.80	0.40	4,000

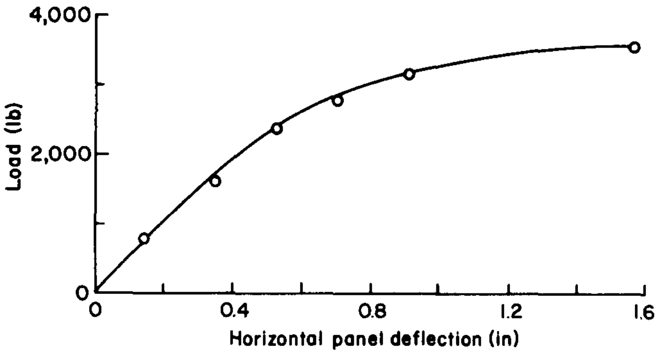

Figure 4-1 – Typical load as a function of deformation curve with increasing load for 8- by 8-foot by 1/2-inch regular density panel sheathed with fiberboard. (ML88 0008)

As previously indicated, wall-racking performance determined by test or by theoretical method does not always include all of the variables (length, openings, etc.) needed to predict the wall's behavior in a building. FPL in cooperation with HUD studied the contribution of gypsum wallboard to the overall racking strength of a building. Effects of horizontal versus vertical wallboard orientation, diagonal bracing, length of wall, door and window openings, and variations in details of corner construction details were included in this study (Wolfe 1983). Additional racking strength studies.at FPL relate to effects of variation of the test methods, inclusion of rigid insulation beneath plywood sheathing, and a variety of sheathing materials on opposite sides of a wall.

Results indicate that gypsum wallboard contributes significantly to the overall racking strength of a light-frame timber building. When installed horizontally, wallboard has greater racking resistance than when installed vertically; the reason being, we believe, that the paper edge of the wallboard has an encapsulating effect on the bottommost and topmost row of nails, which are most highly stressed. (There are paper edges on the long dimension and no paper edges on the short dimension of a gypsum sheet (Wolfe 1983).)

The strength and stiffness resulting from diagonal wind bracing appears to add to that of the unbraced wall. The contribution of the let-in brace is highly dependent on type of brace and quality of construction (Tuomi and Gromala 1977).

The effect of wall length on the ultimate strength of a gypsum-sheathed wall is related to the type of failure that occurs. Shorter walls are generally observed to have failures in the corner fasteners. This agrees with the assumption that the four corner nails are the most highly stressed (eq. (4-1) in next section). In longer walls, however, nail failures occur predominately along the top and bottom plates. This is thought to be because the taped gypsum-sheathed wall acts as a continuous diaphragm, instead of having panel rotation as in shorter walls. Thus a nonlinear relationship exists between racking strengths and length of walls sheathed with gypsum wallboard.

The failures observed in gypsum-sheathed walls that include windows and doors are failures in the sheathing material caused by stress concentration at the corners of the openings, as opposed to fastener failure in walls without openings. The ultimate strength of the wall with openings, however, can be approximated using an effective wall length equal to the total length minus the length of panels with openings (Wolfe 1983).

Table 4-3—Racking performance of 8- by 8-foot wall sections[1]

Framing				Sheathing[4]	Fasteners			Racking performance		Source
Size	Grade[2]	Species[3]	Spacing		Type	Spacing: Perimeter	Spacing: Interior	Load at 0.10 inch horizontal displacement	Ultimate strength	
			in			in	in	lb	lb	
					DIAGONAL LET-IN BRACES					
2 x 4	No. 2	DF	16	Various species of 1 x 4's	2 8d per stud			200	53,000	Tuomi and Gromala 1977
2 x 4	Stud	SPF	24	No. 2 SPF 1 x 4	2 8d per stud	–	–	200	600	Wolfe 1983
2 x 4	Stud	SPF	24	2-inch metal tension strap	2 8d per stud	–	–	600	1,500	Wolfe 1983
					FIBERBOARD SHEATHING					
2 x 4	No. 2	DF	16	1/2-inch regular density	1-1/2-inch No. 11 roofing	3	6	1,000	3,500	Tuomi and Gromala 1977
2 x 4	No. 2	DF	16	25/32-inch regular density	1-3/4-inch No. 11 roofing	3	6	900	4,500	Tuomi and Gromala 1977
2 x 4	No. 2	DF	16	1/2-inch intermediate density	1-1/2-inch No. 11 roofing	3	6	1,100	4,300	Tuomi and Gromala 1977
2 x 4	No. 2	DF	16	1/2-inch nail base	1-1/2-inch No. 11 roofing	3	6	1,600	6,400	Tuomi and Gromala 1977
2 x 3 (flat)	Std.	DF	16	1/4-inch hardboard	4d finish	6	8	900	5,300	NAHB-RF 1971
					FLAKEBOARD SHEATHING					
2 x 4	No. 1	SP	16	10 various types 1/2- to 5/8-inch thick	8d common	6	12	1,400-2,300	4,700-6,200	Price and Gromala 1980
					PLYWOOD SHEATHING					
2 x 4	No. 1	SP	16	1/2 inch CDX southern pine, 3 ply	8d common	6	12	1,300	6,000	Price and Gromala 1980
2 x 4	No. 1	SP	16	5/8-inch CDX southern pine, 4 ply	8d common	6	12	1,400	6,000	Price and Gromala 1980
2 x 4	Con.	DF	16	5/16-inch Douglas-fir	6d common	6	12	[5]1,100	7,300	Adams, undated
2 x 4	Con.	DF	16	5/16-inch group 4	6d common	6	12	[5]1,000	5,900	Adams, undated
2 x 4	Con.	DF	16	5/16-inch horiz. group 4	6d common	6	12	[5]900	5,100	Adams, undated
2 x 4	Con.	DF	16	3/8-inch cedar 303 siding	6d galv.	6	12	[5]1,000	6,900	Adams, undated
2 x 3 (flat)	Std.	DF	16	1/4-inch luaun	4d finish	6	12	900	3,300	NAHB-RF 1971
2 x 2	Unknown		16	3.6 mm luaun (one side)	Glued and stapled	–	–	–	4,900	Pittsburgh Testing Laboratory 1974
2 x 2	Unknown		16	3.6 mm luaun (both sides)	Glued and stapled	–	–	–	7,300	Pittsburgh Testing Laboratory 1974
2 x 3	Unknown		16	3.6 mm luaun (one side)	Glued and stapled	–	–	–	6,200	Pittsburgh Testing Laboratory 1974
2 x 3	Unknown		16	3.6 mm luaun (both sides)	Glued and stapled	–	–	–	11,500	Pittsburgh Testing Laboratory 1974

(Page 1 of 3)

Table 4-3—Racking performance of 8- by 8-foot wall sections[1]—con.

Framing				Sheathing[4]	Fasteners			Racking performance		Source
					Type	Spacing		Load at 0.10 inch horizontal displacement	Ultimate strength	
Size	Grade[2]	Species[3]	Spacing			Perimeter	Interior			
			in			---- *in* ----		------- *lb* -------		
					PLYWOOD SHEATHING—con.					
2 x 3	Unknown		16	4.0 mm luaun (one side)	Glued and stapled	–	–	–	6,300	Pittsburgh Testing Laboratory 1974
2 x 3	Unknown		16	4.0 mm luaun (both sides)	Glued and stapled	–	–	–	12,600	Pittsburgh Testing Laboratory 1974
2 x 3	Unknown		16	1/4-inch luaun (one side)	Glued and stapled	–	–	–	7,800	Pittsburgh Testing Laboratory 1974
2 x 3	Unknown		16	1/4-inch luaun (both sides)	Glued and stapled	–	–	–	14,800	Pittsburgh Testing Laboratory 1974
					COMBINATION OF PLYWOOD AND FIBERBOARD[6]					
2 x 4	Std.	DF	16	1/2-inch group 4 plywood and 1/2-inch regular density fiberboard	1-1/2-inch roofing	4	8	–	8,400	Tissell, undated
					GYPSUM WALLBOARD (TAPED JOINT)					
2 x 4	Stud	SPF	24	1/2-inch one side	1-1/4-inch drywall	8	8	600	1,200	Wolfe 1983
2 x 4	Std.	DF	24	1/2-inch horizontal both sides	1-1/4-inch drywall	8	8	700	4,000	NAHB-RF 1971
2 x 4	Std.	DF	24	1/2-inch horizontal both	1-1/4-inch drywall plus sides adhesive	16	16	1,400	3,300	NAHB-RF 1971
2 x 4	Std.	DF	16	1/2-inch horizontal both sides	1-1/4-inch drywall	8	8	1,300	4,300	NAHB-RF 1971
2 x 4	Std.	DF	16	1/2-inch horizontal both	1-1/4-inch drywall plus sides adhesive	16	16	1,300	4,000	NAHB-RF 1971
2 x 4 (flat)	Std.	DF	16	3/8-inch horizontal both sides	1-1/4-inch drywall	8	8	800	4,500	NAHB-RF 1971
2 x 4 (flat)	Std.	DF	16	3/8-inch horizontal both	1-1/4-inch drywall plus sides adhesive	16	16	800	4,800	NAHB-RF 1971
2 x 4	C&S	DF	24	1/2-inch outside 1/2-inch horizontal inside	1-1/2-inch galv. roofing 1-1/4-inch drywall	4 8	8 8	900	5,300	NAHB-RF 1971
2 x 3	C&S	WCH	16	1/2-inch outside 3/8-inch horizontal inside	1-1/2-inch galv. roofing 1-1/4-inch drywall	4 8	8 8	600	6,100	NAHB-RF 1971
2 x 3	C&S	WCH	16	1/2-inch outside 1/2-inch horizontal inside	1-1/2-inch galv. roofing 1-1/4-inch drywall	4 8	8 8	1,000	6,200	NAHB-RF 1971

(page 2 of 3)

Table 4-3 — Racking performance of 8- by 8-foot wall sections[1] — con.

Framing				Sheathing[4]	Fasteners			Racking performance		Source
Size	Grade[2]	Species[3]	Spacing		Type	Spacing: Perimeter	Spacing: Interior	Load at 0.10 inch horizontal displacement	Ultimate strength	
			in			*in*	*in*	*lb*	*lb*	
GYPSUM WALLBOARD PLUS DIAGONAL BRACES										
2 x 4	Stud	SPF	24	1 x 4 No. 2 spruce-pine- fir brace outside	2 8d per stud	–	–			
				1/2-inch gypsum inside	1-1/4-inch drywall	8	8	900	1,700	Wolfe 1983
2 x 4	Stud	SPF	24	2-inch metal strap outside	2 8d per stud	–	–			
				1/2-inch gypsum inside	1-1/4-inch drywall	8	8	1,000	2,400	Wolfe 1983
2 x 4	C&S	WCH	24	Construction Douglas-fir brace outside	2 8d per stud	–	–			
				1/2-inch horizontal gypsum inside	1-1/4-inch drywall	8	8	400	4,300	NAHB-RF 1971
2 x 4	C&S	WCH	24	No. 2 eastern spruce brace outside	2 8d per stud	–	–			
				1/2-inch gypsum inside	1-1/4-inch drywall	8	8	900	3,600	NAHB-RF 1971
2 x 4	C&S	WCH	16	No. 2 spruce brace outside	2 8d per stud	–	–			
				1/2-inch gypsum inside	1-1/4-inch drywall	8	8	500	4,900	NAHB-RF 1971
2 x 3	C&S	WCH	16	Construction Douglas-fir brace outside	2 8d per stud	–	–			
				3/8-inch horizontal inside	1-1/4-inch drywall	8	8	1,000	4,900	
GYPSUM WALLBOARD PLUS FIBERBOARD SHEATHING										
2 x 3	C&S	WCH	16	1/2-inch fiberboard outside	1-1/2-inch galv. roofing	4	8	400	4,700	NAHB-RF 1971
				3/8-inch horizontal inside	1-1/4-inch drywall	8	8			
2 x 3	C&S	WCH	16	1/2-inch fiberboard outside	1-1/2-inch galv. roofing	4	8	600	5,900	NAHB-RF 1971
				3/8-inch horizontal inside	1-1/4-inch drywall	8	8			
2 x 3	C&S	WCH	24	1/2-inch fiberboard outside	1-1/2-inch galv. roofing	4	8	500	4,600	NAHB-RF 1971
				3/8-inch horizontal inside	1-1/4-inch drywall	8	8			
2 x 3	Std.	ES/LP	24	1/2-inch fiberboard outside	1-1/2-inch galv. roofing	4	8	800	5,200	NAHB-RF 1971
				3/8-inch horizontal inside	1-1/4-inch drywall	8	8			
GYPSUM WALLBOARD PLUS PLYWOOD SHEATHING										
2 x 4	Con.	DF	16	[6]3/8-inch cedar plus 1/2-inch gypsum (same side)	8d galv.	4 or 6	12	[5]1,200	7,900	Adams, undated

[1]Based on an average of 3 or more replicates tested according to ASTM E72 or E564.
[2]Std. = standard, C&S = construction and standard, Con. = construction.
[3]DF = Douglas-fir; SPF = spruce pine fir; SP = southern pine; WCH = west coast hemlock; and ES/LP = Engelmann spruce/lodgepole pine.
[4]4 x 8 panels applied vertically to one side unless otherwise noted.
[5]Approximate values.
[6]A 4 x 8 sheet of each placed side by side to form 8-foot length.

Wall Models

Racking Strength

It has long been recognized that the racking strength of nailed walls depends on lateral nail strength. Empirical relationships were developed for specific sheathings and nail geometries (Neisel 1958, Neisel and Guerrera 1956, Welsh 1963). This approach is limited because a set of tests is required for each new combination of sheathing, framing, and fastener. To remove this limitation, an approach has been developed that expresses wall-racking strength as a function of lateral nail strength, panel dimensions, and nailing geometry (Tuomi and McCutcheon 1978). This approach assumes a linear relationship between nail load and nail distortion. Lateral nail strength is related to wall strength for 4- by 8 foot panels through the following equation:

$$R = r[(K_n + K_m)_p + (a^2K_{na} + b^2K_{nb} + a^2K_{ma} + b^2K_{mb})_f] \quad (4\text{-}1)$$

where:

- R = theoretical racking load per panel
- r = lateral strength of single nail
- K = racking coefficients
- n , m = subscripts denoting number of spaces between nails on the horizontal and vertical edges of the panels, respectively (fig. 4-2)
- a , b = ratios depending upon the nailing pattern (fig. 4-2)
- p = subscript denoting nails around the perimeter of the panel
- f = subscript denoting nails in the interior (field) of the panel.

The racking coefficients, K, are given in table 4-4 for a panel length/height ratio of 0.5. This approach assumes a linear relationship between nail load and nail distortion.

Racking Stiffness

The strength approach has been supplemented to predict deformation behavior by recognizing the nonlinear aspects of the fasteners and the shear properties of the sheathing (McCutcheon 1985). Total racking deformation is given by

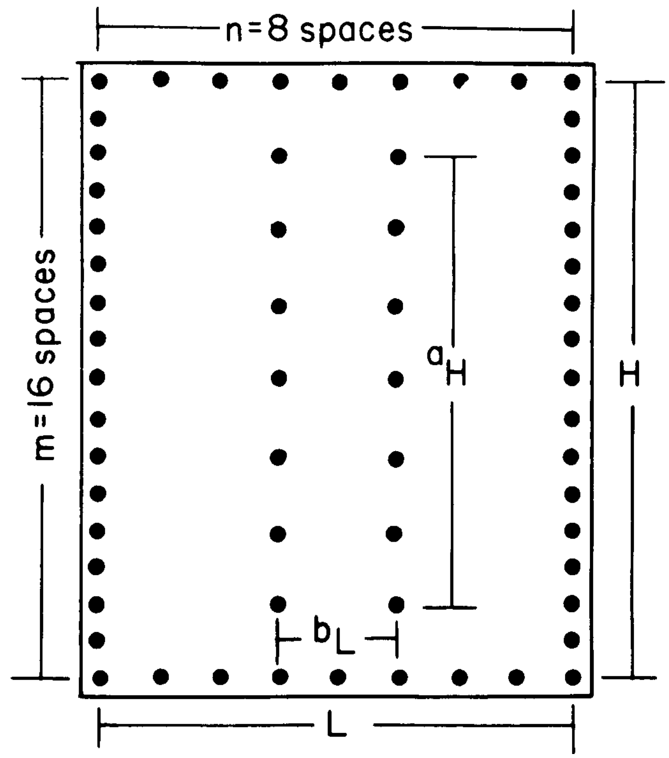

Figure 4-2 – Description of nailing pattern for shear walls and coefficients used in equation (4-1) and table 4-4. (ML88 0009)

$$\Delta_t = \left(\frac{R}{N\bar{A}}\right)^{1/B} + \frac{RH}{NGtL} \qquad (4\text{-}2)$$

where

- Δ_t = total racking deformation, i.e. horizontal movement of the loaded edge with respect to the parallel supported edge
- R = racking load
- N = number of identical vertical pieces of sheathing in the wall
- $\bar{A}$ = function of the geometry and nail-slip curve
- B = exponent to the power curve of nail-slip performance
- H = height of each wall panel
- G = shear modulus of panel material
- t = thickness of panel material
- L = length of each wall panel

Table 4-4– Racking coefficients for use in equation (4-1)

Nail spaces n or m[1]	Sheet length/height, L/H = 0.50					
	K_{na}	K_{nb}	K_n	K_{ma}	K_{mb}	K_m
1	0.09	0.36	0.45	0.09	0.36	0.45
2	0.18	0.36	0.54	0.09	0.72	0.80
3	0.27	0.44	0.71	0.11	1.07	1.18
4	0.36	0.54	0.89	0.13	1.43	1.57
5	0.45	0.64	1.09	0.16	1.79	1.95
6	0.54	0.76	1.29	0.19	2.15	2.34
7	0.63	0.87	1.49	0.22	2.50	2.72
8	0.72	0.98	1.70	0.25	2.86	3.11
9	0.80	1.10	1.90	0.27	3.22	3.49
10	0.89	1.22	2.11	0.30	3.58	3.88
11	0.98	1.33	2.32	0.33	3.94	4.27
12	1.07	1.45	2.52	0.36	4.29	4.66
13	1.16	1.57	2.73	0.39	4.65	5.04
14	1.25	1.69	2.94	0.42	5.01	5.43
15	1.34	1.80	3.15	0.45	5.37	5.82
16	1.43	1.92	3.35	0.48	5.72	6.21

[1]See fig. 4–2 for definition of n and m.

The first part of the equation defines the portion of the deformation caused by nail slip and the second part that caused by shear deformation of the panel material.

Another analytic technique uses a finite element approach and is generally applicable to diaphragms. It, too, uses the nonlinear load-slip behavior of the nails to predict the deformation behavior of shear walls under diverse loads. (The theory is discussed in detail by Foschi (1977).)

Both of these approaches depend on the availability of lateral nail performance data. The lateral nail values given in the codes assume the sheathing and framing materials have similar properties. Improved lateral nail data are needed, applicable to a wide range of conditions, to use these techniques to predict racking strength and stiffness accurately.

Design Approaches

Three approaches to wall-racking design exist – all of them related only to ultimate strength, not to stiffness. The first is the prescriptive approach employed by HUD-FHA. This method has been used since the early 1950’s to define minimum structural requirements for FHA financing. The second, herein called the code approach, has been encouraged by building codes and is based on available research information. The third, and most comprehensive, is the whole-house stiffness approach presented by Whittemore et al. (1948).

The third method is similar to that used in the design of high-rise structures. It has received little attention in the past because of its apparent complexity and a lack of interest in its potential design efficiency.

HUD-FHA Approach

The HUD-FHA prescriptive design approach makes a number of simplifying assumptions that in many cases lead to conservative designs. This approach specifies that all racked walls must contain one 8-foot section that meets the HUD minimum property standards outlined in table 4-2 (FHA 1949). The approach ensures that construction is as good as the traditional wall with board sheathing and diagonal corner-bracing. The method is based on tests of 8- by 8-foot wall sections and does not require knowledge of the actual size and configuration of the building. It places greater emphasis on ultimate strength than on limiting deformation. The factor of safety may vary greatly for different building sizes, configurations, and locations

Code Approach

The Building Code design approach compares a derived windload with individual wall performance. The windward wall at each floor level is assumed to transfer half the total windload to reactions at each end of the house. For the first floor level, therefore, half the load goes directly to the foundation, and half the load is distributed, through floor or roof diaphragms, to the end walls where it is assumed to act as concentrated shear loads along the top plate parallel to the wall length.

For this design approach, wall-racking resistance is assigned on the basis of available test data and compared with the calculated racking load. No stiffness requirements are indicated.

Several building codes list allowable shear resistance per unit length (ICBO 1979). However, these values are limited to specific combinations of sheathing types, framing species and grades, and nail size and spacing. The Uniform Building Code illustrates this. It represents various national, state, and local codes. Additionally, it is applicable for seismic-resistant construction. Allowable lateral nail values and racking strength values are reproduced in tables 4-5 and 4-6. As indicated by footnotes, the racking strength values are to be reduced 25 percent for normal (10 year) duration loading. The lateral nail values are for normal duration loading but may be increased 30 percent for diaphragm of the construction in accordance with national design specifications (NFPA 1986, para. 8.8.5.5).

To illustrate the code approach, consider an 8-foot wall with 1/2-inch CD grade plywood sheathing, Douglas-fir framing, and common 10d nails spaced at 6 inches along the perimeter and 12 inches along the interior studs. From table 4-6, the allowable shear per foot for short duration loading is 310 lb/ft. Reducing this 25 percent for normal duration loading results in a total allowable racking resistance of 1,860 pounds for the 8-foot length.

An alternative procedure is to use the allowable lateral nail values of table 4–5 and the racking theory summarized by equation (4-l). Using the data in the above example and the coefficients of table 4-2, equation (4–1) yields for a 4-foot-wide panel

$$R = 8.35r \tag{4-3}$$

Increasing the lateral nail strength of 94 pounds in table 4-5 by 30 percent gives a total allowable racking resistance of 2,040 pounds for an 8-foot length.

No experimental results are available for direct comparison with the preceding analysis; however, some approximate comparisons are possible. From table 4-3, for southern pine framing, 1/2- or 5/8-inch CDX plywood, and 8d nails, the ultimate racking strength for an 8- by 8-foot panel is 6,000 lbs. Comparing this with the value in our example, we see the need for an average factor of safety of about three.

The Code approach to racking design is fairly easy to apply; however, in improving design efficiency, its contribution is limited. Racking loads are assumed to be resisted totally by the end walls, each of which carries an equal share of the total load. The contribution made by interior partitions and the effects of variation in racking stiffness are ignored. This approach also bases wall design on ultimate strength, giving no guidelines or stiffness information for limiting wall deflections.

Table 4-5 – Safe lateral strength and required penetration of box and common wire nails driven perpendicular to grain of wood

Size of nail	Standard length	Wire gauge	Penetration required	Load[1,2,3]
	in		*in*	*lb*
		BOX NAILS		
6d	2	12½	1¼	51
8d	2½	11½	1½	63
10d	3	10½	1⅝	76
12d	3¼	10½	1⅝	76
16d	3½	10	1¾	83
20d	4	9	2⅛	94
30d	4½	9	2¼	94
40d	5	8	2½	107
		COMMON NAILS		
6d	2	11½	1¼	63
8d	2½	10¼	1½	78
10d	3	9	1⅝	94
12d	3¼	9	1⅝	94
16d	3½	8	1¾	107
20d	4	6	2⅛	139
30d	4½	5	2¼	154
40d	5	4	2½	176
50d	5½	3	2¾	202
60d	6	2	2⅞	223

[1]The safe lateral strength values may be increased 25 percent where metal sideplates are used.
[2]For wood diaphragm calculations these values may be increased 30 percent. (See Uniform Building Code Standard No. 25-17 (ICBO 1979).)
[3]For Douglas-fir, larch, or southern pine. For other species the lateral strength values of box wire nails shall not exceed 75 percent of the values listed in the Standard.

Whole-House Stiffness

An approach via whole-house stiffness provides a means of accounting for factors neglected in the Code approach. This method takes into account the contribution of interior partitions and calculates each wall's contribution to total structural performance according to its stiffness and location.

This method assumes that the ceiling and floor diaphragms are infinitely rigid. Therefore, in estimating translation, all walls oriented parallel to the applied load are assumed to deflect the same amount, and estimates of their individual contributions to the total resistance are directly proportional to their stiffnesses.

If the building is not symmetric with respect to wall stiffness, the translation will be accompanied by a relative rotation of the ceiling and floor diaphragms. This rotation is calculated as a function of the sum of wall stiffnesses and distances from the center of rotation. Total racking deformation may then be calculated for each wall and multiplied by the corresponding wall stiffness to give its contribution to the total racking resistance of the structure. An example of this approach has been presented by Whittemore et al. (1948).

This approach provides greater potential for the efficient design of light-frame racking walls than either the HUD or the Code approach. However, it requires a knowledge of wall stiffness. Whittemore calculated stiffness using the deformation at a preselected allowable load. If this design approach were computerized, the actual load-deflection curve for each wall could be input and an iterative procedure used to estimate maximum deformation under design wind or maximum wind resistance at the allowable deformation level.

Table 4-6—Allowable shear for wind or seismic forces for plywood shear walls with framing of Douglas-fir, larch, or southern pine[1]

Plywood grade	Minimum nominal plywood thickness	Minimum nail penetration in framing	Plywood applied directly to framing					Plywood applied over 1/2-in gypsum				
			Nail size (common or galvanized box)	Nail spacing[2]				Nail size (common or galvanized box)	Nail spacing[2]			
				6 in	4 in	2-1/2 in	2 in		6 in	4 in	2-1/2 in	2 in
				Allowable shear					Allowable shear			
	in	*in*		*lb/ft*					*lb/ft*			
Structural I	5/16	1-1/4	6d	200	300	450	510	8d	200	300	450	510
	3/8	1-1/2	8d	[3]230	[3]360	[3]530	[3]610	10d	280	430	[4]640	[3,4]730
	1/2	1-5/8	10d	340	510	[4]770	[4]870	—	—	—	—	—
C-D, C-C, Structural II and other grades covered in Uniform Building Code Standard	5/16	1-1/4	6d	180	270	400	450	8d	180	270	400	450
	3/8	1-1/2	8d	[3]220	[3]320	[3]470	[3]530	10d	260	380	[3]570	[3]640
	1/2	1-5/8	10d	310	460	[4]690	[4]770	—	—	—	—	—
			Nail size (galvanized casing)					Nail size (galvanized casing)				
Plywood Panel siding in grades covered in Uniform Building Code Standard No. 25-9	5/16	1-1/4	6d	140	210	320	360	8d	140	210	320	360
	3/8	1-1/2	8d	[3]130	[3]200	[3]300	[3]340	10d	160	240	410	410

[1]All panel edges backed with 2-inch nominal or wider framing. Plywood installed either horizontally or vertically. Nails spaced at 6 inches on center along intermediate framing members for 3/8-inch plywood installed with face grain parallel to studs spaced 24 inches on center or spaced 12 inches on center for other conditions and plywood thicknesses. These values are for short-time loads caused by wind or earthquake and must be reduced 25 pct for normal loading. Allowable shear values for nails in framing members of other species set forth in Table No. 25-17 of Uniform Building Code Standards shall be calculated for all grades by multiplying the values for common and galvanized box nails in Structural I grade and galvanized casing nails in other grades by the following factors: Group III, 0.82 and Group IV, 0.65.

[2]Spacing at plywood panel edges.

[3]The values for 3/8-inch-thick plywood applied directly to framing may be increased 20 pct, provided that studs are spaced a maximum of 16 inches on center or plywood is applied with face grain across studs or if the plywood thickness is increased to 1/2 inch or greater.

[4]Reduce tabulated allowable shears 10 pct when boundary members provide less than 3-inch nominal nailing surface.

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Part II
Fire Safety

Fire safety involves the protection of life and property. It generally requires construction that, in case of fire, allows sufficient time for occupants to leave the building and for firefighters to suppress the fire. Protection is usually provided by surfaces with low flame-spread rates and by barriers that contain the fire within a small space for a specified time. The generation of smoke and the toxicity of products of combustion may also endanger life. Performance factors and analysis methods are considered first for different types of fire barriers (walls and floors); then, performance factors are considered as they affect different aspects of fire growth.

Part II
Fire Safety

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Chapter 5

Fire Barriers

Background

As obstacles to fire growth once a fire has fully developed, barriers are rated for their capability to confine fire to one side of the assembly. The rating is determined by subjecting the assembly to a standard fire exposure (ASTM Standard E-119 (ASTM 1983)) and observing the time until failure of stability, integrity, or insulative capacity, that is until a limiting state is reached at which

(1) elements collapse (stability),

(2) cracks develop allowing flames to pass through (integrity), or

(3) temperatures rise 250 °F on the nonfire-exposed surface (insulative capacity).

The rating of an assembly is given in terms of the time to reach one of the limiting states.

The codes provide fire endurance requirements for frame construction – that is, walls or partitions, floors, and roof assemblies wholly or partly constructed of wood studs and joists with minimal nominal dimension of 2 inches. Such buildings are further classified as protected or nonprotected. The term “protected” is applied to assemblies rating a fire endurance of 1 hour or more.

For load-bearing assemblies, such as floors and exterior walls, times to reach all three limiting states are measured and the shortest period employed to rate the unit. For nonload-bearing walls or partitions, only the integrity and insulative capacity limits are used to rate the assembly.

Many codes require that the paneling of a wall or partition provide thermal protection to the wood studs or combustible insulation in the cavity between studs. A rating has been established for the surfacing material (finish rating) that defines the minimal acceptable time during which the interface temperature should not rise 250 °F on the average, or 325 °F at any spot, during a standard ASTM E 119 fire test.

There are two basic ways for structural members and assemblies to be accepted as meeting the code performance requirements for fire endurance:

(1) (a) By testing a representative member or assembly according to the ASTM E 119 standard fire test, or
(b) by comparison of a proposed member or assembly with previously accepted tested units.

(2) By analysis of performance based upon material properties and sound engineering principles.

Up to about 10 years ago, code acceptance of the fire barrier performance of elements or assemblies was given only after conducting a fire test of a representative unit. Later, increasingly, code authorities have accepted engineering analyses of performance during standard fire exposure, thereby opening a way to save the high cost of conducting tests. This approach has been well developed and is used to classify concrete and steel members and assemblies. Only recently have such analyses been proposed in the United States for timber or wood units.

Various procedures are available to assess the fire barrier effectiveness of walls and floors. Lists have been produced of members and assemblies already experimentally evaluated by independent or recognized laboratories. Some of the major codes include abbreviated rating lists and drawings of such assemblies. The most comprehensive lists of tested assemblies are the Underwriters’ Laboratories Fire Resistance Directory (UL 1985b) and the American Insurance Association Fire Resistance Ratings (1972). The HUD Minimum Property Standards (U.S. Department of Housing and Urban Development 1973a) contains ratings for light-frame assemblies that are not included in the two lists previously mentioned.

Fire Resistance Rating

Assemblies may be accepted that have not been tested but whose materials, having characteristic differences from test assemblies, are known to provide equivalent or better performance. The recommended procedure is by the application of one of the ten following rules governing the influence of materials used on fire endurance of an assembly (fig. 5-1, Harmathy 1965).

Rule 1 – Insulative performance is defined as the time until an average temperature rise of 250 °F (or maximum temperature rise of 325 °F) on the nonfire-exposed surface. The insulative fire endurance of a construction consisting of a number of parallel layers is greater than the sum of the insulative fire endurances characteristic of the individual layers when exposed separately to fire.

The validity of this rule is seen from tests of plywood (White 1981), in which the observed times for the temperature criteria were 2.7, 6.9, and 12.10 minutes for thicknesses of 1/4, 1/2, and 3/4 inch, respectively.

Rule 2– The fire endurance of a construction does not decrease with the addition of further layers (to the fire-exposed surface).

This rule applies not only to insulative performance but to fire endurance generally. Thermal expansion characteristics, load-bearing capacity, and thermal insulation characteristics of the additional layer must be considered before this rule is applied. The validity of this rule is subject to certain limitations.

Rule 3 – The fire endurance of constructions containing continuous air gaps or cavities is greater than the fire endurance of similar constructions of the same weight, but containing no air gaps or cavities.

Harmathy notes that constructions containing combustible materials within an air gap may be regarded as exceptions to this rule because of the possible development of burning in the gap. Test results (FPL 1961) for plywood faces on wood studs suggest that the unfilled wall space does not improve the total fire resistance of the assembly, particularly when the plywood adhesive is not a phenolic resin.

Rule 4 – The farther an air gap or cavity is located from the exposed surface, the more beneficial is its effect on the fire endurance.

Rule 5 –The fire endurance of a construction cannot be increased by increasing the thickness of a completely enclosed air layer.

Harmathy notes that if the thickness of the air layer is larger than about ½ inch, the heat transfer through the air layers is practically independent of the distance between them. In tests of plywood wall panels (FPL 1956), the widths of stud in the range of 1 % and 3⅝ inch had no appreciable influence upon the resistance of the unfilled wall assembly.

Rule 6 – Layers of materials of low thermal conductivity are better utilized on that side of the construction on which fire is more likely to occur.

The rule may not be applicable to materials undergoing physiochemical changes accompanied by significant heat absorption or heat evolution.

Rule 7 – The fire endurance of asymmetrical constructions depends on the direction of heat flow.

Rule 8 – The presence of moisture, if it does not result in explosive spalling (as in concrete), increases the fire endurance.

The charring rates of wood (Schaffer 1967) and the thermal barrier performance of plywood (White 1981) depend on the moisture content. The higher the moisture content, the slower the charring rate and the greater the times to reach critical temperatures on the unexposed side of the plywood.

Rule 9 – Load-supporting elements, such as beams, girders, and joists, yield higher fire endurances when subjected to fire endurance tests as parts of floor, roof, or ceiling assemblies than they would when tested separately.

Rule 10 – The load-supporting elements (beams, girders, joists, etc.) of a floor, roof, or ceiling assembly can be replaced by other load-supporting elements that, when tested separately, yield fire endurances not less than that of the assembly.

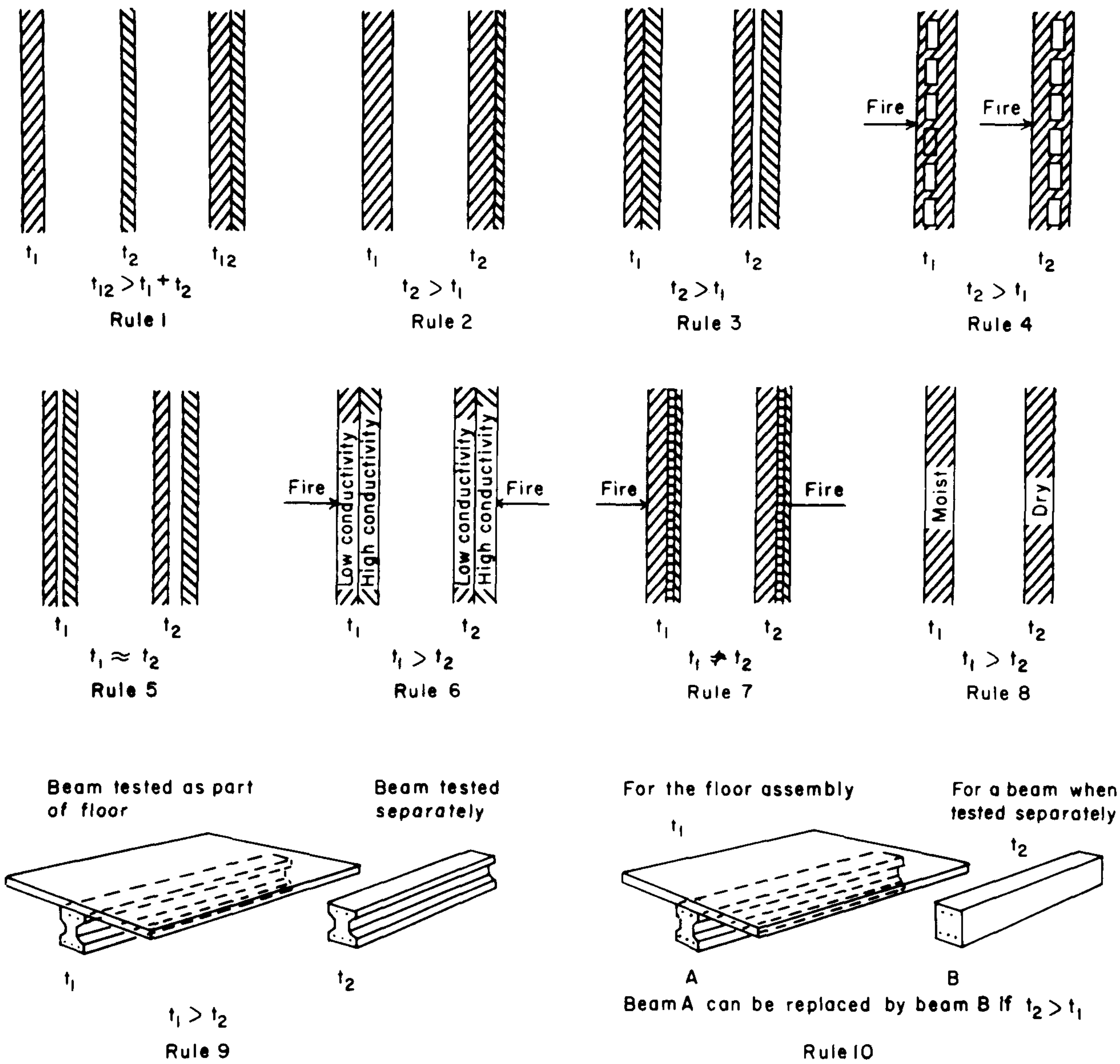


***Figure 5-1 –Diagrammatic illustration of 10 rules for fire endurance (t* = fire endurance time) (Harmathy 1965). (ML88 0010)**

Fire Stops

Inadequate fire and draft stopping of concealed passages is recognized as a major cause both of casualties and of high property loss in all types of construction. The movement of flame and gases through concealed spaces to other parts of a building is often the major cause of rapid involvement of a building in fire. It is imperative that adequate fire and draft stopping be designed, constructed, and maintained.

Fire stops and draft stops differ only in that fire stops are required to have the fire resistance equivalent of 1-1/2 inches of lumber. In light-frame construction, fire stops are required in stud spaces at ceiling and floor levels to prevent spread of fire in the vertical direction in concealed spaces (fig. 5-2). Fire stopping in the horizontal direction is required by solid blocking of floor joists over points of support and, in some cases, partitions. As seen in figure 5-3, fire stopping is also needed at stairwell and chimney locations.

The need for draft stopping in large concealed spaces has been recognized for many years. Draft stopping is usually provided by requiring a plywood or gypsum board barrier at 3,000-square-foot intervals in attic spaces. With new design techniques utilizing suspended or dropped ceilings, a need has been created for draft stopping in such concealed areas equivalent to that provided by solid blocked wood-joist construction where the ceiling is applied directly to solid joists.

Use of parallel-chord trusses has created other concealed spaces, particularly where the trusses are used in floor-ceiling construction. The probability of fire and smoke spread is greater in a floor-ceiling assembly constructed with parallel-chord wood trusses with open webs than with solid wood joists. Further, there is an important difference between the open space created by a suspended ceiling and that created by use of parallel- chord floor trusses. Under fire conditions in a ceiling suspended below wood joists, the joists themselves tend to serve as a baffle to the spread of heat in the concealed space. In parallel-chord wood truss construction, there is little such containment.

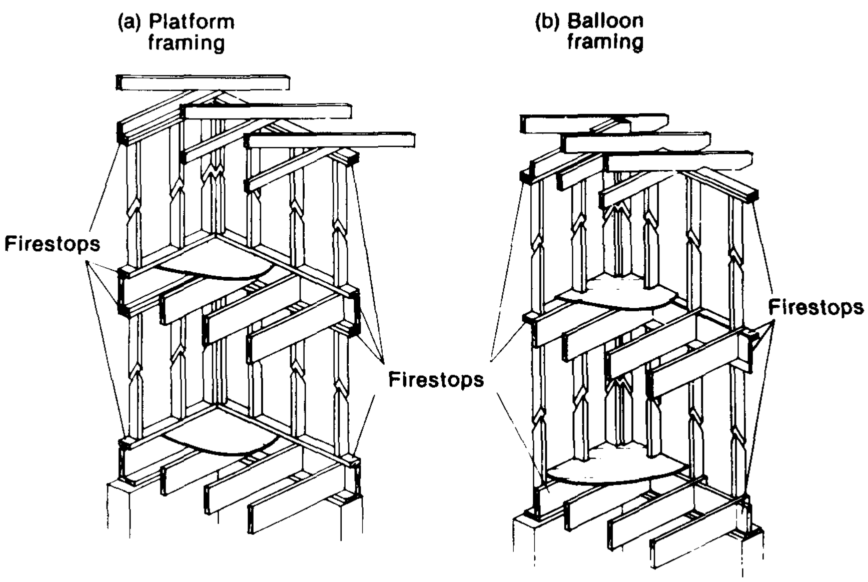


Figure 5-2 – Typical firestopping in concealed spaces of stud walls and partitions, including furred spaces at ceiling and floor levels (a) Platform framing, (b) Balloon framing (NFPA 1980). (M149 464)

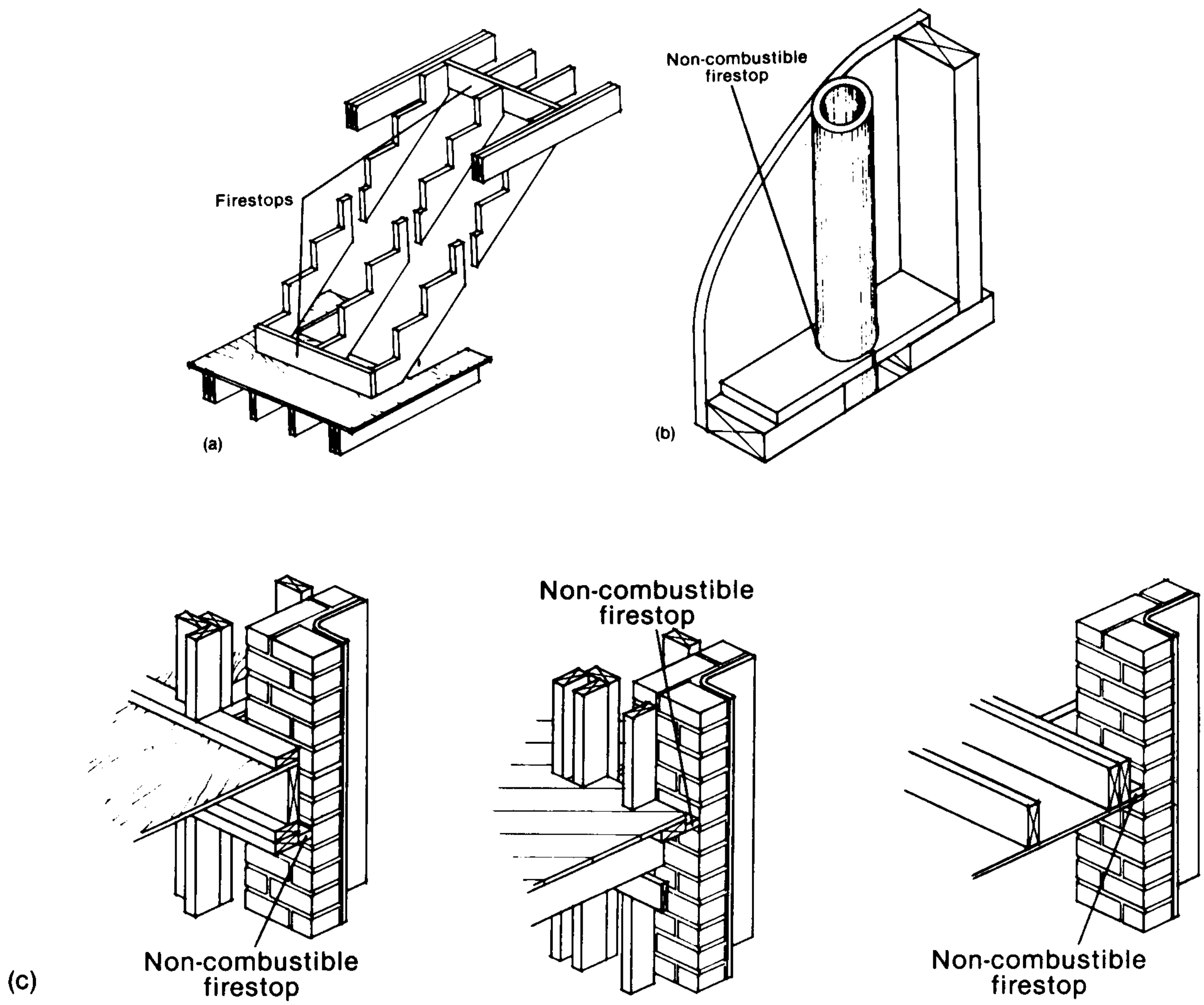


Figure 5-3 –Fire stopping is concealed (a) between stringers at the top and bottom of stairs (M149 462), (b) at openings around vents, pipes, ducts (M149 463), (c) in chimneys and fireplaces at ceiling and floor levels with noncombustible materials (M149 465) (NFPA 1980).

The NFPA (1980) developed fire- and draft-stopping provisions as recommended practice to be included in the model building codes. Specific examples of recommended fire-stopping details in light-frame housing are shown in figures 5-2 to 5-5. In construction, fire stopping is required to be maintained and must be maintained to be effective. Fire stopping shall consist of one of the following or equivalent: (1) 2-inch nominal lumber, (2) two thicknesses of l-inch nominal lumber with broken lap joints, (3) 3/4-inch plywood with joints backed by 3/4-inch plywood, (4) approved noncombustible materials (such as gypsum wallboard and some mineral-based insulation).

Draft stopping details are shown in figure 5-5 for maintaining separation between occupancies in multifamily residences.

Draft stopping recommendations for floor-ceiling assemblies and attics are also advocated as follows by NFPA (1980).

Floor-Ceiling Assemblies

(a) Single-family dwellings –place in floor-ceiling assemblies separating usable spaces into two or more approximately equal areas with no area greater than 500 square feet. Draft stopping shall be provided parallel to the main framing members (fig. 5-6).

(b) Multifamily (two or more) dwellings, motels, hotels – place in the floor-ceiling assemblies above and in line with the tenant separation, when tenant separation walls do not extend to the floor sheathing above
(fig. 5-5a).

(c) Other buildings – place in floor-ceiling assemblies so that horizontal areas do not exceed 1,000 square feet.

Attics

(a) Single-family dwellings – none required.

(b) Multifamily (two or more) dwellings, motels, hotels – place in the attic, mansard, overhang, or other concealed roof spaces above and in line with the tenant separation, when tenant separation walls do not extend to the roof sheathing above (fig. 5-5b).

Exception (1) – where corridor walls provide a tenant separation, draft stopping is only required above one of the corridor walls.

Exception (2) – where flat roofs with solid joist construction are used, draft stopping over tenant separation walls is not required.

Exception (3) – where approved sprinklers are provided, draft stopping shall not be required.

(c) Other buildings – place in attic spaces so that horizontal areas do not exceed 3,000 square feet.

Exception (1) – where flat roofs with solid joist construction are used, draft stopping over tenant separation walls is not required.

Exception (2) – where approved sprinklers are provided, draft stopping is not required.

Ventilation of concealed roof spaces shall be maintained in accordance with the building code.

Draft-stopping materials shall be not less than 1/2-inch gypsum board, 1/2-inch plywood, or other approved materials adequately supported.

The integrity of all draft stops shall be maintained.

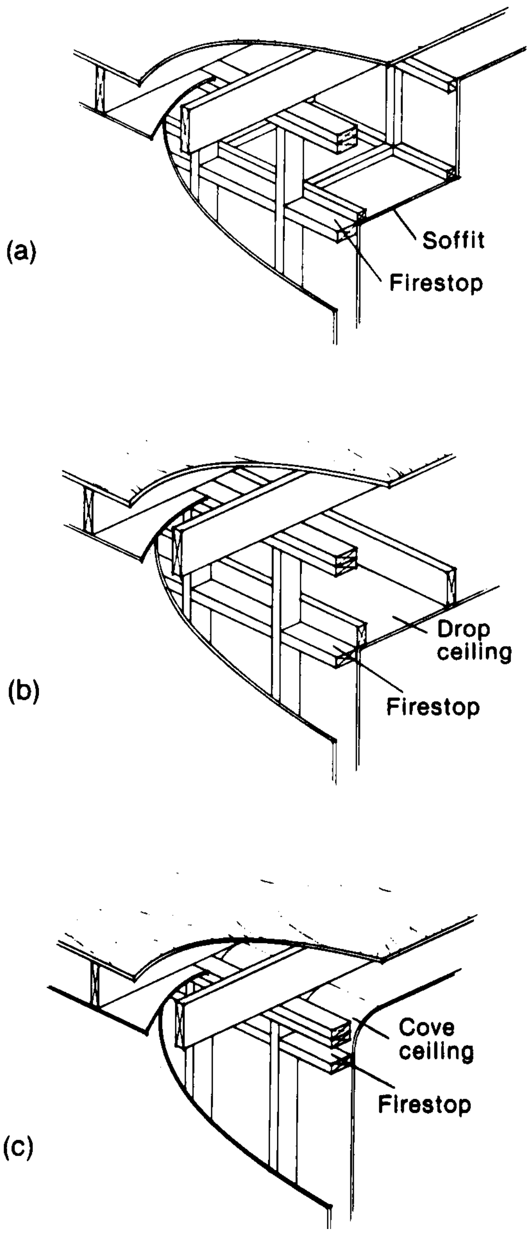
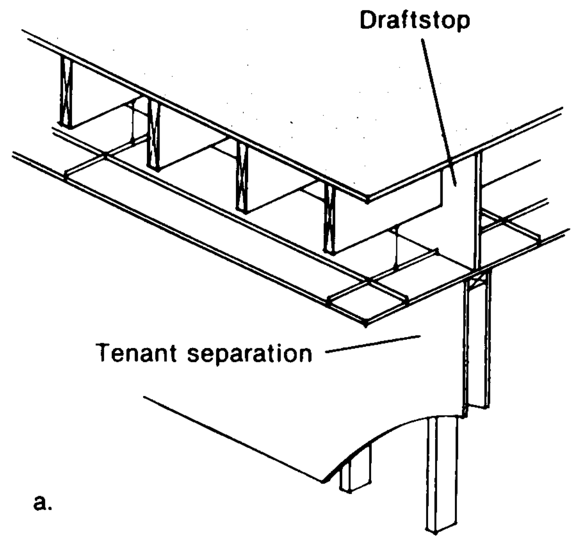


Figure 5-4 –Fire stopping at interconnections between concealed vertical and horizontal spaces: (a) soffit (M149 466), (b) drop ceiling (M149 460), and (c) cove ceiling (M149 461) (NFPA 1980).



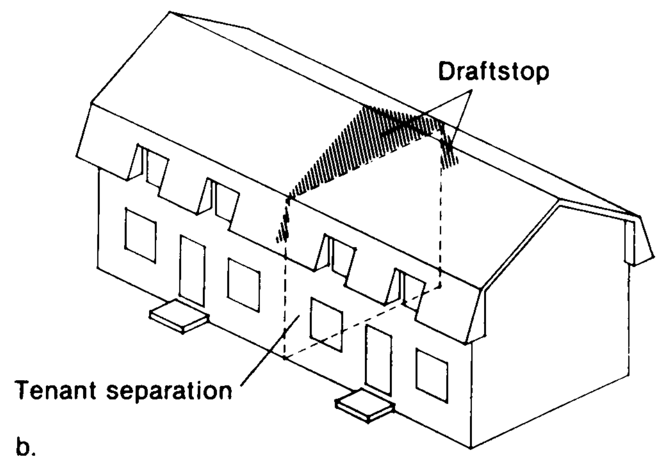


Figure 5-5 –Draftstops in multifamily buildings (a) in floor-ceiling assemblies (M149 458-1) and (b) in attics, mansaards, overhang, or other concealed roof spaces above and in line with tenant separation when tenant separation walls do not extend to the roof sheathing above (M149 459) (NFPA 1980).

Performance Factors and Analysis Methods – Walls

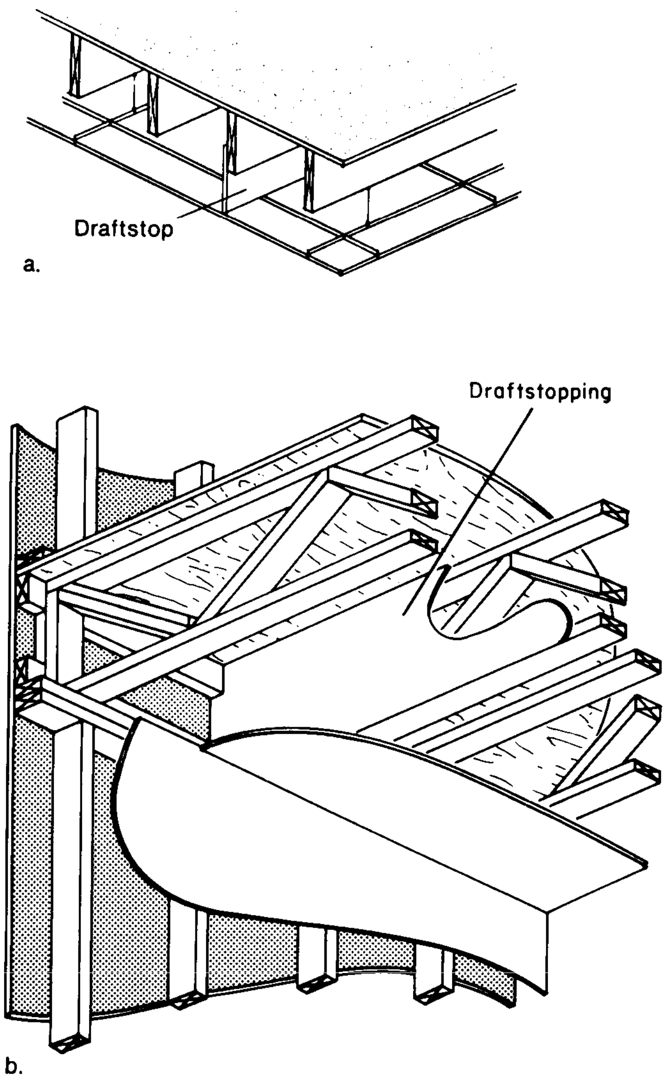


Figure 5-6–Draft stopping parallel to the main framing member in (a) wood joist floor-ceiling assembly and (b) wood truss floor-ceiling assembly. (ML8 0011)

Walls are important as barriers for the containment of fire. During a fire, a wall should prevent the passage of flames, continue to support its load, and prevent the ignition of combustibles near or on the unexposed side of the wall. Containment of a fire also depends on the performance of any doors and windows in the wall.

The ASTM E 119 standard test (ASTM 1983) provides a measure of the fire resistance of a wall. A specimen with area not less than 100 square feet is constructed in the furnace opening. For tests of bearing walls, a superimposed load is applied to the construction in a manner calculated to develop the working stresses contemplated by the design. The ASTM E 119 also provides for a hose stream test for walls with resistance periods not less than 1 hour.

Requirements for fire resistance of walls are given in the model building codes. Whereas, code requirements are very numerous for walls in multifamily frame residences, they are few for walls in one- and two-family dwellings. As mentioned previously, protected frame construction has the more stringent fire endurance requirements.

In the Basic Building Code (BOCA 1984), the degree of fire hazard for each type of occupancy determines the requirements for fire walls, fire separation walls, and the segregation of mixed uses. The fire grading ranges from 1 hour for one- and two-family dwellings to 3 hours for theaters.

Light-frame wood construction is included in one of five types of construction in the Basic Building Code (BOCA 1984). Combustible construction (Type 5) is further subdivided into protected and unprotected. For protected frame construction, a 1-hour fire resistance rating is required for most structural elements. Unprotected frame construction requires the 1-hour rating for only a few structural elements, e.g., an exterior wall erected less than 6 feet from the adjacent lot line. A 2-hour rating is required for fire walls and party walls in both types of frame construction. Regardless of construction type, the rating for fire walls and fire separation walls cannot be less than the fire rating for the use group.

Performance Factors

As stated previously, tested wall assemblies have been listed and details of construction can be obtained from the listings. Fire endurance and finish ratings are shown in table 5-1 for a range of load-bearing wall systems.

Data on fire endurance of walls are limited. Most wall tests are funded by private concerns and not reported in the published literature. Also, the rating listed is not necessarily the full fire resistance of the assembly. Ratings are usually set at times that are listed in building codes, e.g., 45 minutes, 1 hour, 2 hours. When an assembly is being tested to achieve a certain rating, the test is often terminated when that rating is obtained even though the end point criterion has not been reached.

Much of the published information on walls with fire resistances less than 1 hour are in two NBS publications of the 1940s (CHC 1942, Ingberg 1941). Some of the data are listed in a recent publication that provides guidelines on fire ratings of archaic materials and assemblies (National Institute of Building Sciences 1980). Also in the 1940s, tests were conducted at the Forest Products Laboratory on the fire resistance of plywood-covered wall panels (FPL 1961) and the effect of wood-fiber blanket insulation on the fire resistance of walls (FPL 1956).

Walls with gypsum wallboard or plaster are listed in the UL Fire Resistance Directory (UL 1985b), the American Insurance Association's Fire Resistance Ratings (1972), and the Gypsum Association's Fire Resistance Design Manual (1984). Gypsum wallboard and plaster walls have ratings of 30 minutes to 2 hours. The basic 1-hour wall is a wood stud wall with 5/8-inch-thick type X gypsum wallboard as the membrane on each side of the studs.

In recent years fire endurance tests on walls were conducted as part of Operation Breakthrough (Eickner 1975, U.S. Department of Housing and Urban Development 1976). Sandwich panels as well as traditional wood stud construction were tested.

Ratings can also be found in the HUD Minimum Property Standards, the HUD Manual of Acceptable Practices (U.S. Department of Housing and Urban Development 1973a,b) and the Fire Protection Handbook (National Fire Protection Association 1981).

Structural Integrity

Recent tests have shown that innovative structural members may have structural integrity problems when tested for fire resistance. The relatively good structural behavior of a traditional wood stud in a fire test results from the solid mass of the stud and the uniformity of its load-bearing capacity with depth of penetration. Innovative designs for structural members often reduce the mass of the member and locate a major part of the load-bearing capacity at the outer edge of the member. In fire tests, charring the outer portion of such a member results in its early structural failure. The load-bearing sandwich panel exemplifies such a structural element. Structural sandwich panels have high-strength facings bonded to a low-density plastic foam or paper honeycomb core. The load-bearing capacity is in the outer faces of the panel. The traditional wood stud wall with a 1/4-inch-thick lauan paneling as the fire-exposed membrane has a structural integrity resistance of 21 minutes. A sandwich panel with A-C Douglas-fir plywood facings 1/4-inch-thick and polyurethane foam core 3 inches thick failed in 3 minutes in the ASTM E 119 standard fire test (Eickner 1975). The structural fire resistance of structural sandwich panels can be improved to a satisfactory level by adding facings of gypsum wallboard or fire-resistive coating as protection (Eickner 1975, Holmes et al. 1980).

Other Significant Influences

A wall must prevent the passage of flame or hot gases during the rated fire resistance period. The performance of the penetrations and the joints in the wall are critical to preventing the passage of flames or hot gases. Common penetrations in walls are holes for pipes and utility wires. In fire-rated walls, these penetrations should be protected. Mineral wool packing, cementitious materials, and intumescent mastics can be used to seal these openings.

Details of the joints in the fire-exposed membrane can be critical to the fire resistance of a wall. Some fire-rated walls with gypsum wallboard require the joints to be covered with tape and joint compound. The joints of plywood or lumber may be installed with tongue-and-groove on sides and/or ends for added fire resistance. The accuracy of theoretical methods for predicting fire resistance is limited by uncertainty concerning critical details of the joints.

Table 5-1 — Fire endurance and finish ratings of some typical load-bearing stud wall assemblies[1]

Wallboard material	Insulation	Fire endurance rating[2]	Finish rating	Reference[3]
		min	*min*	
Plywood paneling, 1/4 inch	Void	[4]20	–	HUD 1973b
	Glass-fiber	[4]20	2	Holmes et al. 1980
Tongue-and-groove wood boards, 3/4 inch	Void	20	–	CHC 1942, Ingberg et al. 1941, HUD 1973b
	Mineral wool	30	–	CHC 1942, Ingberg et al. 1941, HUD 1973b
Gypsum wallboard, 3/8 inch	Void	20	10	CHC 1942, Ingberg et al. 1941, HUD 1973b
	Void	30	8	UL 1985b
1/2 inch	Void	30	15	CHC 1942, Ingberg et al. 1941, HUD 1973b
	Mineral wool	45	15	CHC 1942, Ingberg et al. 1941, HUD 1973b
5/8 inch	Void	45	20	HUD 1973b
Type X gypsum wallboard, 1/2 inch	Void	45	15-26	UL 1985b, HUD 1973b
5/8 inch	Void	60	20-27	AIA 1972, Gypsum Assoc. 1984, UL 1983
5/8 inch + 5/8 inch	Void	120	66	AIA 1972, Gypsum Assoc. 1984, UL 1985b
Gypsum wallboard, 3/8 inch + 3/8 inch	Void	60	20	AIA 1972, Gypsum Assoc. 1984, UL 1985b
1/2 inch + 1/2 inch	Void	60–90	30	AIA 1972, HUD 1973b

[1]Nominal 2 x 4 wood studs, 16 inches on center.
[2]Test results have been rounded off.
[3]HUD = U.S. Department of Housing and Urban Development, CHC = Central Housing Committee on Research Design and Construction, UL = Underwriters' Laboratories, AIA = American Insurance Association.
[4]Structural integrity only.

The field performance of a fire-rated wall depends on the conformance of the actual wall with the wall tested and the adequacy of the ASTM E 119 test method. Lack of conformance can result from poor design or construction of the wall in the field or from the ideal condition of the test wall. Questions have been raised about the adequacy of the test method in its specification both of the procedure and of the assumptions on which the application of the test results is based.

When a fire-rated wall has been designed, care must be taken that critical details are not modified in its construction. The method of fastening facings to frame, the joints, the quality and quantity of materials, the structural load on elements, and the quality of workmanship are all factors that determine the fire-resistant performance of a wall. Only one wall of a given type is generally tested, and the quality of materials and workmanship of the tested wall is likely to be high. Possible wear and tear of the materials and the conditioning of the test specimen before testing (Malhorta 1980) are factors to consider when evaluating the field performance of a fire-rated assembly.

Questions about the standard test method involve insufficient specification of the boundary support conditions, construction of specimen, environment in the furnace, and the end point criteria (Malhorta 1975, Pettersson 1980). Simplified boundary conditions used in the test may not adequately reproduce the conditions of interaction in a building that affect the performance of a construction. The standard time/temperature curve determines the ASTM E 119 fire exposure. Neither the mode of heating nor the design of the furnace are specified. With variations among the laboratories in the fuel and the type of equipment used, considerable variation is possible in the fire resistance results. With regard to the end point criteria, doubts exist about the precision of the methodology and the practical application of the data.

The current test method is based on the assumption that the fire severity (the temperature increase and duration of high temperatures) is solely determined by the fire load. However, the fire severity depends on ventilation and the compartment characteristics in addition to the fire load. In a real fire, there would be a growth period before flashover (Holmes et al. 1980), but the wall would be expected to withstand the fire for a period of time corresponding to an equal total severity. With the wide variations recorded in time/temperature curves of compartment fires, this relationship may not be true.

Application of the standard test method also assumes that fire spreads from one compartment to another either by heat conduction through or by collapse of a compartment boundary, and that only one side of a compartment boundary can become exposed to fire. Harmathy (1976, 1977) considers the spread of fire to be mainly a convective-radiant process through doors left open, broken windows, and improper fire stopping, and that the true fire resistance of key structural components must be judged by the ability of these components to withstand fire exposure from two sides.

Currently, fire resistance design methods are deterministic. The building code requirements assume there is no variability in performance. Whereas evaluation of a wall is based on a single test result, in the field there is considerable variability in the performance of walls of similar construction. In order to achieve more rational safety requirements, reliability y-based design methods are being developed. The aim of improved analytical design methods is to characterize fire exposure realistically and generate results in terms of probability, so that fire resistance requirements may better reflect actual field performance. Efforts are also underway to improve the specifications in the ASTM E 119 test standard.

Doors

Doors are penetrations in walls that can be critical in preventing the spread of fires. Doors left open or doors with little fire resistance can easily defeat the purpose of a fire-rated wall. The fire test and code requirements for doors differ somewhat from those for walls.

The standard methods of fire tests of door assemblies are given in ASTM E 152 (ASTM 1981). In a furnace similar to a wall furnace, the door, frame, and portion of a wall are subjected to fire exposure defined by the ASTM E 119 time/temperature curve. After a specified time period, the door is subjected to a specified standard firehose stream. During the fire endurance test and the hose-stream test, the door must not develop openings anywhere through the assembly and must remain in place without separating excessively from the hinge or latch side of the frame. As required in ASTM E 152, temperature rise on the unexposed surface is recorded during the first 30 minutes of the test. Temperature rise and ignition of cotton waste are generally not a basis for failure. Warp criteria are specified in ASTM E 152. Temperature rise criteria of 250 °F (average) and 450 °F (at any spot) are required in some doors. It is assumed that no combustibles will be stacked against the door, hence temperature rise is not a limiting criterion.

Fire resistance requirements for doors are given in the building codes. In the National Fire Protection Association's standards, openings are classed as A, B, C, D, or E in accordance with the character and location of the wall in which they are situated (National Fire Protection Association 1983). These openings require doors with ratings of 20 minutes to 3 hours.

In the Basic Building Code (BOCA 1984), doors in fire separation walls of 1-hour construction must have a 3/4-hour rating. In the case of door assemblies from rooms opening onto a corridor required to be of 1-hour fire- resistance-rated construction, the requirement is for a 20-minute fire protection rating when tested without the hose stream. The 20-minute rating can be achieved with 1-3/4-inch-thick solid core wood doors or solid wood core doors (Degenkolb 1975). When selecting a fire-rated door, details about which type of door, mounting, hardware, frame, and closing mechanism are acceptable for any given location should be obtained from authorities having jurisdiction.

Listings of fire-rated doors, frames, and accessories are provided by UL (1985a) and other testing agencies. The fire-resistant performance of a door assembly depends upon the individual behavior of the door, frame and hardware, and their interaction. The components selected must be compatible.

Because of the number of variables involved, doors must be fire tested to determine their rating. Studies have shown what is usually required in a fire-rated door.

From testing 26 solid-core and particleboard-core wood doors, Galbreath (1975) obtained some minimum requirements for a door assembly with a 20-minute rating. Solid-core doors should be fabricated without gaps exceeding 1/16 inch. A wood frame should be of pine or denser wood and with a l/2-inch rebate to provide the door stop. When a wood door is installed in a wood frame, precautions are necessary to minimize flame penetration between door and frame. Intumescent strips applied to edge of door or frame seal the gap between door and frame during fire exposure. For a wood frame, the strike plate should be fastened with three 1-1/4-inch screws. A steel frame should be of 16-gage steel and should have four U-shaped anchors 18-gage thick on each jamb. A steel frame should be secured against warping. In a wood stud wall, a steel frame can be restrained by steel anchors and tight-fitting wood blocking. The latch should have a throw of at least 1/2 inch.

Eickner (1973) in reporting his tests of six solid core wood flush doors noted that the critical locations for early fire penetration were around the lock set, along the upper edge of the door and at the upper and lower unsupported corners. In two of the doors, 1/8- and 1/4-inch voids were intentionally fabricated into the cores. Voids of such limited size did not enhance failure.

Degenkolb (1975) considers the height of a latch to be critical to the door performance under fire conditions and that doors should be accepted with no greater length between the latch and the top of the door than was tested. Also, he recommends doors be accepted only for up to the height tested.

Briber (1966) discussed the construction, testing, and use of composite fire doors. He noted that the performance of a composite door depends upon the core, frame, and veneer face components of the door. The thickness, make up, and strength of the unexposed face veneer and the glueline between the face and the core affect the ability of face veneer to provide the necessary stability for the door to withstand the impact of the hose-stream test. If the rails and styles of the frame are treated wood, the treatment must penetrate throughout the cross section of the wood. For a steel frame, the members must be of the proper gauge and design to prevent warpage. The type of material and the manner in which the core is actually placed in the frame are important. The heat transmission and shrinkage properties of the core materials should be considered carefully. The use of a number of blocks with tongue-and-groove edges in the layup of the door, for example, can reduce the overall shrinkage of the core section. Hardware used in a door should not contain soft metal parts since such soft parts rapidly melt or disintegrate during a fire. Ordinary wood doors of the flush and paneled types have failed in 4-3/4 to 8-1/2 minutes by allowing passage of flames (UL 1938).

Existing ordinary doors and door frames may be modified to enhance their fire resistance considerably, but the improvements will probably not raise them to the level provided by the lowest rated fire door (National Institute of Building Sciences 1980, Shoub and Gross 1966).

The field performance of doors depends upon the use of the proper components in the door assembly and its installation. The fit of a door is more important than the dimensions of the rebated frame in determining the fire performance (Morris 1971). Actual performance in a fire depends on the door not being blocked open and the passageway on each side of the door being open. Because an open door provides no protection, self-closing doors are sometimes required. Wedges should not be used to hold open doors that are intended to provide fire protection. Hold-open devices are available, having automatic releases that respond to the presence of a fire.

A topic of dispute regarding the test standard, is the proper furnace chamber pressure for a door test. ASTM E 152 (ASTM 1981a) requires the pressure in the furnace chamber as nearly equal to the atmospheric pressure as possible. In some laboratories, this has meant that a slight negative pressure is used. In other laboratories, part or all of the furnace may have positive pressure. Positive pressure can greatly reduce the resistance time of some doors. In Europe, a positive pressure must be provided inside the furnace. When Britain began to require positive pressure, new doorsets had to be of much better construction and had to include some method of sealing the gap between the door and the frame (TRADA 1978). An intumescent strip or similar form of seal is generally used to resist the action of the positive pressure during fire.

Analysis Methods

The first eight of Harmathy’s ten rules (Harmathy 1965) are applicable to walls.

It is readily observed that the paneling plays a key role in fire endurance time. Increasing the thickness of gypsum wallboard increases fire endurance proportionately. As a result of this kind of observation, one can design load-bearing walls to attain given fire endurance levels. This is shown in table 5–2.

In the additive method (AC-NBC 1980, SBCC 1982), ratings are assigned to various elements of an assembly. The fire resistance rating of the total assembly is estimated by simply adding the assigned ratings of the elements. These elements include the membranes on the fire-exposed side, the framing members, and protective measures. The membrane on the nonfire-exposed side is required to remain in place and be a barrier to flame at least until collapse of the framing members occurs.

In the procedure, wood studs 16 inches on center are assigned a rating of 20 minutes. Times for protective membranes are listed in table 5-2. One protective measure for walls is the addition of mineral wool insulation which has an assigned time of 15 minutes. When fire exposure can be expected to occur only on one side of a wall, the membrane on the nonfire-exposed side consists of sheathing, paper, and exterior finish listed in table 5-3 or any membrane with fire resistance of at least 15 minutes (table 5-2). This procedure is limited to ratings of 1-1/2 hours or less (National Research Council of Canada 1965) and to 1 hour or less by the Standard Building Code (SBCC 1982).

While the structural fire resistance currently cannot be theoretically quantified, a general indication of the structural integrity can be obtained by evaluating the load-bearing capacity of a reduced cross section of the structural element.

Table 5-2 – Fire endurance time assigned to wallboard membranes (AC-NBC 1980)

Wallboard membrane	Fire endurance time
	min
Fiberboard, 1/2-inch	5
Douglas-fir plywood,	
phenolic bonded, 3/8 inch	5
1/2 inch	10
5/8 inch	15
Gypsum wallboard, 3/8 inch	10
1/2 inch	15
5/8 inch	30
Gypsum wallboard, type X, 1/2 inch	25
5/8 inch	40
Gypsum wallboard, 3/8 inch + 3/8 inch	25
1/2 inch + 3/8 inch	35
1/2 inch + 1/2 inch	40

Table 5-3 – Membrane on exterior face of wood stud walls[1]

Sheathing	Exterior finish
5/8-inch tongue and groove lumber[2]	Lumber siding
5/16-inch exterior grade plywood	Wood shingles and shakes
1/2-inch gypsum wallboard	1/4-inch plywood exterior grade
5/8-inch gypsum wallboard	1/4-inch hardboard Metal siding Stucco on metal lath Masonry veneer
None	3/8-inch exterior grade plywood

[1]Exterior membrane may be any combination of sheathing and exterior finish.
[2]Used in conjunction with sheathing paper.

The exposure to fire in the standard fire test occurs at the underside of the floor assembly. This is because it is assumed that a fire on top will take a longer time to penetrate the floor than one below. The fire endurance period is ended when the floor fails to sustain the applied load, when the transmission of hot gases or flames through the assembly is sufficient to ignite cotton waste, or when the transmission of heat through the specimen has raised the average temperature on its unexposed surface more than 250 °F above its initial temperature or an individual thermocouple indicates a 325 °F rise.

The floor test specimen is required to have an area equal to or greater than 180 square feet and neither dimension less than 12 feet. The applied load should be sufficient to generate the maximum allowable stresses. The floor may be tested with the floor edges restrained or unrestrained, against thermal expansion. Floors with restrained edges are capable of resisting the rotation at the edges due to thermal expansion.

Building codes generally do not have fire resistance requirements for one- and two-family dwellings. For wood-frame constructions with fire resistance requirements, the model building codes (BOCA 1984, ICBO 1985, SBCC 1982), generally require 1 hour of fire resistance. The codes also require the 1-hour resistance for floors between separate living units in multifamily residential construction.

In general, conventional unprotected joist floors (floors not having a ceiling membrane) are recognized to have a 10-minute fire endurance based upon a structural integrity criterion only. Hence, the unprotected joist floor has become the standard of comparison for new assembly designs in one- and two-family housing.

Performance Factors

Ceiling Membrane

Selected fire resistance ratings are listed in table 5-4. The observed failure times exceed the rating period in many cases; examples are given in table 5–5. The listing is limited to floors without any ceiling, or with a ceiling of gypsum wallboard or a wood-based product having a fire resistance rating of 1 hour or less. The references given in the table also have listings for floors with lath and plaster as the ceiling, fire resistances in excess of 1 hour, and resilient furring channels for attaching the ceiling membrane to the joists. Fire resistance ratings provide limited information. The ratings are generally only in terms of 5-, 15-, or 30-minute intervals. Usually no information is provided as to the actual time of failure, the number of assemblies tested, the type of failure (burn through or structural), or the critical factor in the failure.

While fire resistance ratings provide limited information, the ratings given in table 5–4 do give an indication of the relative performance of floors with different types of ceilings. The results for Nos. 1, 3, and 4 (table 5–4), for example, show how the treatment of the joints in the ceiling membrane affects the fire resistance rating. The results for Nos. 7, 18, and 19 and Nos. 15, 16, and 17 (table 5-4) show how thickness affects the performance of gypsum and plywood ceilings, respectively. The same result for Nos. 4 and 12 illustrates the problem with fire resistance ratings.

Some available times for structural failure of unprotected floor assemblies are listed in table 5-6. A footnote in The Protection Handbook (National Fire Protection Association 1981) states that NBS tests on two specimens of open-joist floors, each 4-1/2 by 9 feet, resulted in fire endurance times of 12 and 15 minutes. It should be noted that for tables 5-4, 5-5, and 5-6 the results may be affected by construction details that are not given in the tables.

The initial fire resistance is provided by the ceiling membrane. Common ceilings are gypsum board, plaster on gypsum, metal or wood lath, plywood and other wood products, and acoustical tile. The method of fastening the ceiling to the framing members and the treatment of the joints in the ceiling are significant factors in the fire resistance of the floor assembly. The longer, thinner nails, particularly those with cement coating, conduct less heat to char the wood surrounding them than do the common type of wire nails and provide greater depth of penetration (National Fire Protection Association 1981). Whether the joints in the gypsum board are exposed, covered with fiber tape embedded in compound, or covered with paper tape embedded in cementitious compound can affect the resistance of the ceiling.

Gypsum board can be used to provide an effective protective membrane. About 21 percent by weight of the gypsum is chemically combined water of crystallization. When the gypsum is heated, the water is released as steam until the slow process of calcination is completed. The temperature directly behind the plane of calcination is only slightly higher than that of boiling water (212 °F) and that is considerably below the temperature at which wood ignites (Gypsum Association 1984). Even after the gypsum is completely calcined, the residue is a thermal barrier. With regular gypsum board, shrinkage during the calcination process causes cracking and destruction of the membrane. Type X gypsum board has textile glass filaments and other ingredients that help to keep the gypsum core intact. Type X gypsum board, by definition, is a gypsum board that provides a l-hour fire resistance rating for 5/8-inch thickness, or a 3/4-hour fire resistance rating for 1/2-inch thickness when applied in a single layer and properly fastened to each face of load-bearing wood-framing members, when tested in accordance with ASTM E-119 (Gypsum Association 1984).

Other Significant Influences

The floor membrane contributes to the fire resistance by delaying flame passage and temperature rise on the unexposed surface after the ceiling has failed. The flooring also contributes to the load-bearing capacity of the floor joists. Tongue-and-groove type flooring is desirable because flames easily penetrate plain-edged flooring.

Fire resistance may be increased by the addition of insulation or reinforcement of the floor system membranes. But mineral fiber or glass fiber arbitrarily emplaced in a floor-ceiling assembly may reduce the fire resistance of the assembly (Gypsum Association 1984). (Increased temperatures within the assembly may result because the insulation restricts the passage of heat to the unexposed surface.)

Other factors contributing to the standard fire resistance of a floor assembly are the quality of materials and workmanship, moisture content of the components, and the exact test procedures. Factors in the test procedures are edge restraint, deviation from the standard fire exposure, internal furnace pressure, type of flames produced in furnace, and the amount of the applied load. For materials with significant thermal expansion, the edge restraint of a floor can significantly increase the fire endurance obtained in the standard test.

Table 5-4 – Fire resistance ratings for selected floors

No.	Floor	Ceiling	Rating time	Reference
1	2- x 10-in nominal wood joists, 16 in on center; 1-in nominal tongue-and-groove wood subfloor and finished floor or 5/8-in plywood finished floor with long edges tongue-and-groove and 1/2-in interior plywood with exterior glue sub-floor. A layer of commercial rosin-sized building paper between floor layers.	1/2-in-thick type X gypsum wallboard; paper tape embedded in cementitious compound over joints and exposed nail heads covered with compound.	1 hour	UL 1985b
2	See No. 1.	5/8-in-thick type X gypsum wallboard; fiber tape embedded in compound over joints and exposed nail heads covered with compound.	1 hour	UL 1985b
3	See No. 1.	1/2-in-thick type X gypsum wallboard; fiber tape embedded in compound over joints and exposed nail heads covered with compound.	45 minutes	UL 1985b
4	See No. 1.	1/2-in-thick type X gypsum wallboard; exposed joints or covered with fiber tape and joint finisher.	30 minutes	UL 1985b
5	Stressed skin prefabricated panel-min 2- x 6-in nominal stringers at 12 in on center with 5/8-in-thick plywood skins.[1]	1/2-in-thick fiber insulation board and 1/2-in-thick type X gypsum board with joints covered with paper tape embedded in cementitious compound.	1 hour; flame penetration at 75 minutes, 28 seconds	UL 1985b
6	Parallel chord joists with 2 x 4 wood chords and tubular steel webs: 5/8-in tongue-and-groove plywood underlayment and 5/8-in-thick plywood subfloor.	Two layers of 1/2-in-thick type X gypsum board. First layer nailed to joists, second layer secured to resilient furring strips. Paper tape embedded in cementitious compound over joints in second layer.	1 hour	UL 1985b
7	2- x 10-in nominal southern pine or Douglas fir (No. 1 Common or better) joists; 3/4-in-thick wood sheathing sub-floor, asbestos paper diaphragm and tongue-and-groove wood flooring.[2]	1/2-in-thick gypsum wallboard.	25 minutes	CHC 1942
8	See No. 7.[2]	Two layers of 3/8-in-thick gypsum wallboard.	30 minutes	CHC 1942, NBS 1946
9	2- x 10-in nominal southern pine No. 1 common joists (16 in on center), 1-in nominal thickness wood subflooring, a layer of rosin-sized building paper, and 1-in nominal thickness tongue-and-groove finish flooring.[2]	No ceiling.	10 minutes	NBS 1946
10	See No. 9.[2]	1/2-in-thick gypsum sheathing under 3/8-in-thick gypsum wallboard.	35 minutes	NBS 1946
11	See No. 9.[2]	3/8-in-thick gypsum linerboard under 1/2-in-thick wallboard.	40 minutes	NBS 1946
12	See No. 1.	3/8-in-thick type X gypsum wallboard; joints with or without fiber tape and joint finisher.	30 minutes	NBFU[3] 1964
13	See No. 14.	Composite 1/8-in-thick asbestos cement on 7/16-in-thick fiberboard.	30 minutes	AC-NBC 1980
14	Joists with thickness not less than 2 in, 16 in on center, 1/2-in-thick plywood or 11/16-in tongue-and-groove softwood subfloor and hardwood or softwood finish flooring on building paper or any other membrane that has a contribution to fire resistance of at least 15 minutes.	1/2-in-thick fiberboard.	15 minutes	AC-NBC 1980
15	See No. 14.	3/8-in Douglas-fir phenolic bonded plywood.	15 minutes	AC-NBC 1980
16	See No. 14.	1/2-in-thick Douglas-fir phenolic bonded plywood.	20 minutes	AC-NBC 1980
17	See No. 14.	5/8-in-thick Douglas-fir phenolic bonded plywood.	25 minutes	AC-NBC 1980
18	See No. 14.	3/8-in-thick gypsum wallboard.	20 minutes	AC-NBC 1980
19	See No. 14.	5/8-in-thick gypsum board.	40 minutes	AC-NBC 1980
20	See No. 14.	Double 1/2-in-thick gypsum wallboard.	50 minutes	AC-NBC 1980

[1]Loaded with a 47.5-lb/ft^2 life load or total dead and live load of 54 lb/ft^2, 13.5-ft span.
[2]Initial maximum fiber stress is limited to 1,000 psi.
[3]National Board of Fire Underwriters

Table 5-5 – Structural failure times for selected floors

No.	Floor	Ceiling	Miscellaneous notes	Failure time	Reference
1	2- x 10-in nominal wood joists, 16 in on center, 1- x 4-in tongue-and-groove finish flooring building paper, and 1- x 6-in tongue-and-groove subfloor.	Two layers of 1/2-in gypsum wall board with a 1-in hexagonal mesh 20-gauge wire fabric between the layers.	Load calculated to stress joists initially to 1,000 lb/ft^2.	1-hour rating. Structural failure at 69 minutes.	NBS 1950
2	Wood floor trusses of 2- x 4-in, 24 in on center 3/4-in-thick tongue-and-groove plywood underlayment and finish flooring of 1/16-in-thick vinyl asbestos tile.	Single layer of 5/8-in-thick type X gypsum board. Joints taped and covered with joint compound. Joints not over truss bottom chord were back-blocked with gypsum wallboard.		45-minute rating. Structural failure at 50 minutes.	Beineke 1977
3	See No. 2	Single layer of 5/8-in-thick type X gypsum board connected to resilient channels. Joints taped and covered with joint compound but not backblocked.		Structural failure at 58 minutes.	Beineke 1977
4	2- x 10-in joints, 16 in on center, 3/4-in plywood, felt and 25/32-in tongue-and-groove hardwood flooring.	5/8-in type X gypsum wallboard, joints exposed.	Two tests.	Structural failure at 45 minutes in both tests.	Bletzacker et al. 1969
5	See No. 4	Suspended 5/8-in lay-in acoustical panels.		Structural failure at 32 minutes.	Bletzacker et al. 1969
6	See No. 4	Suspended 5/8-in lay-in type X gypsum panels.	Two tests.	Structural failure at 54 and 57 minutes.	Bletzacker et al. 1969
7	Same as No. 4 except plywood and joists are fire-retardant treated.	Suspended 5/8-in lay-in type X gypsum panels.	Two tests.	Structural failure at 54 and 51 minutes.	Bletzacker et al. 1969
8	2- x 10-in nominal construction grade Douglas-fir joists, 16 in on center, 1/2-in-thick grade A-C plywood subfloor and 1/2-in- thick grade C-D plywood underlayment.	No ceiling.	Loading was 63.7 lb/ft^2; span was 13-1/2 ft.	Structural failure at 11 minutes, 38 seconds. Flame penetration at 13 minutes, 30 seconds.	Son 1973
9	2- x 8-in nominal construction grade Douglas-fir joists, 16 in on center, (a) 1/2-in-thick plywood with 1/16-in-wide square edge joints and nominal 2- x 3-in blocking of joints, or (b) 5/8-in-thick plywood with tongue-and-groove on all four edges.	No ceiling.	Loading was 21 lb/ft^2 or 40 percent of working stress of joists; span was 13-1/2 ft.	Structural failure at 13 minutes. Flame penetration at (a) 11 minutes, and (b) 11 minutes, 50 seconds. Temperature failure at (a) 9 minutes and (b) 10 minutes.	Son 1973

Table 5-6 – Predicted and actual times-to-failure (t_f) for unprotected floor fire endurance tests having applied load to develop allowance design stress of 1,450 psi in joists (NFPA 1974)

Sample	Nominal joist size	B[1]	C[2]	Predicted t_f	Observed t_f Assembly	Observed t_f Joist[3]
	in	*lb/in²*	*in/min*		--- *min*	- -
No. 2 Douglas-fir "S-dry" w/vinyl tile, 19/32-in plywood	2 x 8	7,500	0.0245	9.4	10.2	5.0
No. 2 Douglas-fir "S-dry" w/nylon carpet, 19/32-in plywood	2 x 8	7,500	0.0245	9.4	12.86	11.5
No. 2 MG southern pine "S-dry" w/vinyl tile, 23/32-in plywood	2 x 10	9,300	0.03	10.3	13.34	9.0
No. 2 MG southern pine "S-dry" w/nylon carpet, 23/32-in plywood	2 x 10	9,300	0.03	10.3	12.06	12.06

[1]Douglas-fir upper exclusion limit rupture strength, from Hoyle and Maloney 1976; southern pine upper exclusion limit rupture strength, from Doyle and Markwardt 1966.
[2]Assumed charring rate.
[3]Failure time for first joists to fail, not assembly failure time.

There are also factors that affect the actual performance of a floor in the field. Penetrations and openings for such things as hot air heat ducts, plumbing pipes, and light fixtures can permit early fire penetration. Gypsum board of less than required thicknesses, inadequate nailing of gypsum, and an underlayer of two-layer ceiling made of incomplete scraps can also lead to premature failure in the field.

Analysis Methods

Joist Floors

Traditionally, the structural design of wood floors has been based on treating the joist as a simple beam. Since composite action and load sharing contribute to the structural performance of the floor system, the design value plus a factor of safety is still less than the actual load-bearing capacity. Recent developments have led to improvements in the analysis methods for floor and wall systems (McCutcheon 1977, Pettersson 1980, Polensek 1976, Vanderbilt et al. 1974). The ability to predict the actual load-bearing capacity of a floor should allow an analysis of the reduction in cross-sectional area required during the fire exposure for the floor to fail to support the design load.

A similar approach has been proposed for the analysis of fire-exposed unprotected joist floor assemblies (Woeste and Schaffer 1981). The failure during fire exposure is assumed to be caused by charring of the three exposed sides of a joist; this loss of section, coupled with loss of strength resulting from elevated temperature, causes rupture of the joist. Burn-through and elevated temperatures of the unexposed surface are not considered in this analysis where the failure criteria relate directly to the floor-subfloor design, which can be analyzed separately. Load sharing and composite action are not accounted for directly in the analysis; however, they should eventually be included in an experimental verification of the model.

A typical floor-joist section is shown in figure 5-7; the shaded region shows an idealized charred area. Schaffer (1977) reports bottom corners became rounded while charring; furthermore, the radius of the corners can be approximated by the depth of the char. The moment of inertia is not used to account for this rounding because it complicates the computations in the analysis, and it is clear that the error involved by assuming straight boundaries is of minor concern.

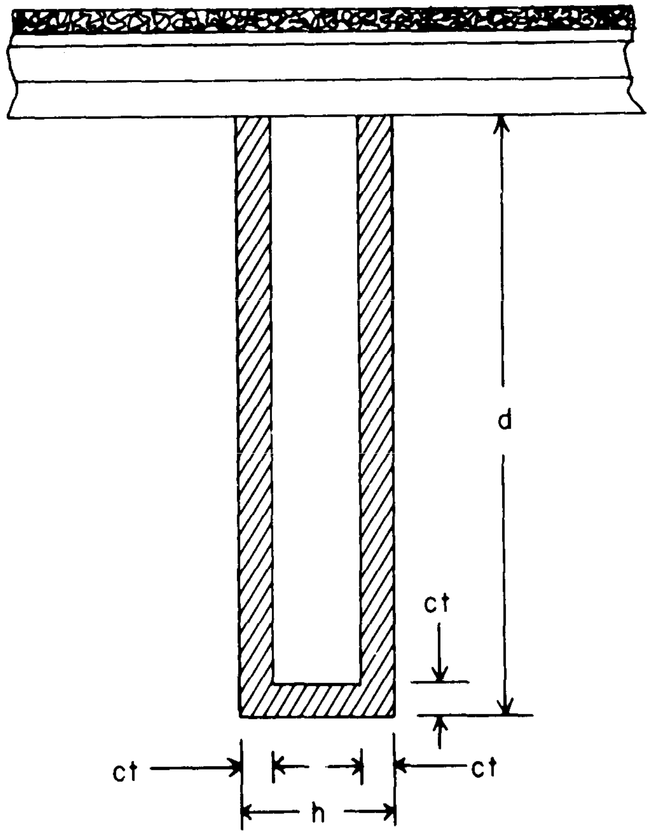


Figure 5-7 – An idealized exposed floor joist subjected to fire on three sides. Subfloor protects top side of joist. Although it is known bottom corners are rounded, straight boundaries are used as an approximation. (ML88 0012)

By use of the flexure formula, an equation can be written to quantify failure in a fire situation as

$$\frac{MY(t_f,C)}{I(t_f,C)} = \alpha B \qquad (5\text{-}1)$$

where

$\underline{M}$ = applied moment caused by dead plus live load (in-lb)

$\underline{t_f}$ = time to failure (min)

$\underline{Y(t_f,C)}$ = distance to extreme fiber being a function of time to failure and char rate, C (in)

$\underline{I(t_f,C)}$ = moment of inertia about the midheight axis of the remaining uncharred section (in^4)

$\underline{\alpha}$ = an exposed joist performance factor that relates normal-temperature strength to high-temperature strength

$\underline{B}$ = joist modulus of rupture at room temperature (lb/in^2).

In order to accommodate heat accumulation within the residual charring cross section, it is necessary to modify the temperature strength reduction factor, α:

$$\alpha = \left[1 + \left(\frac{b+2d}{bd}\right)\gamma t\right]^{-1} \qquad (5\text{-}2)$$

The (b + 2d/bd) term is viewed as a geometric factor to account for heat flowing into the cross section, bd, through the heated perimeter, b + 2d. The term, γ, was estimated to be 0.17 (in/min).

By referring to figure 5-7 and incorporating the above term, it can be seen that equation (5-1) can be rewritten as

$$\frac{M(d - Ct_f)/2}{(b - 2Ct_f)(d - Ct_f)^3/12} = \frac{B}{1 + \left(\frac{b+2d}{bd}\right)\gamma t_f} \qquad (5\text{-}3)$$

where

$\underline{b}$ = initial joist width (in)

$\underline{d}$ = initial joist depth (in)

and the remaining variables are defined as in equation (5-1). Equation (5-3) generates a cubic equation in $\underline{t_f}$ which can be solved rather easily by omitting the cubic term.

Results predicted by equation (5-3) were compared with results of four floor fire endurance tests obtained by the NFPA (1974). The actual times to failure to carry load versus those predicted are given in table 5–6; the predicted times are consistently and conservatively less than the times to failure of the whole floor assembly. The time to failure of a No. 2, 2 x 10 Douglas-fir joist floor assembly varies with level of load application (fig. 5-8). Note in the figure that time to failure, at load level consistent with live loads common in residences of 20 percent of full design load, is expected to be about 22 minutes and, at full design load (maximum allowable bending stress), is only about 10 minutes. Additional ASTM E 119 tests have been done to verify the model (White et al. 1984).

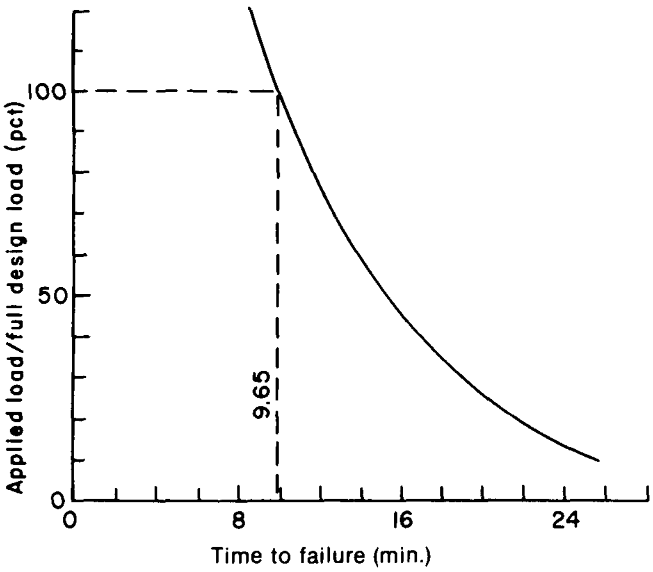


Figure 5-8 – Time to failure of floor assembly under varying loads. (ML88 0013)

Model for Exposed Floor Truss

The lower chord of a floor truss is subjected to both bending and tension, and the well-known interaction equation is used for design purposes.

$$I = \frac{f_b}{F_b} + \frac{f_t}{F_t} \qquad (5\text{-}4)$$

where I denotes the interaction factor, f_b and f_t are applied stresses, and F_b and F_t are allottable design stresses in bending and tension, respectively.

As in previous reliability work at the Forest Products Laboratory (Suddarth et al. 1978), this interaction equation can be modified to indicate failure (with some reservations discussed in the report). However, in a case of fire exposure, one parameter needs to be estimated; by this means, some slight inaccuracy in the neighborhood of the combined stresses associated with a floor truss will be corrected. The failure equation for fire exposure reads

$$\alpha = \frac{f_b}{B} + \frac{f_t}{T} = \frac{1}{1 + g(b,d,t_f,\alpha)} \qquad (5\text{-}5)$$

where the right side of the equation has a form similar to that for the exposed floor joist. Function $\underline{\alpha}$ accounts for the thermal degrade of the section, and $\underline{B}$ is the modulus of rupture from which F_b was derived; and $\underline{T}$, the ultimate tensile strength property from which the design value $\underline{F_t}$ was derived.

Expansion of the interaction formula is done in a manner similar to the model for a joist (Schaffer and Woeste 1981).

The developed model and the parameters may be used to estimate the structural failure of a given floor-truss assembly. This was done for the truss shown in figure 5-9; the lumber of the floor truss was No. 1 Dense KD southern pine. The truss was analyzed with a Purdue Plane Structures Analyzer; and, as was normal, the center panel of the lower chord was most highly stressed.

Solution of the failure-model equation results in an estimate of 11.2 minutes time to failure. The actual failure time in a fire endurance test was estimated at 10.2 minutes (Factory Mutual Research 1977). This test continued to be conducted under reduced load until 14.6 minutes, when fire exposure was terminated without collapse occurring. The predicted time to failure falls within the 10- to 15-minute range. This result is most promising for future use of the model.

It is interesting to examine how time to failure is altered for the same truss by reducing the applied load. The failure-model equation predicts time to failure as a function of applied load. For reduction in load to 50 percent of full design, 5 minutes are added to the predicted time under full design load. If there were no load on the floor assembly except the dead weight (4.9 lb/ft^2) of the assembly itself, a failure time of 21.1 minutes could result. Hence, failure times greater than this are theoretically impossible for this truss design.

Protected Floors

No theoretical models have been advanced for floors with protective membrane ceilings, but the fire resistance of a floor can be viewed as the sum of the resistance of the ceiling and the resistance of the framing members. As discussed for walls, the additive method can be used to calculate the rating of a protected floor assembly. A wood floor with nominal 2-inch-thick joists spaced 16 inches on center is assigned a rating of 10 minutes. The times for the ceiling material are listed in table 5-2. Minimum requirements for the flooring are listed in table 5-7.

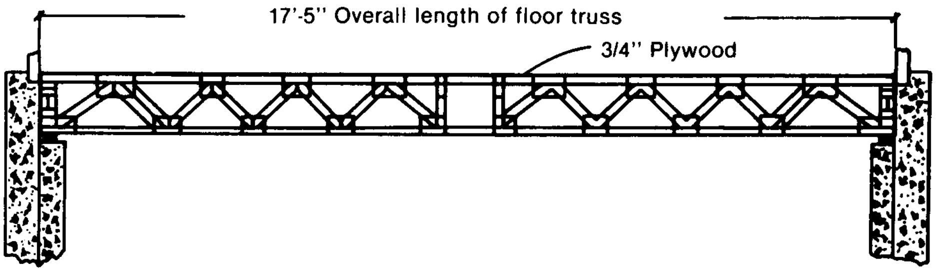


Figure 5-9 – Floor-truss design subjected to test conditions of ASTM E-119. Upper chord was loaded with tanks simulating a uniform load of 55.1 lb/ft² that resulted in a combined live and dead load of 60 lb/ft². (M148 527)

Table 5-7– Flooring or roofing over wood joist framing (SBCC 1982)

Assembly	Subfloor or roof deck	Finish flooring or roofing
Floor	1/2-in plywood or 11/16-in tongue-and-groove softwood	Hardwood or softwood flooring on building paper. Resilient flooring, parquet floor felted-synthetic-fiber floor coverings, carpeting, or ceramic tile on 3/8-in-thick panel-type underlay ceramic tile on 1-1/4-in mortar bed.
Roof	1/2-in plywood or 11/16-in tongue-and-groove softwood	Finish roofing material with or without insulation

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Chapter 6
Fire Growth

Introduction

Materials that make up the exposed interior surfaces of the walls, ceilings, and floors are the interior finish of the structure. The interior finish is usually the first part of a building to be exposed to a fire. A desirable interior finish minimizes the spread of flames over its surface and the thermal penetration through its thickness. Its performance both as deterrent to flame spread and as thermal barrier may affect the growth of a fire. In addition, the rate of heat release from the finish has a major influence on fire growth.

In this chapter the properties of materials involved in fire growth by flame spread, thermal penetration, and heat release are considered separately, and fire performance factors are suggested for assessing and regulating the revelant properties. No established methods exist for analyzing these aspects of fire growth.

One of the most important problems associated with unwanted fires is the smoke they produce. The term “smoke” is frequently used in an all-inclusive sense to mean the mixture of combustion products and air that is present near the fire site. In this context, smoke contains solid particles, droplets of liquid, and true gases. Smoke presents potential hazards because it interacts with light to obscure vision and because it contains noxious or toxic substances. Smoke is discussed briefly in a later section. We also recognize the importance of combustion toxicology; because of the complexity and uncertainly involved, however, we omit discussion and, in the following paragraphs, refer the reader to the literature for further information.

Interest in combustion toxicity has originated fairly recently because studies of fires have revealed that in most instances the primary cause of fire deaths is inhalation of heated, toxic, and oxygen-deficient fire gases. Presently, several States are considering legislation requiring that toxicity data regarding building materials be made available to the consumer.

The toxicity of the products of thermal decomposition of wood and cellulosic substances is not well understood. Part of the reason is that a wide variety of compounds are found in wood smoke. Their individual concentration depends on such factors as the fire exposure, the oxygen and moisture present, the species of wood, the treatments or finishes that may have been applied, and other considerations (Alarie 1985; Jahnsen 1961; Porter 1963). Increased concern about these toxic products prompted the development of several different types of test methods to rank the relative toxicity of materials. The methods vary in several factors, including type of exposure, how the gas is transported, and criteria for measuring lethality, and they are under considerable debate. Kaplan et al. (1982) provide a critical review of the various test methods and discuss the above factors.

Flame Spread

Background

Flame spread is one of the most regulated and most tested of the fire performance properties of a material. Flame spread has been the primary property by which authorities have attempted to eliminate hazardous materials and improve human safety in buildings. Combustible interior finish is often cited as one of the factors contributing to the spread of fire and the loss of life. Relative to other factors, the degree to which the interior finish is a hazard to life is debatable. The contents of a building are often considered more significant both for fire growth and toxicity. Nevertheless, a number of flame-spread tests are used to regulate materials.

Flame-spread requirements in building codes are usually based on results from the 25-foot tunnel furnace (ASTM 1981). For classified materials the flame-spread values range from zero to 200. Values of 0 to 25 are class A or I, 26 to 75 are class B or II, 76 to 200 are class C or HI. The lower the index value, the lower the surface flammability. Although unclassified materials may be permitted in one- and two-family dwellings, class C (that of most woods) is the maximum flame spread permitted in other buildings. Class A and B materials may be required, depending upon the floor area of the building and the type of occupancy. Vertical exits, corridors, and assembly rooms are areas that are likely to require class A or B interior finish. Educational and institutional buildings, theaters, night clubs, and assembly buildings are occupancies with greater restrictions on interior finish. In the building codes, interior finish generally does not include doors, windows, cabinets, flooring, floor covering, paints or wall-paper. Interior trim (baseboards, moulding, door and window trim) is usually only restricted to a 200 or less flame-spread rating.

Performance Factors

Lumber, 1 inch thick, generally has a flame-spread rating of 100 to 150 in the 25-foot tunnel (table 6-1). Wood-based products generally have flame-spread rating of 75-200 (table 6-2).

Table 6-1 – ASTM E 84 flame-spread ratings for different species of nominal l-inch-thick lumber

Species	Flame spread[1]	Reference[2]
Yellow birch	105–110	UL 1971
Pacific coast yellow-cedar	78	CWC 1977
Western redcedar	73	CWC 1977
Western redcedar	70	HPMA 1974
Cottonwood	115	UL 1971
Cypress	145–150	UL 1971
Douglas-fir	70–100	UL 1971
Redgum	140–155	UL 1971
West coast hemlock	60–75	UL 1971
Maple (flooring)	104	CWC 1977
Oak	100	UL 1971
Eastern white pine	85	CWC 1977
Idaho white pine	72	HPMA 1974
Lodgepole pine	93	CWC 1977
Northern white pine[3]	120–215	UL 1971
Ponderosa pine[4]	105–230	UL 1971
Red pine	142	CWC 1977
Southern yellow pine[3]	130–195	UL 1971
Western white pine[3]	75	UL 1971
Poplar	170–185	UL 1971
Redwood[5]	70	UL 1971, CRA 1972
Northern spruce	65	UL 1971
Western spruce	100	UL 1971
White spruce	65	CWC 1977
Walnut	130–140	UL 1971

[1]Values range from 0 to 200. The lower the index value, the lower the surface flammability.
[2]CWC = Canadian Wood Council; HPMA = Hardwood Plywood Manufacturers Association; CRA = California Redwood Association; UL = Underwriters' Laboratories.
[3]Because of wide variations among species of the pine family and local connotations of their popular names, exact identification of the types of pine tested was not possible. The effects of differing climatic and soil conditions on the burning characteristics of given species have not been determined (UL 1971).
[4]In 18 tests of ponderosa pine, three had values over 200, and the average of all tests was 154 (UL 1971).
[5]Redwood lumber with 3/8–in nominal thickness had a flame spread of 95 (California Redwood Association 1972).

Table 6-2 – ASTM E 84 flame-spread ratings for some common materials

Materials	Thickness	Density	Flame spread[1]	Reference
	in	*lb/ft³*		
Wood	0.5	25–45	75–200	HUD 1973
Plywood	0.25	25–40	110–200	HUD 1973
Douglas-fir plywood	0.25	33	120	HUD 1973
+ latex paint	+0.004		100	HUD 1973
+ natural gum varnish	+0.004		160–175	HUD 1973
+ synthetic varnish	+0.025		160–500	HUD 1973
+ shellac 3 coats	+0.006		300–800	HUD 1973
+ polystyrene tile	+0.075		590	HUD 1973
Gypsum board	0.375	51	10–20	HUD 1973
Fiberboard	0.50	16	200–350	HUD 1973
Hardboard	0.25	60	130–200	HUD 1973
Particleboard, phenolic or urea binder	0.375–0.75		145–200	HUD 1973
Fire-retardant treated softwood plywood	–	–	<25	APA 1972
Fire-retardant coated softwood plywood	–	–	10–25	APA 1972
Plywood, fire-retardant core treated only	0.25	–	40–80	HUD 1973
Fire-retardant treated lumber	–	–	15–50	APA 1972

[1]Values range from 0 to 200. The lower the index value, the lower the surface flammability.

Fire-retardant treatment is used to produce wood products with class A or B ratings (Holmes 1976). Treated products with a special designation "FR-S" from UL (1985b) have a flame-spread classification of not over 25 and no evidence of significant progressive combustion in an extended 30-minute ASTM EM 84 test. Flame-spread ratings for proprietary products are listed by UL (1985 b).

Flame spread is affected by many parameters. Physical and geometrical parameters include orientation of surface, direction of propagation, thickness of specimen, specimen size, surface roughness, presence of sharp edges or crevices, initial fuel temperature, environmental pressures, flow velocity of environment, external radiant flux, and humidity (National Materials Advisory Board 1979). Chemical parameters that affect flame spread include the composition of the solid and the composition of the atmosphere (National Materials Advisory Board 1979). As a result the desired correlation between laboratory test results and behavior in real fires is often not obtained. Flame-spread tests are not a true indicator of a property that can be measured with consistency and accuracy. Clark (1981) discusses some of the factors affecting fire propagation and why different test procedures give different results.

Although the 25-foot tunnel test method appears to be a good measure of fire hazard for many materials and fire situations, no test method should be assumed to be accurate for all materials and fire situations. The ASTM E 84 flame-spread test was originally developed for rating wood-based products, and regulations based on ratings from this test have proven to be adequate in actual fire situations involving wood interior finish. However, it has been shown that the ASTM E 84 method does not predict the fire hazard of foam plastics as they are used in buildings. The real fire hazard of some of these foam plastic materials has been shown in the corner/wall tests.

Research into the relationship between flame-spread results and behavior in a real fire has been active in recent years. Although current test methods are good tools in eliminating hazardous materials, better understanding of flame spread should result in more rational classification of materials.

Thermal Barrier Characteristics

Background

The interior finish provides a thermal barrier between its substrate and a fire. The substrate being protected can be the structural members of the assembly or combustible materials such as foam plastic insulation. The amount of protection is usually expressed as the finish rating or the protective membrane performance, which is measured in minutes from the time the assembly is subjected to the fire exposure specified in ASTM E 119 (ASTM 1983a) to the time the surface of the element being protected reaches an average temperature rise of 250 °F or maximum temperature rise of 325 °F.

While finish ratings have been recorded for fire-protective finishes over wood framing (CHC 1942, Ingberg and Mitchell 1941, UL 1985b), finish ratings have become part of the building codes with the need to provide a thermal barrier over foam plastic insulation. Building codes require the interior of a building to be separated from foam plastics by a thermal barrier having a 15-minute or greater finish rating. In addition to providing thermal protection, the thermal barrier must remain in place for the rated period. Generally 1/2-inch-thick regular gypsum wallboard is accepted as a 15-minute thermal barrier.

Performance Factors

Finish ratings for different finishes over wood framing are listed in two National Bureau of Standards (NBS) publications (CHC 1942, Ingberg and Mitchell 1941) (table 6-3). Finish ratings for proprietary noncombustible products over wood framing are given in the Fire Resistance Directory of Underwriters' Laboratories, Inc. (UL 1985b).

The use of wood-based paneling as thermal barriers over foam plastics has been investigated by the Forest Products Laboratory (White 1981, 1982). Small-scale specimens (20 by 20 in) of plywood, particleboard, solid wood, fire-retardant-treated plywood, and hardboard were tested in a vertical exposure furnace in which the fire exposure followed the ASTM E 119 time/temperature curve. Increasing density, moisture content, and thickness of the wood-based panels were found significantly to increase the times for the critical temperature rise on the surface of the foam plastic substrates. The type of substrate can have an effect on the performance of the thermal barrier (White 1981, 1982). In tests of 5/8-inch-thick plywood and 1/2-inch-thick gypsum wallboard over calcium silicate board, the mean times to achieve the 250 °F average or 325 °F maximum temperature rise at the panel-substrate interface were not significantly different (White 1982). Plywood made with phenolic resin provides more fire resistance than that made with other glues (FPL 1961).

Corner tests on assemblies of protected polystyrene foam showed that the addition to the insulation of any covering material having a flame spread of less than 150, as measured by the 25-foot tunnel test, was beneficial in reducing the rate of early fire spread (D'Souza et al. 1981). Based on compartment corner tests, it was concluded that class I flame spread

Table 6-3 – Fire-protective finishes over wood framing

Facing	Limit of protection	Reference
	min	
1/2-in fiberboard, 16 lb/ft^3	3	Ingberg and Mitchell 1941
1/2-in fiberboard, 26 lb/ft^3	8	Ingberg and Mitchell 1941
1/2-in fiberboard, 26 lb/ft^3, flameproofed	12-1/2	Ingberg and Mitchell 1941
3/8-in gypsum wallboard	10	Ingberg and Mitchell 1941
1/2-in gypsum wallboard	15	Ingberg and Mitchell 1941
1/2-in type X gypsum wallboard	20	HUD 1973
5/8-in gypsum wallboard	20	HUD 1973
5/8-in type X gypsum wallboard	30	HUD 1973
Two layers of 3/8-in gypsum wallboard	20	HUD 1973
Two layers of 1/2-in gypsum wallboard	30	HUD 1973

classification (rating of 25 or less) polyurethane spray foam applied behind an adequate thermal barrier such as 1/2-inch gypsum wallboard presents no greater property loss or heat stress hazards than when fiberglass or no insulation are used (Condit and Cianciolo 1977).

From room corner test results and small-scale furnace test results, Lie (1975) concluded that the time of failure determined by the furnace test is a conservative estimate of the time that is available to evacuate the fire area before the foam insulation starts to contribute significantly to fire growth. In the furnace test, the average furnace temperature closely followed the ASTM E 119 time/temperature curve. The proper use of various tests in evaluating thermal barriers has been disputed. Stahl (1978) considers ASTM E 119 a valid test method for evaluating life-safety characteristics of construction materials and assemblies, while the approved tests such as the Factory Mutual Corner/Wall Test and the ICBO Enclosed Room Fire Test are not. The Society of the Plastics Industry (Anon. 1979) considers that the Factory Mutual Corner/Wall Test and the ICBO Enclosed Room Fire Test are valid for evaluating foam plastics product performance.

Background

The total heat of combustion of wood varies from about 8,000 to about 12,000 Btu per pound of original wood, depending on species, resin content, moisture, and other factors. The contribution to fire growth from this total depends on the circumstances of the fire exposure and the completeness of combustion.

In recent years, it has become recognized that heat-release rate (HRR) is a more important criterion than total heat available. For example, the National Bureau of Standards “potential heat” method (Loftus et al. 1962) deals with the total available heat of combustion of a substance. It gives about the same value to untreated wood as it gives to wood that has been treated with fire retardant. This particular test method has not been widely used because experience shows that treated and untreated wood differ dramatically in fire behavior. As fire phenomena become better understood, information on HRR will be required for input into mathematical models of fires.

Performance Factors

Currently, there is no provision for HRR in the building codes. Hence, no design procedure using the concept has yet evolved.

The HHR measuring apparatus of ASTM E 906 was developed by Smith of Ohio State University and is sometimes known as the Ohio State University calorimeter; it is shown schematically in figure 6-1. This calorimeter is likely to have an impact on light-frame construction because it has been approved by ASTM (1983b) for use in research and development. Smith has also given some consideration to possible applications of release-rate data (Smith and Satija 1983). HRR measurements in the Ohio State University apparatus are made using data on the temperature increase of air and gases passing through and around the combustion chamber containing the test specimen. Typical release rates are shown in figure 6-2 (Smith and Satija 1981) and table 6-4. Figure 6–2 shows the HRR curves generated by radiant exposure levels of 1.5 and 2.0 watts per square centimeter. In addition, the figure shows the difference in results caused by varying the position of the pilot flame in the apparatus. (“Remote pilot” in figure 6-2 means the pilot flame did not impinge on the specimen surface.) Table 6-4 illustrates

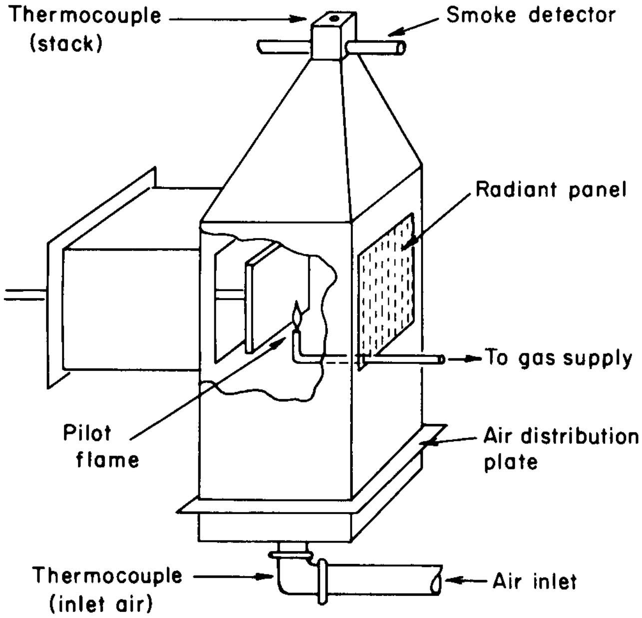

Figure 6-1 – Ohio State University heat-release rate calorimeter (ASTM 1983b). (ML88 0014)

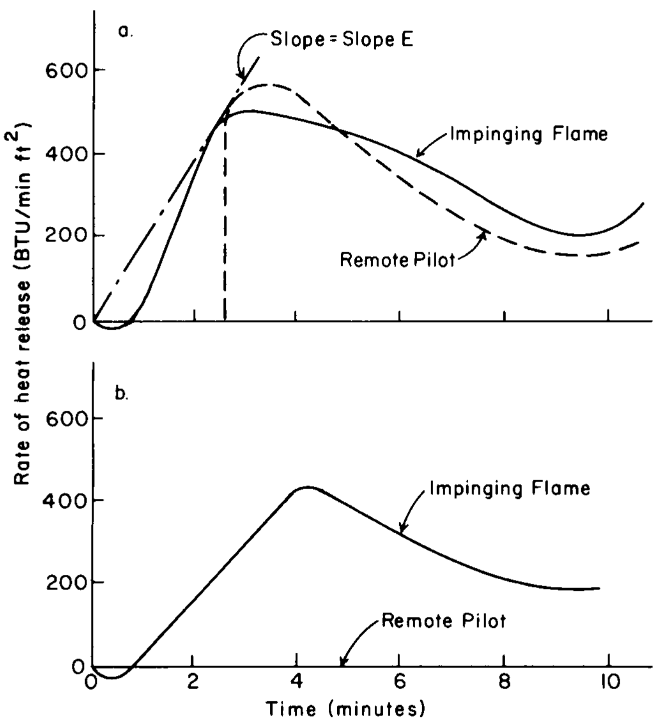

Figure 6-2 – Typical heat-release-rate curves using the Ohio State University calorimeter (a) at 2.0 W/cm² and (b) at 1.5 W/cm² (Smith and Satija 1981). (ML88 0015)

how release-rate determinations for particleboard are affected by varying specimen mounting orientations.

At present, this area of fire research is changing rapidly as a result of the emergence of a technique known as the "oxygen-consumption" method for making HRR measurements. The method is based on the experimental observation that, for a wide variety of organic substances, heats of combustion *per unit of oxygen consumed* are approximately constant, as shown in table 6-5 (Parker 1977, 1984, Huggett 1980). Current developments revolve around the technical aspects of experimental conditions for oxygen measurements (Sensening 1977). Oxygen consumption can then be directly coupled to heat release. A comparative study of methods has shown the oxygen consumption method to be the most advantageous for testing assemblies (Brenden and Chamberlain 1986).

Fire retardant treatments are very effective in reducing or delaying rates of heat release from fire-exposed wood products (Brenden and Chamberlain 1986). Fire-retardant chemicals tend to alter the pathways of thermal decomposition along lines which result in lower heats of combustion for volatile pyrolysis products.

Table 6-4 – Heat release (HR) from particleboard exposed at 2.0 w/cm² (Smith and Satija 1981)

Orientation	Maximum rate of HR	Total HR		
		3 min	5 min	10 min
	Btu/min·ft²	------	*Btu/ft²*	------
Vertical	630	690	2,600	2,950
Horizontal	605	290	1,310	3,350

Table 6-5 – Heat produced per volume of oxygen consumed for some common polymeric materials (Parker 1977)

Materials	Heat of combustion				Oxygen requirement at 25 °C		Heat produced per volume of oxygen consumed at 25 °C			
	Gross		Net				Gross		Net	
	MJ/kg	*Btu/lb*	*MJ/kg*	*Btu/lb*	m^3/kg	ft^3/lb	MJ/m^3	Btu/ft^3	MJ/m^3	Btu/ft^3
Polyethylene	46.6	20,050	43.4	18,670	2.63	41.9	17.8	479	16.5	446
Polypropylene	46.5	20,030	43.3	18,650	2.63	41.9	17.7	478	16.5	445
Polystyrene	41.5	17,850	39.7	17,110	2.36	37.6	17.6	474	16.9	455
Polyvinyl chloride	17.9	7,720	16.9	7,260	1.08	17.2	16.6	449	15.7	422
Polymethyl methacrylate	26.7	11,470	25.2	10,830	1.47	23.5	18.1	488	17.1	461
Phenol-formaldehyde (1:1)	27.9	12,000	26.7	11,480	1.86	29.7	15.0	404	14.3	386
Urea-formaldehyde (1:2)	17.8	7,680	16.8	7,220	1.02	16.3	17.5	471	16.4	443
Melamine-formaldehyde (1:3)	19.3	8,310	18.4	7,950	1.14	18.1	17.0	459	16.3	439
Polyurethane, ester based	23.7	10,180	22.4	9,650	1.32	21.1	17.9	482	17.0	457
Unsaturated polyesters	29.8	12,810	28.4	12,220	1.58	25.2	18.8	508	18.0	484
Butadiene/styrene (25.5 pct) coplymer (GRS rubber)	44.2	19,010	41.9	18,020	2.46	39.3	18.0	484	17.0	459
Butadiene/acrylonitrite (37 pct) copolymer	39.9	17,180	–	–	2.21	35.3	18.1	487	–	–
Natural rubber	45.3	19,490	–	–	2.53	40.3	18.0	484	–	–
Cellulose	16.6	7,160	15.2	6,560	.91	14.5	18.3	494	16.8	452
Carbon	32.8	14,100	32.8	14,100	2.05	32.7	16.0	431	16.0	431
Hydrogen	143.0	61,550	120.6	51,900	6.14	98.0	23.3	623	19.6	529
Methane	55.8	24,000	50.2	21,590	3.07	49.0	18.2	490	16.4	441

Smoke

Background

Generally, two approaches are used to deal with the smoke problem: first, limit smoke production; and second, control the smoke that has been produced. In light-frame construction, emphasis is almost always placed on reducing the smoke yield of materials and assemblies through the use of test methods and building codes. The control of potential smoke flows is most often a factor in the design and construction of large or tall buildings where combustion products may have serious effects in areas remote from the actual site of fire.

Performance Factors

Currently, several laboratory-scale test methods are used to provide comparative smoke yield information on materials and assemblies. Each method has entirely different exposure conditions, none being generally correlated to full-scale fire conditions or to experience. Typical smoke data from these tests is given in tables 6-6 to 6-8.

A considerable amount of work has been done on the problem of estimating smoke flow rates from fire-involved compartments (Fothergill 1978, Heselden and Baldwin 1978, Wakamatsu 1976). Most of this work relates to the smoke that affects large structures, such as hotels and office buildings, rather than the smaller light-frame structures. However, the general concepts used in developing flow models for multicompartment dwellings begin with consideration of a single compartment analagous to a compartment of light-frame construction.

Some of the predictions constructed from models using the combined single-compartment methodology have been checked by Fothergill (1978). He used sulfur hexafluoride (SF_6) tracer gas to stimulate smoke movements and concentrations. Based on these studies, the flow models will be improved and modified. Fothergill has plans to incorporate the improved calculation procedures into a design manual for use by mechanical engineers (Martinez and Cherry 1980).

Table 6-6 – Smoke-developed index – E 84 tunnel test (UL 1985a)

Material	Smoke-developed index
Acoustical tile, mineral type	0 to 10
Asbestos cement board	0
Red oak	100
Red oak (fire retardant treated)	25 to 45
Soft maple (fire retardant treated)	10
Ash (fire retardant treated)	5
Gypsum wallboard	0
Gypsum wallboard (with vinyl facing)	50

Table 6-7 – Smoke determinations,[1] each based on 3 test runs on 10 wood-based panel products[2] irradiated at 2.5 watts per square centimeter

Material	Observed D_m Mean	Observed D_m Range	t_m	t_{16}	SOI	MS
			min	*min*	*min*$^{-2}$	*min*$^{-1}$
	NONFLAMING COMBUSTION					
Rigid insulation board						
(plank – coated)	158	133–172	14.0	2.0	24	39
(plank – coating removed)	506	491–518	10.0	1.2	432	121
(regular-density sheathing, coated)	381	374–390	11.3	1.1	171	59
(regular-density sheathing, impregnated)	482	478–488	10.0	1.1	424	116
(nailbase sheathing)	451	446–460	12.7	1.1	277	82
Medium-density hardboard	86	483–491	13.7	3.2	134	102
High-density hardboard						
(underlayment)	528	505–557	12.0	3.6	147	124
(tempered quality)	437	422–461	17.3	3.8	56	70
(standard quality)	420	416–422	15.3	4.2	73	99
Laminated paperboard	169	137–186	38.7	2.0	8	18
Homogeneous paperboard						
(from wastepaper)	359	356–364	8.3	1.3	267	114
	FLAMING COMBUSTION					
Rigid insulation board						
(plank – coated)	36	34–40	17.7	6.6	0	5
(plank – coating removed)	229	194–261	14.7	5.9	15	44
(regular-density sheathing, coated)	168	120–201	14.7	0.1	854	54
(regular-density sheathing, impregnated)	189	132–293	16.3	4.2	9	24
(nailbase sheathing)	91	75–114	13.0	4.0	3	15
Medium-density hardboard	169	106–205	19.0	4.2	7	28
High-density hardboard						
(underlayment)	74	59–85	14.0	8.4	2	20
(tempered quality)	66	65–68	18.7	8.4	1	18
(standard quality)	75	36–126	17.3	9.3	1	16
Laminated paperboard	60	43–82	23.7	10.9	0	7
Homogeneous paperboard						
(from wastepaper)	68	57–85	11.0	4.2	2	14

[1] D_m, maximum specific optical density; t_m, time at which maximum specific optical density occurs; t_{16}, time to reach a critical specific optical density of 16; *SOI*, smoke-obscuration index; and *MS*, maximum rate of smoke accumulation during a 2-minute period.
[2] These panel products were selected to cover the range of commercially available types; end uses of the products were not considered.

Table 6-8 – Smoke determinations,[1] each based on three test runs on 12 wood species irradiated at 2.5 watts per square centimeter

Material	Observed D_m Mean	Observed D_m Range	t_m	t_{16}	SOI	MS
			min	*min*	*min*$^{-2}$	*min*$^{-1}$
		NONFLAMING COMBUSTION				
Birch	419	382-447	23.0	4.2	39	58
Douglas-fir	438	432-446	27.0	3.0	44	46
Larch, western	323	297-350	24.0	3.8	20	32
Lauan, red	374	363-385	15.7	2.5	70	59
Mahogany	320	315-329	19.7	3.5	30	43
Maple, sugar	448	441-456	25.3	4.7	38	57
Oak, red	372	352-390	23.7	3.8	29	40
Oak, white	409	398-427	25.0	4.0	32	45
Pine, southern	431	395-451	24.3	3.0	58	58
Redcedar, eastern	372	366-382	16.3	2.9	53	51
Redwood	390	377-415	21.0	3.2	38	40
Spruce, Sitka	263	246-280	21.3	4.2	13	28
		FLAMING COMBUSTION				
Birch	79	43-122	26.0	7.0	1	11
Douglas-fir	110	85-146	25.3	6.8	1	10
Larch, western	111	80-145	23.3	7.4	1	12
Lauan, red	96	71-112	17.7	5.4	2	13
Mahogony	109	105-114	20.0	5.2	2	11
Maple, sugar	118	64-159	25.3	10.4	3	21
Oak, red	118	105-133	23.7	11.2	1	22
Oak, white	56	49-62	25.3	11.8	0	8
Pine, southern	156	114-201	27.3	7.8	3	24
Redcedar, eastern	76	68-83	20.7	4.6	1	9
Redwood	85	41-119	21.7	4.7	1	8
Spruce, Sitka	130	115-158	24.0	7.7	2	15

[1] D_m, maximum specific optical density; t_m, time at which maximum specific optical density occurs; t_{16}, time to reach a critical specific optical density of 16; *SOI*, smoke-obscuration index; and *MS*, maximum rate of smoke accumulation during a 2-minute period.

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Part III
Environmental Concerns

A large proportion of light-frame buildings are used for human occupancy, and within them certain environmental conditions must be maintained. Temperature must be controlled within the comfort range, and an efficient thermal envelope is vital to accomplish this economically. Passive solar design provides additional thermal efficiency. The efforts toward energy efficiency have a major effect on moisture accumulation in the building and on moisture movement within floors and walls. Noise control, although affected by thermal efficiency measures, is a separate environmental concern and is increasingly important as more multifamily living units are constructed. Part III deals in turn with each of these environmental concerns.

Part III
Environmental Concerns

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Chapter 7
Thermal Analysis of the Building Envelope

Introduction

Light-frame structures are complex systems with interactions between the subsystems for structural and environmental control. Traditionally, general construction has been referred to as a "building" and heating equipment as a "mechanical" system, separated from the other by construction and design practices. As a result, thermal performance analysis has followed the completion of basic design. At this point erroneous decisions may have become irreversible. The interactions are particularly evident in passive solar buildings, where windows become as much a part of the heating system as of the building envelope, and masonry may be used more for its capacity for heat storage or as thermal ballast than for its load-bearing properties.

For reliable results, architectural and thermal design should be carefully coordinated and continuously checked against applicable code requirements or self-imposed performance targets. The first step in any thermal design analysis should be verification of compliance with basic code requirements (fig. 7-l).

Some performance targets, such as insulation requirements, are identified by specific values. Others, such as air infiltration control, are only implied in general terms. Even such generalized goals, however, can be important design considerations. Design for a construction quality exceeding the applicable standards requires identification of all performance targets, some of which may have to be defined by the designer.

This chapter summarizes code requirements and other related factors to be considered in the design of light-frame wood structures for energy efficiency. Objectives include not only management of heat losses, solar gains, and indoor air quality, but also control of investment in construction materials and in the production of energy. The goal should be thermally, structurally, and economically optimized light-frame wood construction that meets occupancy requirements and performance expectations.

Background

Typical energy codes specify how to meet the required standards. Such specifications are easily enforced but provide little leeway or incentive to improve thermal performance beyond acceptable practice. In contrast, standards of performance intended to control energy usage rather than construction, are not yet well developed. Trends in this direction are illustrated by the U.S. Department of Energy Building Energy Performance Standards (DOE 1979a) although they were never implemented. Other standards, such as the U.S. Department of Agriculture Farmers Home Administration (1980) passive solar design requirements, seek integration of the criteria based on specification and on performance. Until full-scale implementation of such standards, however, conscientious designers must define their own performance targets and budget levels.

ASHRAE Standard 90 (ASHRAE 1980, par. 5.3.2.2) calls for indoor "comfort conditions consistent with the criteria of ANSI/ASHRAE Standard 55-74" with a recommended temperature of 72 °F. The comfort range identified by ANSI/ASHRAE 55-74 (ASHRAE 1977) extends from 73 to 77 °F. For efficient use of passive

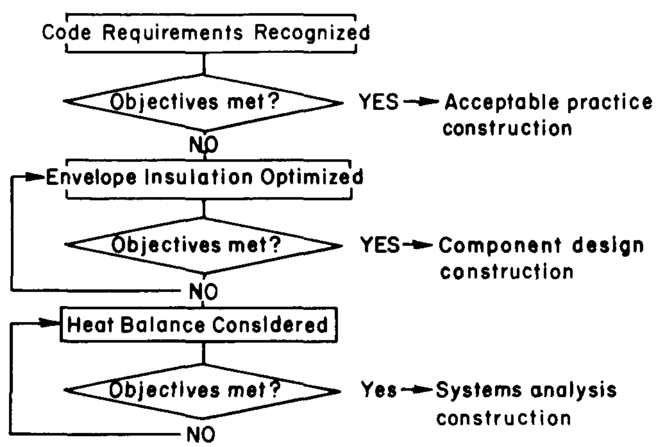

Figure 7-1 – Typical design process. (ML88 0016) solar heat gains, room temperatures must be allowed to swing beyond that range. The Building Energy Performance Standards passive solar design analysis was based on room temperatures between 65 and 75 °F. The range permitted by Farmers Home Administration passive solar design requirements (U.S. Department of Agriculture 1980) is 68 to 80 °F. Disagreements between these standards suggest that the perception of thermal comfort varies with a number of related conditions.

One such related condition is the rate of temperature change. Studies show that temperature ramps of 1 °F/hr are almost imperceptible, and departures of 3.6 °F (2 °C) from a neutral temperature over a number of hours are acceptable to most people (Berglund and Gonzalez 1978). With heavier clothing, sensitivity to temperature variations is reduced, and with winter room temperatures sliding from 80 to 68 °F, the acceptable ramp slope can be estimated at 3 °F per hour. For an up-ramp of 2 °F/hr, the 12 °F temperature rise permitted by Farmers Home Administration design standards should be controlled to take place over a 6-hour period.

At any given air temperature the sensation of comfort is also influenced by the coincident relative humidity level. ANSI/ASHRAE 55-74 identifies the comfort range as a zone between 20 and 60 percent relative humidity (RH) levels. At temperatures above the comfort level the effects of humidity become more pronounced as the body heat control mechanism becomes more dependent on evaporation of skin moisture. At temperatures below the comfort level, effects of humidity on the sensation of warmth (or effective temperature) become minimal. At 68 °F the effective temperature varies only by one-third of a degree Fahrenheit for every 10 percent change in RH. Thus, during the heating season, mechanical humidification is a valid strategy for prevention of excessive skin and membrane dryness but not for control of the sensation of warmth.

Regulatory documents control only indoor design temperatures. Targets for control of solar design temperature ramps and indoor RH levels must be established by the designer. Suggested limits are 2 °F/hr for upramps and 3 °F/hr for downramps. Psychometric relationships (ASHRAE 1977) show that, at a constant humidity ratio, 35 percent RH level at 72 °F translates into 40 percent RH at a temperature reset to 68 °F. For general heating season comfort, indoor conditions in the range of 35 to 40 percent RH are likely to be found satisfactory. This may be easily maintained in reasonably well weather-stripped houses by moisture gain from normal living activities without mechanical humidification.

Initial performance targets are established by code requirements and then expanded by other considerations such as human comfort and building envelope durability. Recent standardization efforts have led to close agreement between different codes and standards, but certain disagreements still exist. This discussion summarizes provisions that are of particular importance to the light-frame designer, and emphasizes differences between related requirements.

Energy codes and standards, or the applicable sections of building codes, can be broadly classified as being oriented either to specification or to performance. Specification codes restrict innovative design but are easily enforced, while performance codes allow wider design latitude but are more difficult to enforce. Energy codes generally provide for both options, and the National Conference of States on Building Codes and Standards (1977) Model Code for Energy Conservation in New Building Construction was structured to allow demonstration of code compliance by any one of three approaches:

1. Acceptable practice, requiring no other analysis than proof of compliance with the stated specification limits.

2. Component design, requiring steady-state analysis but permitting trade-offs between components within the limits of stated overall performance targets.

3. Systems analysis, requiring dynamic performance analysis and allowing credits for renewable energy gains against estimates of steady-state heat losses.

The above Model Code established the concepts of ASHRAE Standard 90A-1980 (ASHRAE 1980), with the component design option corresponding to ASHRAE Chapters 4-9 and the systems analysis option to ASHRAE Chapters 10 and 11. The Model Code leaves the definition of specific performance targets up to the local building code authority, whereas ASHRAE Standard 90 defines such targets in terms of maximum allowable overall thermal transmittance (U_o) for different components at different climatic conditions identified in terms of heating degree-days (HDD) at 65 °F base (HDD_{65}) (NFPA 1978).

The Model Code specifically oriented to residential construction is the One- and Two-Family Dwelling Code sponsored by the Council of American Building Officials and serving as the actual model for most of the corresponding State codes. Prior to the evolution of State and local energy codes for residential buildings, the most widely used thermal design reference for such tasks was the HUD Minimum Property Standards (1980). Because of their established standing, HUD Minimum Property Standards are used as the basic reference to thermal design targets in the following discussion. However, because they are being continuously upgraded for agreement with other related codes and standards, the information is presented only for illustration, not as specific and current design data.

Acceptable Practice Option

Basic code requirements are expressed in terms of limitations on thermal transmittance (U) for different walls, commonly translated for construction specifications into the reciprocal values of thermal resistance (R = 1/U). Load levels are identified by (HDD) ratings, with 65 °F base (HDD_{65}) as the most common reference point. Requirements for acceptable practice according to the current HUD Minimum Property Standards (1980) are shown in tables 7-1 and 7-2. Table 7-3 shows tradeoffs between wall and ceiling insulation that are permitted without more detailed investigation or calculations.

Below the 7,000 HDD_{65} level, requirements are more stringent for electrical than for fossil fuel heating. In localities above 5,000 HDD_{65} rating, houses with heat pumps must be insulated as for electric resistance heating, but below that level they may be built as required for fossil fuel heating. These variations reflect resource utilization considerations.

Maximum glass area permitted by HUD Minimum Property Standards is limited to 15 percent of the gross area of all exterior walls enclosing heated spaces, except "when demonstrated that the winter daily solar heat gain exceeds the 24-hour heat loss, and the glass is properly screened from summer solar heat gain." The September 1980 revision of HUD Minimum Property Standards, however, does not identify the winter conditions under which a positive window heat gain and loss balance is to be demonstrated.

The ommission from energy codes of more specific references to passive solar design conditions is a decided drawback. A possible future direction is illustrated by revisions of the Farmers Home Administration requirements that include specific passive solar design standards (U.S. Department of Agriculture 1980). Farmers Home Administration requirements can be summarized under five heads.

1. Total glass area is limited to 15 percent of the gross exterior wall area enclosing heated spaces. Nonsouth-facing and shaded south-facing glass area is limited to 6 percent of the gross exterior wall area.

Table 7-1 – Basic thermal performance requirements from HUD Minimum Property Standards (1980). Maximum thermal transmittance values for ceiling, wall, and floor sections for electric resistance heat (ER) and heat pump or fossil fuel heat (FF)

Heating degree-days (65 °F base)	Ceilings		Walls		Floors		Windows		glass doors		Storm doors	
	ER	FF	ER	FF	ER	FF	ER	FF	ER	FF	ER	FF
0–1,000	0.05	0.05	0.08	0.08	–	–	1.13	1.13	1.13	1.13	No	No
1,001–2,500	0.04	0.05	0.07	0.08	–	–	0.69	1.13	0.69	1.13	No	No
2,501–3,500	0.03	0.04	0.05	0.08	0.07	–	0.69	1.13	0.69	1.13	No	No
3,501–4,500	0.03	0.03	0.05	0.07	0.05	0.07	0.69	0.69	0.69	0.69	No	No
4,501–6,000	0.03	0.03	0.05	0.07	0.05	0.07	0.47	0.69	0.69	0.69	Yes	No
6,001–7,000	0.026	0.03	0.05	0.07	0.05	0.07	0.47	0.69	0.69	0.69	Yes	No
7,001 +	0.026	0.026	0.05	0.05	0.05	0.05	0.47	0.47	0.69	0.69	Yes	Yes

Table 7-2 – Requirements for heated basement or crawl space walls below grade, from HUD Minimum Property Standards (1980)

Heating degree-days (65 °F base)	Maximum U values
2,500 or less	No requirement
2,501 to 4,500	0.17
4,501 or more	0.10

Table 7-3 – Combinations of adjusted thermal transmittance values for walls and ceilings for electric resistance heat (ER) and heat pump or fossil fuel heat (FF) recognized by HUD Minimum Property Standards (1980)

Heating degree-days (65 °F)	ER		FF	
	Ceiling	Wall	Ceiling	Wall
0–1,000	0.04	0.14	0.04	0.14
	0.03	0.15	0.03	0.15
	0.026	0.16	0.026	0.16
1,001–1,500	—	—	0.04	0.13
	0.03	0.13	0.03	0.14
	0.026	0.14	0.026	0.16
1,501–2,500	—	—	0.04	0.12
	0.03	0.11	0.03	0.13
	0.026	0.12	0.026	0.14
2,501–3,000	—	—	0.03	0.12
	0.026	0.07	0.026	0.13

2. South-facing glazed areas that exceed 6 percent of the gross exterior wall area must be protected with movable insulation (R-4 minimum value), and all south-facing glass requires summer shading.

3. The building is to be oriented so that the longest wall faces within 30 degrees of true south.

4. Glazing areas must be designed for maximum solar gains without over-heating interior spaces. The maximum allowable interior space temperature is 80 °F under the following conditions: (a) thermostat setpoint 68 °F, (b) 5 °F temperature rise from internal heat gains, (c) clear day insolation on January 21, (d) average January daily temperature profile, and (e) infiltration rate of 0.6 air changes per hour.

5. Passive solar design performance must be analyzed on the basis of the inherent thermal mass of wood frame construction. Passive features exceeding the specific limitation of this standard, such as sunspaces and trombe walls, may be used provided they offer equivalent passive solar benefits.

The Farmers Home Administration passive solar design requirements attempt to optimize the building system, and its passive solar design procedure actually constitutes simplified systems analysis for predicting room temperature fluctuations under solar heat-gain impact. It is mentioned in the context of the acceptable practice option only because it is not specifically identified as a systems analysis procedure. On the other hand, it is used in discussing design examples as the basic reference to systems analysis in residential light-frame wood construction.

Component Design Option

Component design allows departures from strict compliance with acceptable practice requirements. The departure from the standard for any one component of the building envelope can be balanced by changes in other components. HUD Minimum Property Standards (1980) component design requirements are shown in figures 7-2 and 7-3. The overall thermal transmittance (U_o) of construction components (e.g. wall with window systems) remains governed by the basic acceptable practice requirements (fig. 7-2 represents averaged wall with window values with glass area at 15 pct of opaque surface area). The range of possible variations in component specifications, however, allows considerable design latitude, as illustrated by a National Forest Products Association analysis of different wood wall systems (NFPA 1978).

HUD Minimum Property Standards component design performance requirements are somewhat more stringent than those of ASHRAE 90A-1980 (ASHRAE 1980). Many state codes are patterned after the ASHRAE standard, and include further adjustments considered appropriate for local conditions. Review of specific State code requirements falls outside the scope of this discussion. The nature and extent of such departures from models is discussed in review of State energy code activities (National Conference of States on Building Codes and Standards 1980).

Typical heating load calculations are based on code-defined indoor and outdoor “design” temperature differentials. ASHRAE Standard 90 provisions for

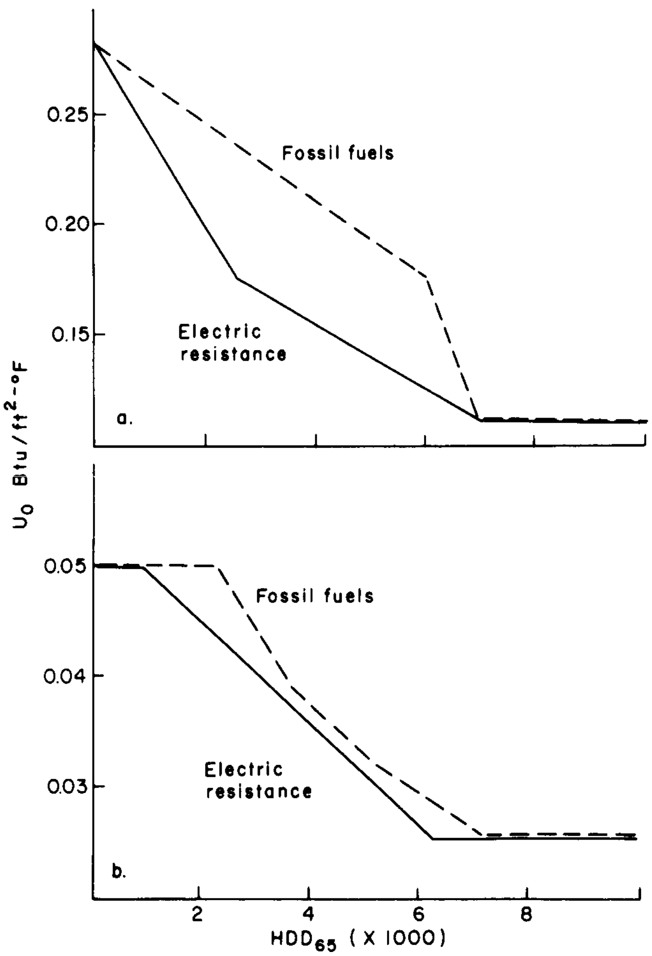

Figure 7-2 – HUD Minimum Property Standards (1980) U_o value for (a) exterior walls and (b) roofs/ceilings. (ML88 0017)

component design generally do not require consideration of design temperatures, except for special procedures such as calculation of crawl space plenum insulation requirements (ASHRAE 1980, par. 4.3.2.5). Design temperatures defined by state and local codes may differ from ASHRAE Handbook (1976) listings for the same locality. Indoor design temperatures generally are assumed to be fixed at the thermostat setpoint. With growing emphasis on passive solar design, future codes may not only recognize acceptable room temperature fluctuations (as in Farmers Home Administration standards), but also devote more attention to the control of such fluctuations.

Systems Analysis Option

Systems analysis is the basic tool for demonstrating compliance with codes based on performance. The acceptable practice and component design procedures are based on one-directional heat flow concepts or "steady-state" conditions. The impact of solar energy on building surfaces can reverse the direction of heat flow, but the elementary analytical procedures allow only indirect recognition of solar gain effects. Such effects may be approximated by adjustments in outdoor reference temperatures (sol-air temperature), adjustments to thermal transmittance values (dynamic or effective U), and similar streamlined procedures. The recognized design method for full consideration of dynamic thermal performance effects is known as systems analysis. This option is commonly identified with computer simulation procedures. For simplified tasks (such as performance analysis on a "design day," as stipulated by Farmers Home Administration passive solar design standards), however, the process can also be reduced to hand calculations. Consistent with the objectives of this chapter, discussion of systems analysis procedures is limited to the level applicable to house design tasks.

ASHRAE Standard 90 requirements for systems analysis and recognition of alternative energy sources are covered by chapters 10 and 11 (ASHRAE 1980). Evaluation of proposed design is based on comparison with a standard design meeting component design requirements. Predicted energy consumption is quantified in terms of annual usage per unit floor area (such as Btu/ft^2/yr) (ASHRAE 1980, par. 10.2). Calculations are based on a full-year (8,760-hr) operation of the building and its service systems, except that for detached single-family residences and light commercial buildings with indoor temperatures controlled from a single point, calculations may be based on simplified energy analyses (ASHRAE 1980, par. 10.4.1). The actual acceptable evaluation method remains to be defined by the applicable code authority.

To recognize solar heat as a nondepletable energy source, passive solar windows must have movable insulation during the heating season and shading devices when cooling is needed. The required insulation, when closed, must reduce window heat losses to the level allowed by ASHRAE 90A-1980 (1980, ch. 4, par. 11.1). Estimates of heat so derived must be identified separately from the overall energy use (par. 11.2). The procedure also separates the estimates of solar gain and of internal heat gains.

The anticipated differences in design accuracy between full-year simulations and more streamlined analytical procedures appear so small that they favor use of the simpler methods, which may find wider applications in the light-frame construction field. Such procedures include the single-calculation ASHRAE degree-day and the multiple-calculation ASHRAE Bin methods (ASHRAE 1976), recognized by ASHRAE Standard 90 (1980, par. 10.4.1, Exception). Comparisons of energy calculations by different methods show that accuracy may be influenced more by the designer's use of data and application of a design procedure than by the sophistication or simplicity of that procedure. In reference to the degree-day method as a less desirable option, it is noted in the DOE Building Energy Performance Standards that "variations of ±20 percent from actual energy consumption may result from using the degree-day method because of its inherent assumptions and the wide variances in occupant living habits" (U.S. Department of Energy 1979b, par. 2.1.1). Consideration of living habits, however, was specifically excluded from DOE Building Energy Performance Standards analyses. Therefore, the actual difference in accuracy between performance simulations and degree-day calculations may not be critical.

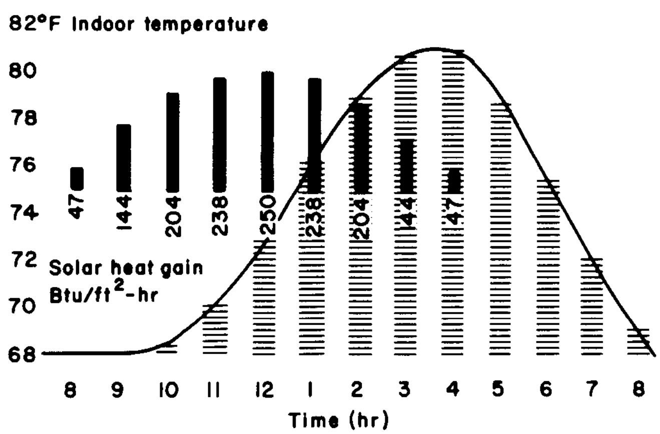

Figure 7-3 – Temperature calculations by thermal time constant method. (ML88 0018)

Energy efficiency features include added insulation as well as improved environmental control systems. New developments in mechanical equipment may lead to substantial improvement of operating efficiencies. Possibilities include new designs for burners, heat pumps, and control systems for more effective thermal zoning. Emerging energy management strategies also include radiant coheating for comfort control at reduced thermostat settings.

The relative effectiveness of improvements in different subsystems remains an important consideration in all cases. The merits of a careful investigation can be illustrated by simple comparisons. Heat losses through the opaque wall surfaces of light-frame wood houses equal approximately 10 percent of the total heating energy input (heating value of fuel). Doubling the value of wall insulation can lead to savings in the range of 5 percent of energy input. By comparison, typical residential furnace inefficiencies can be estimated at 25 percent. Current performance standards require minimum steady-state combustion efficiencies in the range of 74 to 75 percent (ASHRAE 1980, California Energy Commission 1980). Without adequate maintenance actual furnace efficiencies may fall by 5 percentage points, while after tune-up they may rise by a comparable margin (Harrje et al. 1980). Corresponding increases in furnace efficiency can also be attained by such modifications as an added flue damper. Thus, comparable 5 percent savings in fuel usage may be more easily gained by equipment modifications than by added insulation in the opaque wall surfaces.

Another important item in thermal performance is air leakage. The techniques for controlling infiltration have traditionally been to plug holes and cracks, weatherstrip, and generally improve the quality of construction. In recent years, new materials for tightening house construction are being employed: foam plastic sealants that can be squirted like shaving cream into cracks where they expand slightly to ensure a tight seal; plastic sheeting instead of paper; foil insulation backing as a vapor retarder; devices and techniques such as sill plate mastic; outside combustion air intakes for furnaces, water heaters, and fireplaces; duct taping; and exhaust vents with tightly closing dampers.

The single common factor among low-energy houses is the quality of work; that is, the attention to detail during construction. Not only must strict procedures be followed at each step during construction, but the proper sequence of steps must be maintained. For example, there is no reason for the carpenters to seal every crack during rough framing if the electricians and plumbers will later cut holes to accommodate their fixtures.

Another factor commonly overlooked is the energy invested in producing construction materials, which usually increases with their weight. Fully energy-conscious design should also key this investment to the anticipated energy savings or returns. The most efficient design solution should require the least quantity of materials, energy, and effort in construction and in operation of buildings.

Application of design targets for the three different compliance options (acceptable practice, component design, and systems analysis) can be illustrated by design examples simplified to suit the format of this discussion. Reference will be a three-bedroom ranch house measuring 24 by 48 feet, with 8-foot ceiling height, which leads to floor, ceiling, and outside wall areas of 1,152 ft^2. The house is assumed to be located at Madison, WI, with a HDD_{65} rating of 7,206 (ASHRAE 1976).

Acceptable Practice Construction

Design objective: Verification of code compliance.

Design conditions: Limitations on thermal transmittance at given degree-day rating.

For compliance with HUD Minimum Property Standards (1980), the allowable transmittance values can be determined from tables 7-1 and 7-2. The actual floor insulation requirement varies with basement conditions (ibid. par. 607-3.6). For this analysis the floor is assumed to be built over unheated crawl space. The maximum window area without further analysis of winter heat gain and loss balance is limited to 15 percent of exterior wall area (ibid. par. 607-3.3(5)). The required insulation value can be estimated as the reciprocal of the allowable transmittance value ($R = 1/U$), rounded off to the closest commercial insulation rating with the customary allowances for the thermal resistance of uninsulated wall and ceiling cavities (ASHRAE 1977). The number of required glazing layers for conventional materials is similarly estimated on the basis of the required R-value for windows. Then:

Ceiling/roof U = 0.026; required cavity insulation value would be R-38

Walls = 0.05; required cavity insulation value would be R-19

Floor = 0.05; required cavity insulation value would be R-19

Windows = 0.47; required number of glazing layers = 3.

With construction specifications tailored to these requirements, the thermal analysis objectives of proving equivalency between the proposed construction and code requirements have been attained.

Component Design Construction

Design objective: Optimization of building envelope construction.

Design conditions: Steady-state performance analysis for compliance with overall thermal transmittance limitations defined by acceptable practice requirements.

The allowable overall thermal transmittance (U_o) for the house as an entity can be estimated on the basis of its dimensions and limitations set by HUD Minimum Property Standards (figs. 7-2, 7-3). For consistency with the systems analysis example, the air infiltration rate is assumed at 0.6 air changes per hour under average heating season indoor-outdoor temperature differentials. Such assumption is consistent with requirements of the HUD Minimum Property Standards (1980, par. 615-2.5) for ventilation and outside combustion air intake, and with DOE Building Energy Performance Standards (1979b, V-B-3.0, note 8). Component design requires elementary heating load calculations. Basic equations for the building envelope transmission and air infiltration load components are:

$$h_t = U_o A_o \qquad (7\text{-}1)$$

where

h_t = building envelope transmission loss rate, Btu/hr/°F
U_o = overall thermal transmittance of gross surface area, Btu/hr/ft^2/°F
A_o = gross surface area of the envelope or component, ft^2

$$h_s = kV_a \qquad (7\text{-}2)$$

where

h_s = sensible heat loss due to air infiltration, Btu/hr/°F
k = product of the specific heat and density of air, 0.018 Btu/°F/ft^3
V_a = volume of infiltrated outdoor air, ft^3/hr

The HUD Minimum Property Standard requirements for overall thermal transmittance (U_o) of exterior walls are based on a 15 percent glass-to-opaque wall ratio, and at HDD_{65} are limited to 0.11 Btu/ft^2/hr/°F. The nominal heat loss rate at a 1 °F indoor-outdoor temperature differential then can be estimated as:

Ceiling/roof loss = $U_{oc} \times A_c = 0.026 \times 1{,}152 =$ 30.0 Btu/hr/°F (or 9.6 pct of total)
Floor loss = $U_{of} \times A_f = 0.05 \times 1{,}152 =$ 57.6 Btu/hr/°F (or 18.3 pct of total)
Walls/windows loss = $U_{ow} \times A_w = 0.11 \times 1{,}152 =$ 126.7 Btu/hr/°F (or 40.4 pct of total)
Infiltration loss = $0.018 \times 1{,}152 \times 8 \times 0.6 =$ 99.5 Btu/hr/°F (or 31.7 pct of total)
Total heat loss rate = $q_{hl} = h_t + h_s = 313.8$ or 314 Btu/hr/°F (or 100 pct).

For changes in the glass-to-opaque wall area ratio or any other adjustments, the estimate can be broken down further in proportion to the respective areas and transmittances as:

$$q_{hlgl} = q_{hlw/w} \times \frac{AU_{gl}}{AU_{gl} + AU_{op}}$$

$$= 126.7 \frac{173 \times 0.47}{173 \times 0.47 + 979 \times 0.05}$$

$$= 79.1 \text{ Btu/hr/°F}$$

$$Q_{hlop} = q_{hlw/w} - Q_{hlgl} = 126.7 - 79.1$$
$$= 47.6 \text{ Btu/hr/°F}$$

where

q_{hlgl} = heat loss rate for glass areas, Btu/hr/°F
q_{hlop} = heat loss rate for opaque wall surface areas, Btu/hr/°F
$q_{hlw/w}$ = total exterior wall heat loss rate, Btu/hr/°F
AU_{gl} = area × thermal transmittance of a glass, Btu/hr/°F
AU_{op} = area × thermal transmittance of opaque wall surfaces, Btu/hr/°F

Above breakdown reveals that glass losses constitute 25.2 percent of the total building heat loss, and opaque wall surface losses 15.2 percent of total. The magnitude of glass losses suggests that even quadruple glazing may be more cost effective than additional wall insulation. Other designers may favor further reduction in glass area, but favorably positioned windows generally gain more heat than they lose. More detailed investigation of solar heating benefits under the component design option, however, is not possible. Such investigation requires heat balance calculations or systems analysis.

Systems Analysis Construction

Design objective: Improved thermal performance through efficient utilization of energies gained from nondepletable sources.

Design conditions: Dynamic performance analysis for compliance with component design requirements or predetermined energy budgets.

Present options for systems analysis in light-frame construction include computer programs that allow dynamic performance simulation for both commercial and residential design. Residential construction in California is regulated for energy use on the basis of the CALPAS computer program or certified commercial equivalents. Florida energy standards are based on analyses using the U.S. Army's comprehensive computer program, BLAST. Other states have similar requirements based on computer programs. These programs analyze both heating and cooling requirements in locations where cooling is a major consideration. Passive solar load is also considered in the overall analysis. In some cases the actual design is based on point tables which establish U values based on the dynamic computer analysis.

Performance-oriented energy standards attempt to limit building energy consumption to a design energy budget. DOE Building Energy Performance Standards identified total annual energy budgets for space heating and cooling and domestic hot water heating in terms of allowable usage measured in Btu per square foot of floor area. Other standards may define only heating season energy budgets. Where such budgets are not specifically defined, the energy usage level corresponding to acceptable practice requirements can be calculated by a simple multiplication of the nominal heat loss rate and the applicable degree-day load. For the design example house in Madison the implied HUD MPS heating energy budget per square foot of floor area is:

Heating budget = 314 Btu/hr/°F °x 7,206 dd × 24 hr/dd
= 54.3 × 10^6 Btu\season\l, 152 ft^2 (floor area)
= 47.1 × 10^3 or 47.1 MBtu/ft^2/season.

The above heating energy budget calculation is based on a 65 °F degree-day baseline. In well-insulated construction, such as represented by the design example, the actual break-even outdoor temperature (above which no heat is needed to maintain indoor temperature at 72 °F level) should be somewhat lower. The actual break-even temperature is a function of heat gain and loss rates and commonly varies between houses of similar construction quality but dissimilar design. The design task entails calculation of this break-even temperature as the actual heating season load reference level.

The difference between the targeted room temperature and balance temperature is sustained by solar and internal heat gains. The magnitude of these gains can be expressed in terms of a temperature credit applicable to the house under consideration. Under steady-state conditions, when heat is neither gained in nor removed from storage, this temperature credit can be calculated as the ratio between heat gain and loss rates. The resulting energy usage then can be estimated as a product of the nominal heat loss rate and the applicable heating degree-day load calculated at the break-even temperature base (HDD_{t_b}). Although this simplified analytical method is not commonly viewed as systems analysis, it constitutes the basis for more sophisticated procedures. The above relationships then can be expressed by equations as:

$$t_c = \frac{q_{hg}}{q_{hl}} \tag{7-3}$$

where

t_c = heat gain temperature credit, °F
q_{hg} = nominal heat gain rate, Btu/hr
q_{hl} = nominal heat loss rate, Btu/hr/ °F

(For other than hourly calculations the nominal heat gain rate represents the average hourly gain for the period under consideration.)

$$t_{be} = t_t - t_c \tag{7-4}$$

where

t_{be} = break-even temperature, °F

t_t = targeted room temperature or thermostat setting, °F

$$HL = q_{hl} \times HDD_{t_{be}} \times T \qquad (7\text{-}5)$$

where

HL = cumulative heating load for the period under investigation, Btu

$HDD_{t_{be}}$ = degree-days on break-even temperature base, OF/day

T = time factor, 24 hr/day

Internal heat gain temperature credit can be assumed at 4 °F. This is consistent with customary design criteria and the 7 °F temperature differential between 72 °F targeted indoor temperature and 65 °F degree-day baseline. Solar gain credits can be estimated on the basis of averaged calculations. The average solar radiation received on a south-facing vertical surface for a 212-day heating season (October through April) in Madison is 1,000 Btu/ft^2/day (Kusuda and Ishii 1977). South glass area can be assumed at two-thirds of the total glass area of 115 ft^2. The transmittance of triple glazing is 0.68, and the absorptance of the interior space can be assumed at 0.95. The seasonal efficiency of solar heat collection may be assumed at 65 percent. The solar gain portion of the temperature credit then can be estimated as:

$$t_{cs} = \frac{Q_{SG} \times A \times \tau \times \alpha \times eff}{q_{hl} \times T} \qquad (7\text{-}6)$$

where

t_{cs} = solar heating portion of heat gain temperature credit, °F
Q_{SG} = cumulative solar heat gain, Btu/day
A = solar aperature, ft^2
τ = glass transmittance factor, dimensionless
α = space absorptance factor, dimensionless
eff = solar collection efficiency factor, dimensionless, and

$$t_{cs} = \frac{1{,}000 \times 115 \times 0.68 \times 0.95 \times 0.65}{314 \times 24} = 6.4\ °F$$

The total of solar and internal heat gain credits, therefore, is 10.4 °F. The break-even temperature at the customary 72 °F room temperature level is:

$$t_{be} = 72 - 10.4 = 61.6\ °F$$

By linear interpolation between HDD_{65} and HDD_{60} data the number of degree-days on 61.6 °F base can be estimated at approximately 6,640 and the resulting energy consumption as:

Heating budget = 314 Btu/hr/°F × 6,640 dd × 24 hr/dd
= 50.0 x 10^6 Btu/season/ 1,152 ft^2
= 43.4 x 10^3 or 43.4 MBtu/ft^2/season

Solar performance analysis also calls for investigation of daily temperature swings to prove compliance with the provisions of such standards as Farmers Home Administration passive solar design requirements. Daytime performance of solar-oriented buildings is influenced by four factors:

1. Heat gain rate (solar and internal heat gains and heating systems output)

2. Heat loss rate (coupling between indoor and outdoor air temperatures)

3. Occupancy conditions (control of high and low temperature limits)

4. Heat storage rate (coupling between thermal load and ballast)

Solar gain rates can be estimated using either average day (Kusuda and Ishii 1977) or clear day (ASHRAE 1977) tables. Heat loss rates can be assumed to be proportional to indoor-outdoor temperature differentials. Occupancy conditions are identified by the applicable code requirements. Heat storage effects are more difficult to estimate, as they vary not only with the thermal capacity of the available mass and its exposed surface area, but also with its internal temperature gradients. For simplified analyses, therefore, storage is assumed to be isothermal.

One potential option for simplified calculations of room temperature swings may be derived from the thermal time constant (TTC) concept. This concept is incorporated in a simplified energy analysis computer program developed by Kusuda and Saitoh (1980). The format of that program can be simplified for rapid hour-by-hour calculations. The derivation of equations and the calculation of room temperature swings (fig. 7-4) is discussed in a later section. The general relationships can be shown in a still more simplified form as:

$$\text{TTC} = \frac{\text{equivalent thermal mass}}{\text{Heat loss rate}}$$

and

$$\text{Incremental temperature change} = \frac{\text{heat flow balance}}{\text{TTC}}$$

A positive heat flow balance (gains exceed losses) leads to a room temperature rise, while a negative balance results in a temperature drop. The hourly temperature change is inversely proportional to the magnitude of the thermal time constant. The time constant, in turn, at any given heat storage capacity (equivalent thermal mass) level is inversely proportional to the heat loss rate. These relationships suggest that, where increase in thermal time constant is needed, it may be more easily accomplished by the addition of insulation than of thermal mass.

In its simplest form the TTC method is based on lumped building mass assumptions. Such calculations yield averaged interior rather than indoor air and storage mass temperature variations. For the purposes of this example, therefore, it must be assumed that the solar energy received in the room is sufficiently well diffused and distributed to warrant the isothermal air/mass assumption.

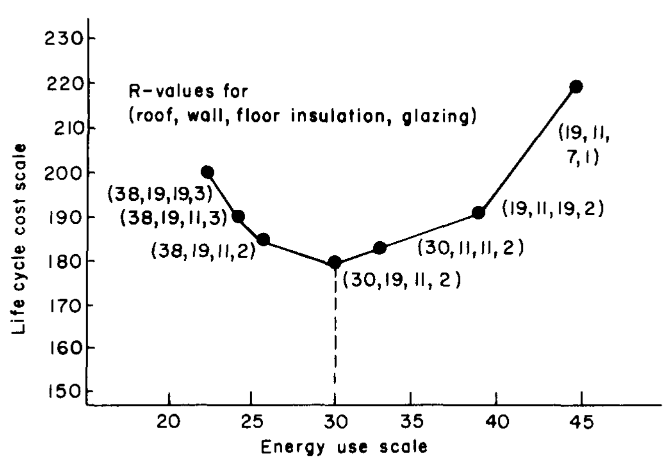

Figure 7-4 – Typical life-cycle cost relationships.
(ML88 5334)

Solar performance analysis (by any applicable method) is done for optimization of glass areas and heat storage capacity. The objective in coordinated light-frame design is admittance of solar energy at a rate that can be accommodated by the readily accessible inherent thermal mass without exceeding allowable room temperature variations. Except for adjustments to time constant values, results from solar performance analysis may not have a significant influence on wall and roof construction specifications. The insulating value of opaque building envelope components must be optimized on the basis of conventional heating and cooling load and life-cycle cost analysis.

Hourly Performance Calculations by the Thermal Time Constant Method

Traditional heating and cooling design calculations are based on steady-state concepts, and exchange of heat with storage is disregarded. Solar and internal heat gain effects are averaged over the entire design period. Investigation of building response to changing temperature profiles and cyclic solar loading, on the other hand, requires consideration of heat storage effects. Dynamic performance analysis is commonly based on computer simulation techniques. Limited consideration of heat storage effects, however, is also possible by hand calculation methods.

The proposed TTC method for hand calculations is derived from a procedure for simplified energy analysis calculations developed by Kusuda and Saitoh (1980). In the original version this procedure allows simulation of gradual indoor temperature change over a number of hours by differential calculations. The modified version relies on linearized arithmetical calculations for approximation of temperature change in 1-hour increments. A series of repeated calculations yields a continuous sawtooth profile that can be smoothed out to a curve by averaging (fig. 7-4 and table 7-4). The hourly calculation procedure is entirely appropriate for analysis of residential buildings, because it allows consideration of different thermostat setback regimes and agrees with the hourly format of solar heat gain tables.

The proposed method in its present format is unverified, and its limitations are untested. The original concept has been derived from energy flow relationships for a structure in a cooling-down mode, when heat recovery from storage and loss to the outdoors is governed by interrelated temperature differentials. Indoor air and storage are assumed to float at a common temperature level, and the relatively good coupling between indoor air and storage, as compared to that between indoor and outdoor air, justifies such simplification. The assumption, however, is no longer valid in the solar gain mode, when a model must also have the capabilities for predicting indoor air/storage temperature differentials. It is possible that the linear TTC procedure can be easily expanded to permit such calculations. At this time, however, such expansion has not been attempted, and discussion is limited to the procedure in its basic format.

The basic heat flow and temperature relationships simulated by a simple thermal capacity model are represented by Kusuda and Saitoh (1980, eq. E-(4)) by a first order differential equation as:

$$MC \frac{dT}{dH} = -K(T - T_o) + SPHG \tag{7-7}$$

where

T = building temperature, °F
T_o = outdoor temperature, °F
MC = building thermal capacity, Btu/°F
K = overall heat transfer factor, Btu/hr/°F
SPHG = total space heat gain due to internal heat gain through windows, and occupancy, Btu/hr
H = elapsed time, hr

Table 7-4 – Building temperature calculations by the thermal time constant method[1]

Hour	SHGF	Q_{SG}	Q_{IG}	Q_{HG}	HSC	t_b	t_o	$t_b - t_o$	dt_b/H
	Btu/ft²/hr	----	*Btu/hr*	----	--------	°F	--------		*°F/hr*
8 a.m.	47	3,558	1,045	4,603	22.0	68.0	10.0	58.0	−2.4
9	144	10,902	1,045	11,947	57.2	68.0	14.0	54.0	+0.2
10	204	15,445	1,045	16,490	78.9	68.2	18.0	50.2	+1.9
11	238	18,019	1,045	19,064	91.2	70.1	22.0	48.1	+2.9
12	250	18,928	1,045	19,973	95.6	73.0	26.0	47.0	+3.2
1 p.m.	238	18,019	1,045	19,064	91.2	76.2	29.0	47.2	+2.9
2	204	15,445	1,045	16,490	78.9	79.1	27.5	51.6	+1.8
3	144	10,902	1,045	11,947	57.2	80.9	26.0	54.9	+0.2
4	47	3,558	1,045	4,603	22.0	81.1	24.5	56.6	−2.3
5	0	0	1,045	1,045	5.0	78.8	23.0	55.8	−3.4
6	0	0	1,045	1,045	5.0	75.4	21.5	53.9	−3.3
7	0	0	1,045	1,045	5.0	72.1	20.0	52.1	−3.1
8	0	0	1,045	1,045	5.0	69.0	19.0	50.0	−3.0
9	0	0	1,045	1,045	5.0	(66.0)	*Additional heat needed*		

[1]SHGF = Solar heat gain factor for single glazing, Btu/ft²/hr; Q_{SG} = Solar heat gain, Btu/hr = SHGF × 115 ft² × 0.77 × 0.95 × 0.90; Q_{IG} = Internal heat gain, Btu/hr; Q_{HG} = Total heat gain, Btu/h = Q_{SG} + Q_{IG}; HSC = Heat source constant, Q_{HG}/q_{h1} in °F, where q_{h1} = 209 Btu/hr/°F; t_b = Building temperature, °F = t_b previous + dt_b/H previous; t_o = Outdoor temperature, °F; dt_b/H = Incremental building temperature change for the hour, °F/hr.

For a time increment of 1 hour this equation can be linearized and rewritten, with some paraphrasing to suit the objectives of this discussion as:

$$\text{ETM} \times \frac{\Delta t_b}{T} = Q_{HG} - q_{hl}\,(t_b - t_o) \qquad (7\text{-}8)$$

where

- ETM = effective thermal mass or heat storage capacity, Btu/°F
- Δt_b = incremental building temperature change, °F
- T = time increment, 1 hr
- Q_{HG} = total heat gain, Btu/hr
- q_{hl} = heat loss rate, Btu/hr/°F
- t_b = building (isothermal indoor air and mass) temperature, °F
- t_o = outdoor temperature, °F

The TTC is defined as a ratio of the overall thermal mass to the overall heat transfer factor of the building, which in the terminology used for equation (7-8) can be expressed as:

$$\text{TTC} = \frac{\text{ETM}}{q_{hl}} \qquad (7\text{-}9)$$

where TTC = thermal time constant, hr

The ratio of heat gains and losses can also be conveniently expressed as a heat source constant, which constitutes a net heat gain credit (or loss debit) quantified in temperature units:

$$\text{HSC} = \frac{Q_{HG}}{q_{hl}} \qquad (7\text{-}10)$$

where HSC = heat source constant, °F

By substitution from equations (7-9) and (7-10), equation (7-8) can be further paraphrased as:

$$\frac{\Delta t_b}{T} = \frac{\text{HSC} - (t_b - t_o)}{\text{TTC}} \qquad (7\text{-}11)$$

Equation (7-11) allows rapid testing of the sensitivity between such relationships as net heat gains and losses, or heat storage effects and indoor-outdoor temperature differentials. It can be used for calculation of hourly temperature ramps and daily temperature extremes (or swings). Equation (7-11) also shows that indoor temperature variations are proportional to the magnitude of the heat source constant and inversely proportional to the thermal time constant.

Equation (7-9) offers two options for adjustments to thermal time constant by changes in either effective thermal mass or insulating value.

The expression "effective thermal mass" as used in this discussion denotes mass that is readily accessible for exchange of heat with room air. It is a function not only of the specific heat and thermal diffusivity properties of materials but also of their surface area exposed to room air. These relationships are not easily quantified. Therefore, in most cases, the expression "building thermal capacity" has been equated with the heat storage capacity of the materials considered to be engaged in the heat storage cycle. For the purposes of the design example analysis, we use the expression in the sense of accessible thermal mass.

On the basis of approximated surface area measurements and typical heat storage capacity design values for gypsum wallboard (ASH RAE 1977) and wood at 10 percent moisture content (FPL 1974), the accessible thermal mass (exposed to room air) of the 1,248 ft^2 ranch house can be estimated as:

$70\ ft^3$ wood $\times$ 12.0 $Btu/ft^3/°F$ = 840 Btu/°F

$210\ ft^3$ gypsum board $\times$ 13.0 $Btu/ft^3/°F$
= 2,730 Btu/°F

$10{,}000\ ft^3$ indoor air $\times$ 0.018 $Btu/ft^3/°F$
= 180 Btu/°F

Total = 3,750 Btu/°F

Allowance for furnishings and equipment = 1,000 (or 27 pct of structural mass)

Total estimated accessible thermal mass
= 4,750 Btu/°F

The TTC of a house is the ratio of its heat storage capacity to heat loss rate:

$$\text{TTC} = \frac{4{,}750\ \text{Btu/°F}}{314\ \text{Btu/°F/hr}} = 15\ \text{hr}$$

This TTC value falls within the anticipated range. Kusuda and Saitoh (1980) suggest TTC values in the range of 10 to 15 for light- to medium-weight one-story houses, and 30 to 35 for comparable two-story houses. By interpolation, values for split level or raised ranch homes could be projected in the range of 20 to 25. For the design example house, if the midwinter solar heat gain is assumed only for the southern two-thirds of the house, and both heat storage capacity and heat loss rate are also assumed to be distributed in proportion to the floor area considered, the TTC of that part of the house remains at 15 hours. The possibility that different TTC values should be considered in analysis of heat gain and loss cycles has already been noted but must be disregarded for this example.

Calculated building temperature variations under Farmers Home Administration design conditions are shown in table 7-3. January 21 clear-day solar heat gain factors are derived from ASHRAE tables (ASHRAE 1977) for 44 °N latitude, approximating the position of Madison, Wis. Gain through glass is calculated with a shading coefficient of 0.77 as for triple glazing, interior surface absorptance of 0.95, and solar heat collection efficiency of 0.90, for a glass area of 115 ft^2. Average January outdoor temperatures for Madison (Oneson 1977) vary from a low of 10 °F to a high of 29 °F. Typical outdoor temperature profiles allow assigning the low temperature to the sunrise hour about 8 a.m. and projecting a rise of 4 °F/hr until noon, with the daily maximum reached at 1 p.m. Afternoon temperatures fall at approximately 1.5 °F/hr for the next 6 hours, and then at 1 °F/hr for the rest of the night. Minimum room temperature is maintained by a thermostat setting at 68 °F.

The 115 ft^2 south glass area constitutes 10 percent of the design example house floor area (1,152 ft^2), or 15 percent of the floor area assumed to receive direct solar gain (two-thirds of the total floor area). Temperature calculations summarized in table 7-4 show slight overheating at the 15 percent south glass area on a January design day. With the same solar heat gain distributed over the entire house (or at the 10 pct south glass area) there would be no overheating. The overheating trend appears consistent with the slightly undersized mass-to-glass area ratio of 27.7 (= 0.67 × 4,750/115), which falls below the commonly recommended ratio of 30 or more (Watson and Labs 1980).

The above analysis suggests that for light-frame wood construction with triple glazing in Madison, the optimum south window-to-floor area ratio falls in the range of 10 to 15. Under the conditions investigated, triple-glazed south windows gain more heat than they lose even without night protection. The heating load for the average January day is 49.6 degree-days, and the 24-hour heat loss for triple glazing is 560 Btu/ft^2. Estimated clear-day solar heat gain with a 0.90 collection efficiency factor is 998 Btu/ft^2, and the average day gain (Kusuda and Ishii 1977) at the same efficiency level is 612 Btu/ft^2.

Actual solar design efficiency analysis must be based on heat balance calculations for the period stipulated by the applicable code (design day or heating season). Seasonal performance analysis may require consideration of actual shadow lines on glass, rather than just a nominal reduction in collection efficiency as used in this discussion (0.65 for the heating season versus 0.90 for January).

The TTC design method appears sufficiently simple in concept and in execution to be applicable to light-frame thermal design tasks, where design objectives may not extend beyond demonstration of compliance with such standards as Farmers Home Administration passive solar design requirements.

Cost Effectiveness

Effectiveness of Added Insulation

The effectiveness of added insulation varies with a number of factors, including climate, original insulation level, and cost of preparations for added insulation. Building codes generally attempt to establish a reasonable balance between all life-cycle costs, which include construction, financing, and energy expenditures. Typical relationships between life-cycle costs and energy consumption are shown in figure 7-4 (U.S. General Accounting Office 1980). Individual points on the curve represent different combinations of ceiling, wall, and floor insulation in R-values and glazing types (single, double, or triple). As life-cycle costs vary not only with construction and energy costs but also with climatic factors, the profiles of this curve vary for different localities. In the case of figure 7-4, the optimal condition is reached with R-30 attic insulation and double glazing. With higher construction standards in this locality, life-cycle costs may rise more rapidly than savings in energy. The added insulation also may not be as effective as suggested by calculations because of overlooked conditions. Adding insulation, therefore, calls for careful analysis of the conditions.

Added Insulation Strategies

Increasing thermal performance standards markedly above code requirements has become known as "superinsulation." The expression is generally applied not only to use of added insulation, but also to glass area and air infiltration control.

To be cost effective, added insulation should be distributed in proportion to its potential for improvement. The previous design example shows heat transmission through a ceiling with R-38 insulation at approximately 10 percent of the total heat loss. The total heat flow through the ceiling, however, may be considerably higher. Much of the heat loss attributed to air infiltration takes place by air flow into the attic rather than directly to the outside. Air flow paths include recessed ceiling lights and holes in the top plates of interior partitions that are needed for wiring and other mechanical work (Harrje et al. 1979). Because of the combined attic heat gains, including solar loading and waste heat recovery from chimney, attic temperatures often are higher and transmission heat losses through ceiling insulation lower than estimated (Burch and Hunt 1978, Harrje et al. 1979).

The relative effectiveness of added attic insulation also diminishes because of such factors as increased settled density (Tye et al. 1980), installed thickness effects (Hollingsworth 1980), and the influence of voids, such as end gaps between insulation batts (Vinieratos and Verschoor 1980). Density and thickness effects vary with different materials and still have not been quantified for regulatory and design purposes. The importance of void control is commonly overlooked, but becomes increasingly more important with added insulation value.

The importance of void control is illustrated by figure 7-5. For any given void area, the degrade in relative thermal performance becomes more pronounced at higher nominal R-values. While at a 1 percent void ratio in R-5 insulation the degrade may be considered negligible, at a nominal R-38 level its effects approach 25 percent of the rated insulating value (yielding the equivalent to approximately R-28 of void-free insulation). As voids are difficult to control, performance analyses should include adjustments for

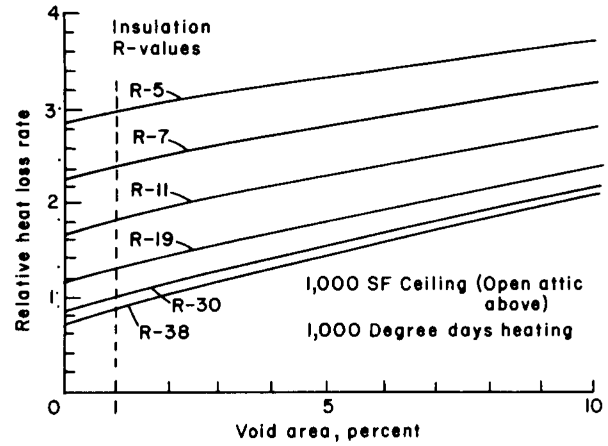

Figure 7-5–Influence of insulation void area. (ML88 5335)

their possible impact on the thermal and cost effectiveness of increased insulation thicknesses.

Windows with other than south orientation may be viewed as voids in an otherwise well-insulated building envelope. For the design example house triple-glazed window losses were estimated at more than 25 percent of the total building heat loss including air infiltration, 37 percent of building envelope transmission losses, and 62 percent of total wall/window losses. Control of glass areas may offer considerably greater potential for further thermal performance improvement than added insulation in already well-insulated opaque portions of the building envelope. Such control includes options of size reduction, change to triple and quadruple glazing, and relocation to south wall.

For the design example house, triple glazing at U = 0.36 would help to reduce nominal heat loss rate (q_{hl}) by 5.4 percent to 297 Btu/hr/°F. While such improvement may not be very efficient, it still may be more cost effective than double-stud construction needed for comparable heat loss reduction through the opaque portions of exterior walls to accommodate R-30 insulation.

Air Infiltration Control

Natural air infiltration is a temperature-dependent phenomenon. It becomes more severe with increasing indoor-outdoor temperature differentials. Actual air infiltration rates may vary in otherwise similar houses because of differences in workmanship, and may be difficult to predict even for houses with known air leakage characteristics measured under standardized test conditions. Both of the weather-related infiltration determinants, indoor-outdoor temperature differential and wind pressure, can vary from house to house with differences in exposure, or with differences in terrain and wind barriers. Standardized models and climatic data references for prediction of air infiltration rates are still under development (Grimsrud et al. 1980).

Air infiltration measurements in test houses show fairly consistent correlations between the applicable indoor-outdoor temperature differentials and windspeed effects. Data for a one-story ranch house (Burch and Hunt 1978), which may also be applicable to the design example house, are shown in figure 7-6. The average heating season outdoor temperature in Madison is 34.1 °F at an average wind-speed of less than 5 miles per hour. The indicated relationships yield an air infiltration rate of 0.6 air changes per hour (AC/hr). This heating season average condition is in good agreement with the 0.6 AC/hr references found in codes and standards (U.S. Department of Energy 1979b, U.S. Department of Housing and Urban Development 1980),

At increased indoor-outdoor temperature differentials the air infiltration rate also increases. Average attic and crawl space temperatures, on the other hand, do not reach the extremes of outdoor temperatures. Because of compensating variations between infiltration and transmission heat losses, the total heat loss rate can be assumed to remain proportional to indoor-outdoor temperature differentials, as shown by figure 7-7.

At heating season average conditions, the estimated infiltration heat loss for the design example house at 0.6 AC/hr constitutes almost one-third of the total heat loss, while at design conditions it approaches 50 percent of the total. More airtight construction could lead to a measurable improvement in energy efficiency. Reduction in infiltration through more careful vapor retarder installation to 0.1 AC/hr may be an attainable target (Besant et al. 1979). The targeted ventilation rate of 0.6 AC/hr could be maintained by supplementing natural airflow with an air-to-air heat exchanger operating at 0.5 AC/hr flow rate. Reliable data on seasonal operating efficiencies of heat exchangers still are not available, and an assumed 80 percent efficiency level may prove to be too optimistic. Nevertheless, the energy savings should be appreciable. Under such conditions the total ventilation heat loss rate would be equivalent to an infiltration rate of 0.2 AC/hr at an actual ventilation rate of 0.6 AC/hr. The energy savings would equal 21.2 percent of the total nominal heat loss rate of 314 Btu/hr/°F.

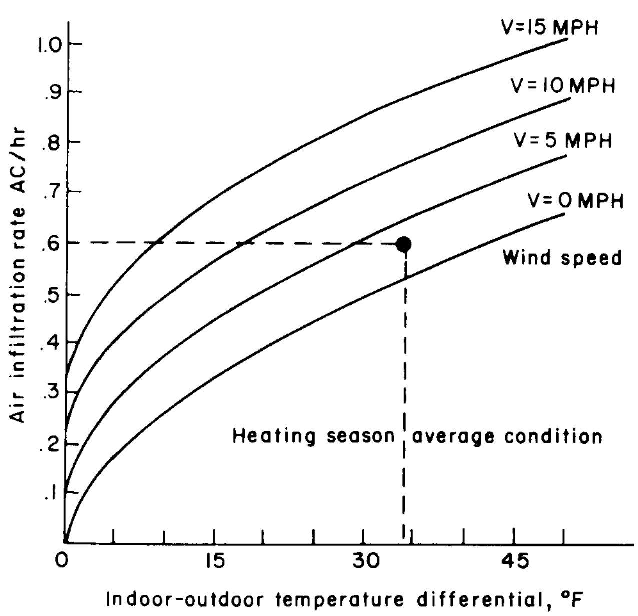

Figure 7-6–Air infiltration rate relationships. (ML88 5336)

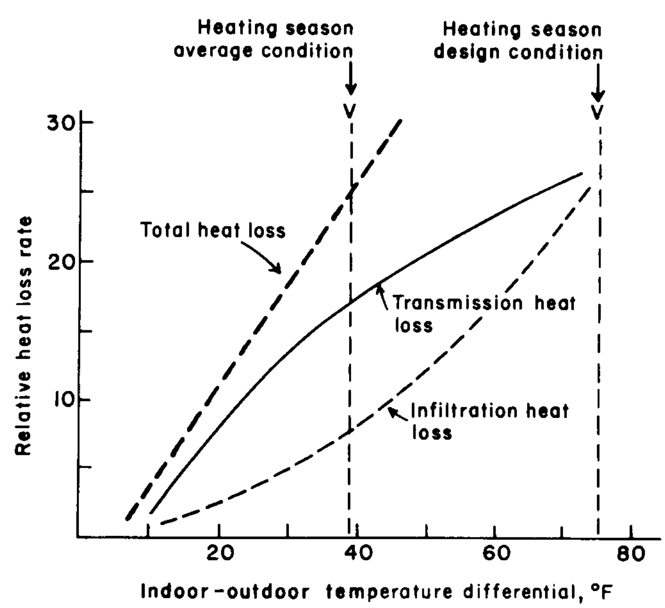

Figure 7-7 – Transmission/infiltration loss relationships. (ML88 5337)

Actual ventilation requirements vary with conditions. The presence of some contaminants, such as radon gas, may be best controlled by more careful choice of building materials rather than by higher ventilation rates. Basic construction quality should aim for minimal air infiltration during weather extremes and unoccupied periods, to be supplemented by positive ventilation meeting occupancy requirements. Consistent with such design strategies, future performance standards may also differentiate between occupied and unoccupied conditions.

Air infiltration control serves dual purposes: it helps to save energy, and it reduces migration of water vapor from the living space into structural cavities. It is a design strategy with a very attractive cost/benefit ratio. For the design example house, the energy savings attributable to reduction in air infiltration by 0.4 AC/hr (67 Btu/hr/°F) are four times as high as those associated with a change from triple to quadruple glazing (17 Btu/hr/°F), and also four times as high as the benefits of added R-66 ceiling insulation (six R-11 blankets).

Cost Effectiveness of Improvements

The key consideration in component design is not necessarily overall energy efficiency, which may remain controlled by acceptable practice requirements, but rather the relative effectiveness of added insulation in different building components. Installed cost of insulation varies not only with direct material and labor costs, but also with the indirect cost of preparations, such as increased wall thickness needed to accommodate additional insulation. Furthermore, the installed effectiveness of added insulation also varies with the reference temperature differential across the given component (because transmission heat loss rate $AU\Delta t$ is a function of both component properties AU and temperature differential Δt). As already noted, seasonal average temperature differentials for different components (ceiling, walls, and floor) do not necessarily vary in direct proportion to indoor-outdoor temperature differentials. Most economic models used for prediction of optimal insulation thicknesses disregard these factors, and tend to mask their effects on the actual installed cost effectiveness of added insulation.

One of the most comprehensive and enlightening economic models developed by Robinson (1979) is based on the premise of "simplest things first." It also proposes that the amount of money spent on all insulating elements of the building envelope (including windows) should equal the present value of all money to be spent on space heat (including provisions for solar heating) for the minimum life-cycle cost over any given amortization period. More detailed discussion of the Robinson model falls outside the scope of this paper.

The basic premises of the Robinson model, however, can also serve as a framework, for still more detailed cost effectiveness analysis that allows consideration of other commonly overlooked conditions outlined above. Consistent with the Robinson premise, the incremental cost of thermal improvements above any given performance standard should equal the anticipated energy savings, up to the point of balanced life-cycle conservation and energy costs. The Robinson model can then be supplemented with the following expression of relationships between improvement costs and installed insulation efficiency for different components:

$$(B'_i + B'_p) - wE'N = \Sigma_j\left(A_j \frac{fR'_j}{R_j(R_j + R'_j)} \Delta t_j\right) T \frac{de}{\eta} N \quad (7\text{–}12)$$

where

- B'_i = incremental budget for improvement in insulating value, \$
- B'_p = incremental budget for preparations to receive improvement, \$
- w = conservation versus energy cost-weighting factor, dimensionless
- E' = incremental annual energy cost-savings target, \$/yr
- N = length of amortization period, yr
- A_j = heat transfer surface area of envelope component j, ft^2
- f = insulation thickness and void adjustment factor, dimensionless
- R_j = initial insulation value of component j, hr-ft^2-°F/Btu
- R'_j = added insulation value of component j, hr-ft^2-°F/Btu
- Δt_j = reference temperature differential across component j, °F
- T = length of heating season, hr/yr
- de = discounted (present value) unit cost of energy, \$/Btu
- η = energy conversion or heating system efficiency factor, dimensionless

The first bracketed quantity in equation (12) $(B'_i + B'_p)$ represents the cost budget for improvements warranted by the desired or anticipated energy cost savings associated with the proposed improvement over the given amortization period (E'N). Weighting factor (w) allows definition of any desired (if other than one-to-one) relationship between these budget items. The second bracketed quantity represents calculation of the difference in heat loss calculations AU' Δ t) attributable to changes in insulating value of any building envelope component (j). The incremental change in thermal transmittance value (U') is expressed in terms of the ratio between added insulation value and its effectiveness in the given assembly $(R'_j/R_j(R_j + R'_j))$. The value of the added insulation is further reduced by thickness and void adjustment factor (f). The reference temperature differential (Δt_j) is the difference between inside (indoor) and outside (ambient environment, attic, or crawl space) air temperatures for the component under consideration. For heating season analysis the most convenient references are average temperatures, which can be derived from degree-day data. The discounted energy cost (de) represents the averaged anticipated energy cost for the amortization period, adjusted by a differential between energy and construction cost escalation rates. The energy conversion efficiency factor (η) allows corrections for different mechanical system characteristics (such as heat pump versus furnace).

Equation (7-8) allows calculation of improvement budgets and comparison of the relative cost effectiveness of different conservation options. Its use is illustrated by investigation of energy savings attributable to different ceiling insulation thicknesses. For the design example house, the thermal resistance of uninsulated ceiling can be assumed at R-2, which with R-38 insulation (two R-19 blankets) yields a total value of R-40 (reciprocal of U = 0.025) required by HUD Minimum Property Standards. At heating season average indoor temperature of 700 °F and attic temperature of 35.9 °F (5 °F above average outdoor temperature at 30.9 °F for Madison), the reference temperature differential (Δ t) is 34.1 °F. The length of the 7-month (212-day) heating season is 5,088 hours. Natural gas cost can be estimated at \$0.50/therm (100,000 Btu), and the furnace efficiency factor at 0.75. For the first year's savings (or improvement budget increment) the energy cost can be entered without further adjustments for cost escalation. The energy cost savings attributable to the first thickness of R-38 insulation as compared to uninsulated (R-2) construction then can be estimated as:

$$E'_R - 40 = 1{,}152 \times \frac{38}{2(2+38)} \times 34.1 \times 5{,}088$$
$$\times\ 0.50/(100{,}000 \times 0.75) = \$633.00/\text{yr}$$

The second thickness of R-38 insulation added to R-40 construction is markedly less cost effective, particularly if estimated with a thickness and void correction factor of 0.9:

$$E'_R - 78 = 1{,}152 \times \frac{0.9 \times 38}{40\,(40 + 38)} \times 34.1 \times 5{,}088$$
$$\times\ 0.50/(100{,}000 \times 0.75) = \$14.60/\text{yr}$$

The general relationships indicated by these calculations agree with the trend shown by figure 7-4. Although equation (7-8) does not allow direct calculations of optimal insulation thickness, it permits consideration of most parameters important in the component design procedure. Such analysis allows sufficiently detailed evaluation of design options for optimization of the building system.

Summary of Analysis Procedures

Actual analytical methods applied in each design stage may vary from the above examples. Nevertheless, the basic framework of conceptual/preliminary/final design or acceptable practice/component design/systems analysis path allows consistent transition from one stage to the next. It also permits selective bypassing of steps that are considered less important. Design goals identified with each of the three stages can be summarized as:

1. Meeting code-defined minimum acceptable performance thresholds by-compliance with acceptable practice construction.

2. Exceeding code requirements as warranted by component design through selective redistribution of such building envelope elements as glazed and insulated areas, increased insulation levels, and more effective air leakage control.

3. Increasing utilization of energies gained from nondepletable sources or recovered from waste heat and solar gain, with performance predictions based on systems analysis procedures.

The acceptable practice option requires essentially no design attention beyond calculation of specification requirements and is the most common choice for demonstration of code compliance. The component design option allows consideration of trade-offs for optimization of insulating values in different building envelope components. Optimization also requires consideration of the relative effectiveness of added insulation in different components. Optimization of glass areas and heat storage capacity requires some heat balance calculations, which fall in the area of systems analysis. For light-frame residential and light commercial buildings, however, codes based on ASHRAE Standard 90 may not require 8,760-hour performance simulations and may accept hand calculations by such procedures as the Degree-Day or Bin methods. After further development and validation, the TTC method may serve as a procedure for hour-by-hour calculations and streamlined systems analysis. Regardless of differences between the three options, the basic design target in all cases is an implied or a stipulated energy budget. Different design options only allow meeting this target with greater sophistication, greater cost effectiveness, and higher degree of certainty in exceeding minimum acceptable performance requirements.

Computer programs are used in most cases to establish requirements. These are based on dynamic analysis and include not only the building envelope, but also solar gain. In warm climates, cooling is considered on an equal basis with heating energy.

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Chapter 8
Passive Solar Analysis

Introduction

Passive solar design in its broadest sense refers to the control of indoor climate through architectural form and materials. The scope of these controls ranges from the broad scale of siting and landscaping down to the selection of weatherstripping. It is convenient to discuss these issues under the topical headings of site planning, building form and orientation, building plan and section, the building envelope itself, and openings within the envelope (Watson and Labs 1980).

Background

The full range of climate control strategies can be identified by applying to the four modes of heat transfer the four regulatory options of (1) admitting, or (2) preventing exterior heat energy from entering the interior space, or (3) rejecting, or (4) containing heat energy generated within the building space. Sixteen hypothetical strategies of climate control are thereby created, although only half of these are actually usable in practice (table 8–1). The goal of winter climate control is to promote the gain of externally supplied (solar) heat and to resist losses from the interior, while summer strategies aim to resist external gains and promote loss of excess internal heat.

The total number of usable strategies is limited by the availability of environmental heat sources and sinks at the building site. The sun is the only practical source of heat supply during the heating season, although under some circumstances, outdoor air may offer a source of warmth for an underheated interior. Environmental heat sinks can be available for all modes of heat transfer by the sky, the earth, and the atmosphere, although the cooling power of each is regionally variable, being related to prevailing meteorological and ground temperature conditions.

While passive solar design directly applies only to the strategy, “promote solar gain, ” virtually every region of the United States possesses an overheated, as well as an underheated, season. Solar design, therefore, in its narrow sense, is insufficient for climate control in temperate zones. The challenge to the temperate zone architect is to integrate locally effective methods of summer and winter climate control with one another in such a way that the execution — or manifestation in physical form or materials – of one strategy does not significantly compromise the effectiveness of others. Subsequent discussions examine current architectural practices of climate control.

Performance Factors

Winter Application

Solar heating and material controls against heat loss are complementary climate control strategies. Between these, however, exist certain inconsistencies which have led many designers to favor an approach to small-scale energy-efficient building design, either predominantly by solar heating or predominantly by heat conservation. Both approaches can be realized in light-frame construction, although solar heating normally requires incorporation of amounts of thermal storage capacity beyond what is intrinsic to light-frame systems, while design for heat conservation differs little from ordinary practice insofar as materials of construction are concerned. The departure from normal light-framing practices for energy efficient design occurs mostly in the nature of details, to be examined in a later section.

Another means of conserving internal heat is to build in a less severe exterior climate. This can be achieved on-site by means of underground construction, which requires building systems and detailing quite different from that of light framing. Ground climate and the relative advantage of various above ground passive climate control techniques versus those realized through underground construction have been studied in detail by Labs (1981), and are discussed by Labs and Watson (1981).

The designer's or builder's choice to emphasize either solar heating or heat conservation may be based on any one, or combination, of a number of factors, including expertise of the architect, regional climate, nature of the site, including slope, orientation, and shading due to vegetation, and the marketplace or the preference of the individual client or buyer. Given a north-sloping, heavily-wooded site in a cloudy northern climate, one would logically opt for an energy conservation rather than solar design; given favorable sun exposure in a moderately cold but clear climate, however, one would have both options available as acceptable approaches to energy efficient construction. Under the latter circumstances, selection of the strategy for winter climate control should be based on consideration of its compatibility with the most appropriate summer control strategies, in addition to other nonclimate-related programmatic issues.

From the standpoint of solar heating versus heat conservation alone, a regional index of the relative suitability of solar heating is provided by comparing the amount of solar radiation received on a south-facing vertical surface to the heating demand. One specific index of this sort is the ratio of normal daily average insolation on a south surface for the month of January ($Btu/ft^2/day$) to January monthly heating degree days (base 65 °F). Values have been computed from the *Passive Solar Design Handbook* (Balcomb 1980); these are mapped on figure 8–1. Higher values favor solar heating, while lower values favor heat conservation as the primary strategy for wintertime climate control. The index is not in itself an indicator of solar feasibility; instead, it is an aid in extrapolating the successfulness of passive solar design from one area to another.

Summer Application

The number of options available for summer climate control are greater and more varied than for winter, as may be seen from table 8–1. Controls against conduction, infiltration, and solar gain are universal to construction systems, and need not be dealt with here. The strategy of radiant cooling as used here applies primarily to high mass exterior wall construction; it is a means of carrying over daytime heat to be released at night through radiation to the sky. Light-frame structures are incapable of executing this cooling mode, which is most effective in the arid Southwest.

Light framing does, on the other hand, lend itself to large and abundant exterior openings that take advantage of ventilating breezes. This fact, and the low mass intrinsic to light-frame construction, makes it well suited to climate responsive design in hot, humid regions. Principles of design for ventilation are discussed in a number of references old and new (Olgay 1963, Reppert 1979, Simon 1947), and the interested reader is referred to these for additional information.

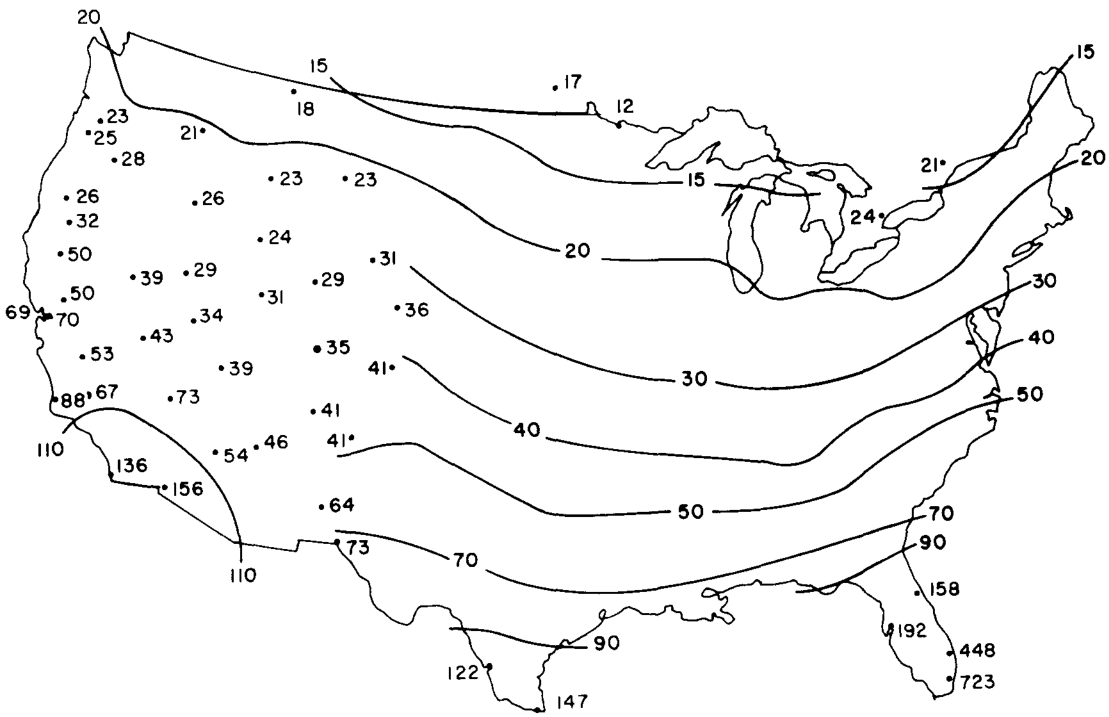

Figure 8-1 – Ratio of January monthly insulation on south vertical surfaces to January monthly heating degree days, base 65 °F. (ML88 0019)

Table 8-1 – Strategies of climate control

Mechanism of strategy	Climate control strategy			
	Conduction	**Convection**	**Radiation**	**Evaporation**
Heat source		Atmosphere[1]	Sun	
Heat sink	Earth[1]	Atmosphere[1]	Sky	Atmosphere
		WINTER		
Promote heat gain			Promote solar gain	
Resist heat loss	Minimize conduction	Minimize infiltration		
		SUMMER		
Resist heat gain	Minimize conduction	Minimize infiltration	Minimize solar gain	
Promote heat loss	Earth cooling	Promote ventilation	Radiation to sky	Evaporative cooling

[1]The earth and the atmosphere can serve as heat sinks but can also be heat sources during the overheated period, depending on time of year and local climatic conditions. Sink and source here are defined by direction of energy flow when indoor temperature is held within comfort limits of 65 to 78 °F.

Passive solar heating systems consist of either three or four basic components, (1) a collector, or glazed aperture which admits solar radiation to the interior of the system while suppressing convective heat losses to the exterior, (2) an absorbing surface which converts shortwave solar radiation into thermal energy, (3) the space to be heated, and 4) an optional medium for thermal storage. A distinction is made between "passive" and "active" systems by defining the former as systems in which heat energy is transported from one component to the other through natural mechanisms of heat transfer; within active systems, in contrast, heat energy is transported by mechanical means, usually by use of pumps or fans. Systems in which heat transfer occurs primarily by natural processes, but which may be assisted by mechanical devices, are described as hybrid solar systems.

There are many different possible solar systems, distinguishable by the various physical interrelationships between aperture, absorber, thermal storage medium, and the space. Defining relationships are diagrammed in table 8–2; the number of primary alternatives is, theoretically $2 \times 3 \times 3 \times 2 = 36$ total options, although not all of these are commonly found in practice. The suitability of light-frame construction for passive solar design is largely related to the nature of the thermal storage component of the system, and the overall character of the architectural design itself is often also closely related to the mode of storage embodied in the design. The basic absorber: storage and storage: space relationships are discussed below.

No Thermal Storage

All materials possess some heat capacity, so no solar system is entirely without thermal storage. However, light-frame structures possess little inherent thermal capacity as compared to recommended levels for passive solar houses, so we shall, for convenience, describe normal light construction as devoid of (significant) storage.

Table 8-2 – Passive solar system design alternatives

Collection	Absorption	Storage	Retrieval
Aperture options	**Absorber: space relationship**	**Absorber: storage relationship**	**Storage: space relationship**
None	**Direct**	**None**	**None**
Wall	**Indirect**	**Integral**	**Integral**
Roof	**Isolated**	**Remote**	**Remote**

Direct Gain

The value of thermal storage was not recognized at all in the postwar generation of solar houses, in which the three elements of solar design comprised proper orientation to the sun and summer breezes, use of large windows on south facades, and summer sun control by use of roof overhangs, attached visors, and other shading devices (Simon 1947). These houses were of the "direct gain" type, in which windows serve as solar apertures and the absorption surfaces are the surfaces of the living space itself. Lacking sufficient thermal storage capacity, however, low mass structures are susceptible to overheating during daytime — consequently wasting solar heat — and to excessive heat losses at night because of their large window areas. Studies show that low mass solar buildings without night window insulation perform best in cold, clear climates, where a relatively high fraction of the heating load occurs during daylight hours (Wray 1981). The same studies reveal that "low mass, sun-tempered direct gain buildings require less auxiliary heat than do the conventional structures they are intended to replace, but are inferior to high-mass designs." The researchers further deduce, "apparently, the low mass, sun-tempered buildings can, at best, meet only the daytime portion of the heat load, having insufficient thermal storage for nighttime carryover, " and they conclude, "the comfort and energy-saving characteristics can be improved by making sure the northern zones of the house are available for thermal storage either by providing a forced air distribution system or by sizing connecting apertures such that free convection maintains adequate thermal uniformity."

Isolated Gain

Because one of the disadvantages of increasing daytime heating in direct gain solar systems is an accompanying increase in nighttime heat losses, alternative low mass approaches have been advanced which isolate the collector and absorber surfaces from the living space itself. The thermosiphoning air panel is presently gaining interest, especially for retrofits to frame construction (Hagan et al. 1980, Wilson 1980). Thermosiphoning units are built onto the exterior of a conventional insulated stud wall, and are coupled to the interior by natural convection through vents at the top and bottom of the units. The lower vent is fitted with a damper which admits return air from the room to the collector in the daytime heating mode, but which blocks reverse cycling so that the system behaves as an insulated wall at night. An invalidated performance calculation procedure for such units has been described by Kohler (1981). Another essentially massless exterior collector is the attached solar greenhouse, which may be coupled to the interior in much the same way as thermosiphoning units. An attic space with a glazed roof can also serve as a collector-absorber system of low inherent mass, but because of the large amounts of gain that can be captured through a roof plane, solar attics are usually coupled by mechanical devices to a remote storage reservoir.

Integral Thermal Storage

Since light-frame construction by nature provides insufficient thermal storage for large solar contributions to the heating load, a deliberate effort must be made to enhance the heat storage capacity of the system. Various approaches include (1) utilizing multiple layers of gypsum board on walls and ceilings, (2) applying masonry veneers to walls and making use of ceramic and stone flooring materials, especially on concrete slabs, and (3) incorporating lightweight, high thermal capacity materials into walls and ceilings. Free-standing thermal storage units such as water drums or water columns can also be used; while these may be integral with the space from a thermal standpoint, they are independent (except for necessary support) of the building frame. “Integral” as we use it here refers to the relationship between the storage medium and the materials of construction. Both direct and indirect gain systems may make use of integral storage.

Direct Gain

Phase-change materials may provide the key to the sufficiency of light-frame construction for passive solar design. One difficulty in utilizing phase-change materials in direct gain systems has been in achieving intimate coupling between the storage medium and the space. This problem is minimized if the surface of the phase-change unit itself is exposed to the space – as in the case of phase-change floor and ceiling tiles developed at the Massachusetts Institute of Technology (Johnson 1980). These have a melting point of 73 °F and a stabilized heat content of 200 Btu/ft^2 of tile. Very good, but less than anticipated, performance has been obtained with l-inch-thick envelopes laid between ceiling joists over a gypsum board ceiling (Holland 1980); shortcomings in response of the assembly have been attributed to unsatisfactory conductivity of the gypsum board, and not to any deficiency of the product or the conceptual arrangement. A more conductive ceiling material would enhance the performance of the assembly, and the manufacturer suggests the alternative of laying the phase-change material bags over an open grid, slotted, or ribbed ceiling, in order to couple the units directly with the room air.

Among less exotic methods of increasing integral heat storage capacity are nailing up double layers of gypsum wall board and pouring concrete slabs over wood-framed decking (Coonley 1979). This practice is justified by findings of Wray and Balcomb (1979), who state that, “for a given M/A (mass to glazing area ratio), the best performance is achieved with the thinnest layer of mass which of course covers the largest fraction of the interior surface.” This is not to suggest that maximum performance – which may require mass thicknesses equivalent to 8 inches of concrete – can reasonably be achieved with this additive, veneering approach.

The thermal storage capacity of interior stud walls can also be increased by filling the cavity spaces with water containers. Stacked cans would serve this purpose, although the ultimate performance of such an arrangement depends on the intimacy of the coupling between the storage medium and indoor air.

Indirect Gain

Several lightweight alternatives to the masonry or concrete thermal storage wall are available which are well suited to light framing systems. One product is a translucent, fiberglass-reinforced polymer pod containing a phase change salt hydrate with a thermal storage capacity of 400 Btu/ft^2 at 81 °F. Each pod measures 48 by 16 by 2 inches, weighs 29 pounds, and has a visible light transmittance of about 25 percent. Rack-mounted behind a glazing panel, the pod assembly is said to store as much heat as a 10-inch masonry wall, with 80 percent less thickness and 95 percent less weight, while still serving as a lighting unit (Sedrick 1980). Other phase change applications are discussed in a survey article by Swet (1980).

A different type of manufactured storage unit is a one-piece 59-gallon fiberglass-reinforced polyester water tank which is designed to fit within the stud framing of an exterior wall. One face of the 92- by 22- × 6-1/2-inch tank is factory finished for direct exposure to the room interior, while the opposite face is coated with a black nickel foil selective surface having an absorptance of 0.97 and an emissivity of 0.1. The tank is shipped empty, is installed resting on the sole plate in the stud cavity, and is then filled with water. It is then capped with glazing on the exterior side. With a filled weight of 450 pounds, the unit has a thermal storage capacity of 30.1 $Btu/°F/ft^2$, or, according to manufacturer's information, a capacity comparable to a 16-inch masonry wall, with one-third the volume and one-fifth the weight. A particular proposed application of the unit is for solar mobile home construction (Moore and Hemker 1981).

Another modular water storage tank system has been described by Maloney (1980). Seamless, 4-foot-square modules are formed with a flange, allowing direct nailing to 2 by 8 stud wall framing. The modules are molded with a recessed channel to accept an intermediate 2 by 3 stud for use as a nailer, in the event that the builder does not wish to expose the face of the tank directly to the room. Otherwise, the translucent module can serve as a day-lighting unit. It is proposed that the module be placed only in the upper half of the wall and that a low-cost, flat plate collector be fixed in the stud cavity beneath. The water tank module thus serves also as a storage tank and radiator in a thermosiphoning system. The area behind the collector is to be insulated, and both the collector and the water module are glazed with an acrylic sheet. Alternatively, two water modules can be stacked per stud space.

A third indirect gain modular storage unit is a transparent, water-filled, triple-glazed windowlike unit developed at Ames Laboratory at Iowa State University. Although not commercially available, the units could be custom fabricated in much the same way as the prototypes. These were constructed with 3/8-inch clear acrylic inner and outer panes, with an absorber plate (3/8-inch neutral gray, 80 pct absorptance) positioned midway between. To keep hydrostatic pressures at a manageable intensity, the units were made 23 inches high and were built with three internal vertical ribs, tying the outer panes together (Fuchs and McClelland 1971). Recent computer simulations of performance in different climates reveals little benefit in overall thicknesses in excess of 4 inches, and that "module thickness and absorber plate transmittance can be varied substantially with minor sacrifices in thermal performance" (Hull et al. 1980). In application, the system is conceived as a transparent alternative to an unvented Trombe Wall; although resembling a window in section, it is independent of the exterior glazing system. This system is claimed to possess a thermal advantage over direct gain and Trombe Wall systems, since solar energy is absorbed within the unit rather than at its outside surface. This reduces the exterior surface temperature and, consequently, outward heat losses. Outward view is preserved over the entire wall surface, while overheating, glare, and color bleaching associated with direct gain systems are eliminated.

Another water system is a 7-inch-diameter, 28-gallon, galvanized steel, plastic film-lined water storage tube which is coated with a black nickel selective surface around half its circumference. The units are designed to fit three each in the cavity of a 24-inch, 2 by 10 stud wall, or two each per cavity of a 16-inch, 2 by 8 exterior wall. The walls are to be sheathed with drywall on the inside and glazed on the outside. A continuous slot is provided at both top and bottom of the interior sheathing, to allow the entire wall to act as a warm air convector. A similar arrangement, made by stacking 5-gallon metal cans, faced on one side with a selective surface copper foil, has been described by Arasteh et al. (1980) as a south wall retrofit. In this case, the original stud framing was left in place, but stripped of its inside and outside sheathing. Water cans were stacked so as to leave an air space between their faces and that of the outside of the existing studs, to which a double-skinned acrylic glazing was attached. An air space was left between the cans and the ceiling and between the cans and the floor to permit convective transfer of heat between the wall collector assembly and room air. A plastic film damper was provided at the bottom vent slot to prevent reverse cycling at night.

Remote Thermal Storage

Remote thermal storage is often used in conjunction with direct gain and attached greenhouses and other isolated gain collector-absorber assemblies, as part of a hybrid solar system. Bins of rocks or racks of water bottles or phase change canisters usually make up the storage reservoir. The heat storage may be coupled to the living space through a radiant floor slab or through forced or natural convection. The purpose of the remote storage in a passive system is to augment – not to substitute for – the integral storage capacity of the structure. It is recommended that no more than one-third of a spaces's net heat (i.e., solar influx minus daytime losses) be transferred out of a space to a rock bed (Balcomb 1980). While a remote storage reservoir can help alleviate overheating in low mass structures, it should not be regarded as more than a minor component of the overall passive system.

Remote storage reservoirs may be required as a major component of certain hybrid systems, such as the solar attic. In this scheme, a glazed south-facing roof admits solar energy to a low mass attic interior, which serves as the absorber. Hot air is drawn out of the attic by fan, which then charges, typically, a rock storage bed (Bourdette 1977). If the storage reservoir is passively coupled to the living space, then the overall system is hybrid; if heat drawn from the reservoir is supplied to the living space also by mechanical means, then the system is active.

Heat Conservation

Past wisdom has advised the optimization of heat conservation measures – most notably, of insulation – on the basis of the least total cost of the installed insulation plus anticipated fuel use over some projected payback period (Stephenson 1976). With rapid inflation of fuel costs and with uncertainties about fuel supplies, many home designers and buyers have looked beyond the conventional optimization procedure and sought to reduce heat losses to such an insignificant level that the heating requirement is largely met by internal heat gains from the inhabitants, appliances, lighting, and other sources. Houses designed in this way have popularly come to be known as superinsulated houses. Superinsulated houses almost without exception are of frame construction and, although details of assembly differ from conventional framing, superinsulated houses use standard framing materials. Details of construction are given in a number of current publications, so the following section will only attempt to identify sources of information.

A second energy conservation approach is the "double shell" or "double envelope" house (referring to two separate building skins), or simply, the "envelope" house (referring to the air envelope between the building skins). There is much debate about the envelope concept and how well it works. Only in the past year have rigorous test results been published. A frequent comment of investigators is that envelope houses perform well, but that this is a result of their being well insulated and solar heated through the south side and not especially attributable to the envelope itself. Some issues and literature concerning the envelope house are introduced below.

Superinsulated House

A superinsulated house, according to William Shurcliff (1980), one of its leading promoters, has a south window area no greater than 8 percent of the floor area and is so well insulated and so airtight that it needs almost no auxiliary heat. The goal of superinsulated design, as evidenced by Shurcliffs characterization, is essentially to do away with the central heating system. The 8 percent limit on south glazing area is somewhat arbitrary, but was chosen because, "if the area is much greater, intake of solar energy may be more important than conserving heat from internal sources" (Shurcliff 1980). Thus, a superinsulated house is not a solar house, a point repeatedly made by energy conservation designers.

The superinsulated house concept is generally acknowledged to have been formulated at the Small Homes Council of the University of Illinois, and introduced with the publication of its Spring 1976 Council Note C2.3 (Schick and Jones 1976), "Illinois Lo-Cal House." The eight-page brochure illustrating Technical Note 14, which describes Lo-Cal designs and thermal analyses in greater detail, was subsequently published in 1979 (Schick et al. 1979), when a package of construction details also was made available.

Among other publications describing superinsulated construction, perhaps the most specific is *Energy Efficient Housing: A Prairie Approach,* (Energy Research Development Group 1980), prepared by the same group at the University of Saskatchewan that was responsible in part for the well-known Saskatchewan Energy Conservation House. Other sources include *The Well- Tempered House: Energy Efficient Buildings for Cold Climates* (Argue 1980), and *How to Build a Superinsulated House* (Project 2020 1978). A number of conference papers have also suggested details for superinsulated construction; among these are papers by Mead (1980) and Hughes (1981).

Envelope House

Envelope house is one house within another: a twin stud north wall is built with a continuous air space that is carried through the attic and crawl space, closing the system (or convective loop) in a sunspace on the south side. Air heated in the sunspace flows up into the attic, while air falls through the cavity in the north wall because of heat losses through the exterior skin. This rising and falling action drives air forward around the inner house during the daytime. Excess heat in the airstream is supposed to be stored in the earth of the crawl space for release at night, whereupon the loop is supposed to reverse its direction of flow. The overall effect, its proponents claim, is to bathe the inner house in a tempered climate of sun-heated air, thereby reducing the temperature differential and the rate of heat loss between inside and outside (i.e., the air envelope). Too much has been said about the envelope concept – and remains uncertain – to be summarized here. However, some points of contention that merit consideration and further research are enumerated below.

1. The location of heat storage in the house is not well documented. Several writers argue that heat storage in the crawl space is insignificant, while others believe that the geosolar aspect of the design is what accounts for its successful performance. Inasmuch as heat conduction theory can be used to demonstrate the lack of participation of the crawl space in heat storage (Labs 1981), it is likely that, if coupling with the ground is important at all, it is because the ground serves as a source of moisture to humidify the house and its construction materials. Large increases in moisture content may significantly increase the integral thermal storage capacity of the building shell, thereby providing the temperature stability that envelope house advocates claim as so remarkable. Such findings would have important implications, for the conceptual design of the house itself.

2. The similarities between the envelope concept and a passive solar house with sunspace and fan-charged rock bed beg for comparison. Because the envelope necessarily wastes heat on the north side in order to propel the loop, one would expect that a more direct and better insulated coupling between the sunspace and rock bed would be more energy efficient. The question may be asked whether a fan in such a hybrid system uses more energy than the envelope wastes. A simplified computer analysis (Kohler and Lewis 1980) suggests that “the envelope house would use almost three times the auxiliary energy of an otherwise identical house where the envelope is replaced by a fan-forced rock bed.

3. Integrating windows into the envelope so that the airstream of the loop passes between panes of glazing largely obviates the need for insulating shades and shutters, and the air-warmed windows as well as the nature of the twin wall construction eliminates major causes of indoor drafts. This is a compelling aspect of the envelope concept, especially for a number of building types and rental properties in which the occupant may have little direct incentive to make use of operable insulating devices.

Arguments for and against the envelope house are clearly outlined by Shurcliff (1980), and construction particulars are described in *The Double Shell Solar House* (Booth 1980) and a number of related books. Good performance analyses are still lacking, but a collection of a dozen technical papers in the proceedings of the 5th National Passive Solar Conference is highly recommended reading (Hayes and Snyder 1980).

Summary: Solar Design Process

From the previous discussions, it should be evident that a wide range of energy efficient building options suitable to light-frame construction are available to the designer, beginning with the choice between solar and energy conservation approaches. While regional climatic conditions must necessarily influence this first decision, the spectrum of choices remaining thereafter is still so broad that the designer still can respond freely to programmatic, aesthetic, and site-specific issues. The entire range of solar design alternatives and products has yet to be discussed in a single work, as advances in technology and the availability of new products continues to move forward. As more manufactured solar components enter the marketplace, more of the 36 hypothetical systems suggested in table 8-2 will be seen in practice. At this time, however, design information is limited to the most common solar system types.

Popularly used solar design data are generalizations expressed as rules of thumb. The first codification of these for standard passive solar systems are contained in Mazria's *The Passive Solar Energy Book* (1979), which remains useful to the practitioner as well as serving as an excellent introduction to passive solar design in general. The current primary technical reference for the thermal aspects of solar design is *The Passive Solar Design Handbook, Volume II: Passive Solar Design Analysis* prepared by Los Alamos Scientific Laboratory (Balcomb 1980). This book presents several levels of analysis methods, from rules of thumb to detailed engineering calculations. The number of prototypical solar systems described in the book has been expanded in subsequent technical papers on greenhouse design and low-mass construction (Jones and McFarland 1980, Wray 1981), which are expected to be included in future editions of the handbook. Also to be included in future editions is a discussion on optimizing heat conservation practices in passive solar design; a summary of this discussion is presented by Balcomb (1981).

Two other important handbooks on solar design emphasize details of solar construction. *The California Passive Solar Design Handbook* (Niles and Haggard 1980) provides technical thermal design data based on computer simulations of different solar systems in 14 California locations and architectural details for the execution of a wide variety of designs. *The Passive Solar Construction Handbook* (Winter Associates 1981), as its name implies, is primarily a manual of typical solar design details, although it also contains enough fundamental thermal design information to be complete in itself as a guide for preliminary sizing of solar systems. Both handbooks make important additions to the designer's library.

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Chapter 9

Moisture Movement and Management

Introduction

New designs of light-frame structures incorporate innovative measures to conserve energy, labor, and materials. This trend is expected to continue and has cast some doubt on the adequacy of existing standards and technologies for moisture control, which were mostly developed in the 1930's and 1940's. In this chapter, the reasons and need for moisture control are discussed, current standards and technologies reviewed, and the analytical methods described that are available to evaluate performance of innovative designs. Although other moisture problems are briefly mentioned, the primary focus is on prevention and effects of condensation in walls, ceilings, roofs, and attics.

Background

Objectives of moisture control include health and comfort of occupants, the long life and minimum maintenance of materials, and, more recently, efficient thermal performance of the building. A few of these aims are dictated by codes or standards. For all, certain criteria must be established for operating conditions in the living spaces of the building and for controlling conditions in the building components and materials.

Human Comfort

The human comfort range for humidity is directly related to temperature. Generally, a combination that allows moisture to evaporate from the body at a rate that maintains ideal body temperature is the optimal condition (ASHRAE 1977). Physical activity generates heat and thus requires a faster evaporation rate to maintain comfortable body temperature. Clothing restricts the escape of heat and moisture, and so has a major effect on the comfort range. The human body can make limited adjustments with long-term exposure to certain conditions, but is less able to adjust quickly to sudden or frequent changes. Very low humidity during the heating season may result in dry skin and respiratory irritations. This effect is usually not perceptible at indoor temperatures when RH is 30 percent or higher.

Protection of Interior Materials

The primary materials affected by moisture changes inside the house are wood and wood products. Dry conditions cause shrinkage with consequent loosening of joints or opening of cracks. Humid conditions cause buckling, particularly in thin panel products. If indoor air has a dewpoint temperature higher than wall or window surface temperature, moisture condenses, resulting in stains on the window sash as well as mildew growth on walls, ceilings, or other cold surfaces. Dimensional changes in either direction cause failure of some paints and finishes, and cycling between wet and dry may loosen nails.

To prevent these problems, moisture content (MC) of wood must be kept reasonably constant through seasonal changes. In much of the United States, interior wood is at 8 to 9 percent MC (FPL 1974). Indoor winter conditions of 70 °F and 30 to 40 percent RH should result in an equilibrium moisture content (EMC) of 7 to 8 percent, so the slight difference should not cause problems. Essentially the same MC is found in the Southeast in buildings that are air-conditioned. In the dry Southwest, MC may be as low as 6 percent, but the 7 to 8 percent target for the heating season is still practical. A good target is to limit variation to 3 percent MC in order to prevent damage to interior wood trim, wood furniture, and other wood products. Winter indoor conditions of 30 to 40 percent RH generally accomplish this.

Durability of Concealed and Exterior Materials

Cold weather condensation has frequently caused decay in structural wood components of roofs and floors. Although cases of decay in walls are rare, problems of paint failures and stains on siding as well as distortion of siding do occur. Dimensional changes in thin panel products cause buckling that affects the durability of roofing or siding.

Specific conditions are necessary for growth of wood decay fungi. Temperature must be between 40 °F and 100 °F, and wood must be saturated. This means the wood must be at 30 percent MC or higher (FPL 1974). However, when readings of 20 percent MC are made, some parts of the member are often saturated; so 20 percent is frequently recognized as a danger point. Free water is necessary to develop saturation conditions in wood, so condensation that remains for a long period of time on the surface of wood is required for decay.

The design target for preventing decay is to limit the presence of condensation: (1) to periods of extreme cold when temperatures at the location of the water are below 40 °F, or (2) to daily cycling of condensation and evaporation in locations such as attics where there is a daily cycling of temperature.

To prevent problems of distortion in siding or sheathing, moisture changes in these materials should be limited to 5 percent MC. This limit should also prevent dimensional change in wood siding that might cause paint failures or splitting of the siding.

Moisture storage capacity of wall materials has been recognized as an important variable in moisture control (Joy 1951). When moisture storage is available the effects of condensation may be considerably alleviated. Wood sheathing and siding can absorb condensation moisture for many hours before the MC is raised more than the 5 percent limit mentioned above.

Codes and Standards

Codes and standards that address moisture control at all are prescriptive rather than performance oriented. HUD Minimum Property Standards (1973) have both vapor retarder and ventilation requirements. However, the major model codes state no vapor retarder requirements but do allow a reduction of ventilation in some cases where vapor retarders are used. Model codes include: Basic Building Code (BOCA 1981), Southern Standard Building Code (SBCC 1982), and Uniform Building Code (ICBO 1985). None of the codes or standards include any requirement for controlling indoor humidity, but that appears to be the most critical element for limiting moisture in structural spaces. Air leakage into structural spaces is the major source of moisture, and that also is not addressed. A brief statement of MC requirements in major codes and standards follows.

Vapor Retarders

HUD-Minimum Property Standards 607-2.4 – a vapor retarder with a perm rating[1] not exceeding 1 is required on the warm side of all insulated walls. For ceilings under a ventilated roof or attic space, no vapor retarder is required when 1/150 of the ceiling area is provided for ventilation, or when 50 percent of the otherwise required 1/300 of ceiling area is at least 3 feet above the eaves and the remaining ventilation required is at the eaves. For all other conditions a vapor retarder with a perm not exceeding 1 is required on the warm side of the ceiling. Roof decks shall have a vapor retarder with a perm rating of not more than one-half near the warm face.

[1]A perm, the unit of permeance, is defined as 1 grain/hour-square-foot-inch of mercury vapor pressure difference.

Attic Ventilation

(1) Basic Building Code 507.2 – not less than two opposite windows, louvers, or vents with a total clear area of opening not less than one-third of 1 percent of the horizontally projected roof area.

(2) Southern Standard Building Code 1707.8 – furnish cross ventilation for gable and hip roofs. Free ventilating area shall be not less than 1/150 of the ceiling area. Area may be reduced to 1/300 where a vapor retarder with a perm not exceeding 1 is placed on the warm side of the ceiling, or at least 50 percent of the vent area is in the upper portion of the space with the balance at cave or cornice at least 3 feet lower.

(3) Uniform Building Code 3205 (c) – cross ventilate each space. Net free area shall be not less than 1/150 of the area ventilated, except where 50 percent of the vent area is in the upper portion of the space and the remaining vents are in cave or cornice located at least 3 feet lower.

(4) HUD-Minimum Property Standards –provide a net free area 1/150 of the area ventilated, except 1/300 may be used when (a) a vapor retarder with a perm less than 1 is used in the ceiling, or (b) at least 50 percent of the required area is provided with fixed louvers in the upper portion of the space at least 3 feet above an cave containing the remaining required ventilation. As an alternative, mechanical ventilation must provide 10 air changes per hour or 0.9 $ft^3/min/ft^2$ of attic floor area, plus 15 percent for dark roofs. Provide an air intake of 1 ft^2 of free opening per 300 ft^3/min of fan capacity.

Crawl Space Ventilation

(1) Basic Building Code 709.2.1 – the crawl space shall have screened openings not less than 1 ft^2 for each 150 square feet of foundation area. Opening may be reduced to 10 percent of the above if an approved vapor retarder is installed over the ground surface.

(2) Southern Standard Building Code 1302.5.3 – ventilate by approved mechanical means or by openings in foundation walls. Openings shall have a net area of not less than 1 square foot for each 150 square feet of crawl space, and shall be covered with corrosion-resistant wire mesh one-fourth to one-half inch in any dimension. Openings shall be not less than 2 ft^2 for each 100 linear feet of wall, plus 1/3 ft^2 for each 100 ft^2 of crawl space. Where an approved vapor retarder is placed over the ground, the opening area may be reduced to 10 percent of that required above.

(3) Uniform Building Code 2516(c)6 –ventilate by approved mechanical means or by at least two vents located at corners on approximately opposite sides. Net area shall be 1 ft^2 for each 150 square feet of underfloor area. All vents shall be covered with corrosion-resistant wire mesh one-fourth inch in any direction. Required net area to be reduced to 10 percent of the above if the ground is covered with an approved vapor retarder.

(4) HUD-Minimum Property Standards 403-3 – net free area shall be at least 1/150 of the area ventilated and include cross ventilation.

In order to avoid moisture damage, several general strategies may be followed. Indoor moisture levels can be controlled by dehumidification or ventilation; vapor entry into structural components can be reduced by applying vapor retarders, or excess moisture can be removed by providing for venting. All three control measures can be taken simultaneously. A discussion of these strategies follows, preceded by a general review of moisture transfer mechanisms.

Moisture Transfer Mechanisms

Moisture in buildings occurs as water vapor, liquid water, or, in some cases in colder climates, as ice. Liquid water can move from one location to another by gravity or capillary action. Most water vapor transfer takes place by diffusion or convection or by a combination of these mechanisms.

Diffusion always takes place in one direction: vapor diffuses from a location with a high vapor density to one with a lower density. Fick's law states that the rate of vapor transfer is proportional to the difference in vapor density. However, when describing vapor transport through building components, Fick's law is usually expressed in terms of vapor pressures instead of densities.

Convection takes place when moisture is carried with an airflow. The direction of the flow does not depend on vapor density differentials and may be opposite to the direction of the diffusion flow. The amount of vapor carried depends on the rate of flow of air and the moisture content of the air. The air pressure differentials, which drive the air currents, may be caused by wind, fans, stoves and furnaces, and the stack effect.

Fans not only produce air currents within a building but also create pressure differentials across outside walls, doors, and windows, causing exfiltration of indoor air or infiltration of outside air, depending on the location in the house. Combustion air requirements for gas, oil, and wood stoves and furnaces lower indoor air pressure, causing infiltration of outside air.

The stack effect is caused by the difference between indoor and outdoor temperatures. The lower density of the warm inside air creates air infiltration into the lower part of the building and exfiltration from the upper part. In buildings with an attic, the stack effect forces indoor air into the attic and outdoor air infiltrates through walls, doors, and windows. A chimney also drastically changes air pressures and flows by lowering air pressures throughout the building.

Wind pressures are an additional source of air infiltration and exfihration. Wind pressure differentials across walls and roof depend on windspeed, wind direction, terrain, and shape of the building (ASTM 1980, Blomsterberg et al. 1979, Gids et al. 1979). Outdoor air pressures are generally greater than indoor pressures at the windward side and lower than indoor pressures elsewhere. This is likely to create infiltration at the windward side and exfiltration at all other sides of the house.

The actual airflows depend on the combined pressure differentials caused by heating equipment, wind, and stack effect and are extremely difficult to predict. The actual combined effect certainly is smaller than the sum of the separate effects. The air change rate can be measured with the tracer gas method, but such measurements do not show the magnitude or direction of air and moisture flow through individual building components.

Interior Humidity Control

Houses have traditionally required mechanical humidification during cold weather because moisture created in the house leaves through air leakage and the cold entering air is quite dry. However, the large reduction of air leakage in energy efficient houses has in most cases eliminated the need for humidification, and moisture from household tasks alone results in high-humidity levels (TenWolde and Suleski 1984). Relative humidity of 60 to 70 percent is being reported in some houses even during subzero weather. This results in condensation running off the windows and staining the sash, as well as mildew growth on the walls behind furniture and in corners or other cold surfaces. These high humidities also contribute to concealed condensation in walls, attics, or other structural components. Current good practices in vapor retarder application and ventilation generally prevent condensation damage where indoor relative humidities are not as well known.

Maintenance of reasonably low levels of interior humidity is one of the most effective ways of preventing moisture problems caused by cold weather condensation

(Anderson and Sherwood 1974, TenWolde and Suleski 1984). Where mechanical humidification is used, this control is simply a matter of setting the humidifier no higher than 40 percent during cold weather. Where internal gains are too high, moisture can be removed by exhaust fans at major sources such as bathrooms, laundries, and kitchens. Forced ventilation of the whole house or part of the house can be accomplished by air-to-air heat exchangers with limited heat losses. The economic viability of this technology in the United States is not yet certain. Moreover, in colder climates the efficiency of the heat exchanger is limited by the occurrence of frost in the exhaust. For instance, with an indoor temperature of 70 °F, 40 percent RH, and 20 °"F outdoor temperature, the efficiency should not be over 50 percent in order to avoid condensation in the exhaust and subsequent frost formation. Development is needed of heat exchangers specially designed to solve this problem. However, in many areas of the country, heat exchangers offer good prospects for humidity, odor, and pollutant control.

Vapor Retarders

Attempts at insulating buildings in the 1930's revealed the potential for condensation on cold-side materials. Reduction in heat loss resulted in lowering the temperature of exterior materials below the dewpoint temperature of the inside air. The solution appeared to be to provide a barrier that would prevent indoor moisture from entering walls or ceiling, and so the term "vapor barrier" was created. Recently the term "vapor retarder" was adopted to prevent misconceptions because vapor barriers are often thought to stop all moisture movement even though they only reduce the rate of movement.

Vapor retarders are rated for permeance. An accepted unit of permeance is a perm, or 1 grain per square foot per hour per inch of mercury difference in vapor pressure between the two sides. An early definition of "vapor barrier" was any material with a perm rating of less than 1. Although this definition still persists, current building materials and methods often require much lower perm ratings for vapor retarders. Four-roil polyethylene film, which is commonly used, has a perm rating of 0.08.

The integrity of vapor retarders is critical to their performance. Punctures, tears, etc., negate their effectiveness in preventing diffusion of water vapor (Sherwood 1983). Vapor retarders are also effective draft stops and may prevent movement of water vapor carried by air as well as movement by diffusion. It should be recognized that in buildings much of the moisture transfer into and through structural spaces is by air movement. Air leaks at electrical outlets and ceiling fixtures, and around windows, doors, flues, and plumbing stacks, allow moisture completely to bypass the vapor retarder.

Vapor retarders may be in the form of structural materials, flexible sheets, or coatings. The most common application in new construction is flexible sheets. Coatings, such as vapor retarder paint, are often more convenient for retrofit because they can be applied to exposed surfaces (Sherwood 1978).

Ventilation

Even before the extensive use of insulation, the necessity for ventilation was recognized. Crawl spaces under floors have always required ventilation to carry away moisture from the soil. Ceiling insulation has resulted in low attic temperatures with the consequent potential for condensation if moisture is not vented to the outdoors. Vapor retarders have a major influence on the amount of ventilation required. HUD Minimum Property Standards permit crawl space ventilation to be reduced to one-tenth when a soil cover vapor retarder is used, and attic ventilation can be reduced to one-half when a ceiling vapor retarder is used.

Ventilation is best accomplished in attics by placing outlet vents near the peak and inlet vents at eaves, so the stack effect keeps air moving continuously. Wherever ventilation is used, good distribution of air movement over the entire area is important.

Although many methods and computer design tools are available to help in the design of energy efficient buildings, only a few methods exist for analyzing water vapor components. Even the simplest moisture analysis methods are relatively complicated and time consuming because of the complex nature of moisture transfer with associated phase changes.

Available design methods either address the problem of proper wall design or the problem of adequate design of attic ventilation. The wall design methods are primarily graphical methods and require no complicated computations by the user. Applying the methods, however, can be very time consuming. Moreover, they are entirely based on diffusion theory, ignoring convection effects. Two attic simulation models are in existence that require a large computer. Both models simulate moisture transfer by convection and diffusion. All methods provide a way to predict the presence or absence of condensation in the wall or on the roof sheathing under certain static weather and indoor conditions. This is generally accomplished by calculating water vapor pressures and determining if saturation conditions exist.

Moisture Profile Method

The most commonly used design method is the moisture profile or dewpoint method which is described in the ASHRAE Handbook (ASHRAE 1977). The method is based entirely on diffusion theory, thus ignoring any convection effects. Assuming steady-state conditions, the temperatures can be calculated at points within a wall or ceiling from indoor and outdoor temperatures and the thermal resistances (R-values) of each layer of material. Each temperature corresponds with a saturation vapor pressure at that point. Similarly, actual vapor pressures at those points can be computed from indoor and outdoor vapor pressures and the vapor flow resistances (Rep-values[2]). If the calculated vapor pressure is above the saturation vapor pressure, condensation occurs. The most likely locations for condensation in a wall are the inside (warm) surface of the sheathing (Sherwood 1983) and the inside surface of the siding. It is not always clear which is the actual location. Multiple locations are also possible. The moisture profile method requires the user to choose a location for condensation, usually at the interface between two layers of material. Here the vapor pressure per definition must equal the saturation vapor pressure, which changes vapor pressure differentials across the rest of the wall, and consequently the vapor pressure profile should be recalculated to check if condensation is possible at any other location. If other possible locations are found, the process is repeated. This sometimes leads to elimination of the first location (see following example). The process is repeated until the user has identified all locations for condensation which can exist simultaneously. The rate of moisture accumulation may then be calculated from the difference between vapor flow to and from the condensing surface.

A numerical version of the moisture profile method has been developed for the TI-59 programmable calculator (Lewis et al. 1980). The program, named WETWALL, is easy to use and substantially reduces the analysis time requirements. However, the program does not incorporate the iterative calculation method described above, and therefore does not always correctly identify the location for condensation. Consequently, calculated results for moisture accumulation may be too low. WETWALL is therefore only recommended if the user is interested in the occurrence of condensation, and neither location nor rate of accumulation is important to the user.

Example: Calculations using the moisture profile method are for the wall design shown in table 9–1 and 20 °F outdoor temperature, 50 percent RH (vapor pressure = 0.0514 in of mercury), and 70 °F indoor temperature, 40 percent RH (vapor pressure = 0.2961 in of mercury). The wall has no vapor retarder other than the layer of paint on the gypsum board. The saturation vapor pressure profile corresponding with the temperatures (fig. 9-1) is shown in figure 9-2 together with the vapor pressures calculated from Rep values and indoor and outdoor vapor pressures. For instance, the vapor pressure at the inside of the sheathing is:

$$P_{vapor} = 0.2961 - \frac{0 + 1 + 0.03}{2.26} (0.2961 - 0.514)$$
$$= 0.1846 \text{ (in of Hg)}$$

The shaded area in figure 9-2 marks the region where calculated vapor pressures are above the saturation

[2]A Rep, the unit of vapor flow resistance, is defined as 1 hour-square-foot-inch of mercury vapor pressure difference/grain.

[3]Values for saturation vapor pressures can be found in psychometric tables or diagrams.

level. If we assume that condensation occurs at the surface nearest to the intersection of saturation and vapor pressure profiles, the vapor pressure at the inside surface of the sheathing must equal the saturation pressure. Vapor pressures in the rest of the wall must be recalculated, and the results are shown in figure 9-3. The shaded area indicates the existence of saturation conditions throughout the sheathing and siding.

If we assume condensation conditions at the inside surface of the siding, vapor pressures are as shown in figure 9-4. Vapor pressure at the insulation-sheathing interface is now depressed well below the saturation level. In other words; existence of condensation conditions at the siding precludes the occurrence of condensation at the sheathing; thus, in this example, condensation cannot occur simultaneously at both locations.

If we assume condensation at the exterior paint layer, recalculation of vapor pressures shows that condensation conditions persist at the inside surface of the siding; i.e., simultaneous condensation is occurring at both points and throughout the siding.

With the final vapor pressure profile the rate of moisture accumulation may be determined by calculating the difference in vapor flow to and from each condensing surface. The approximate rate of accumulation at the inside of the siding is:

$$m_c = \frac{0.2961 - 0.1209}{1.06} - \frac{0.1209 - 0.1057}{0.2}$$

$$= 0.0893 \text{ grain/hr-ft}^2$$

In the rest of the siding accumulation is approximately:

$$m_c = \frac{0.1209 - 0.1057}{0.2} - \frac{0.1057 - 0.514}{1.0}$$

$$= 0.217 \text{ grain/hr-ft}^2$$

The total accumulation rate is 0.1110 grain/hr-ft^2. Actually, a little less is accumulating on the surface and a little more in the interior of the siding because the vapor pressure profile is following the nonlinear curve of the saturation pressure profile within the siding. However, total accumulation is correct.

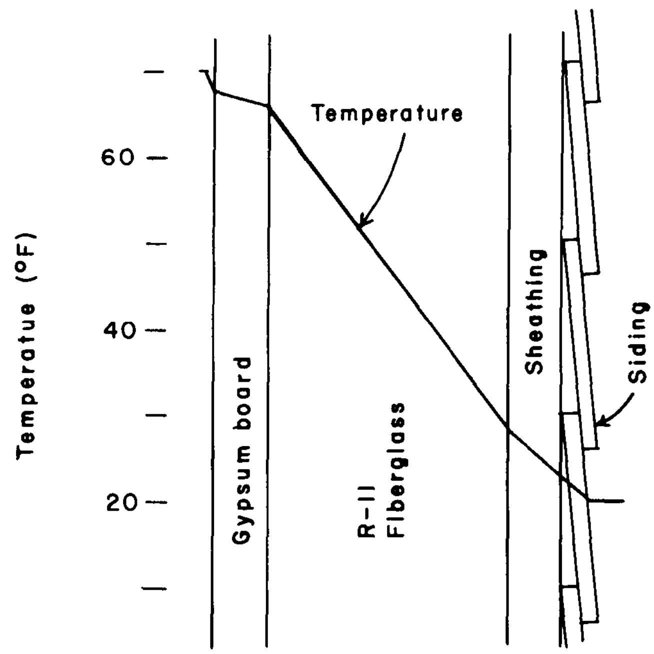

Figure 9-1 – Example of wall temperature profile. (ML88 5338)

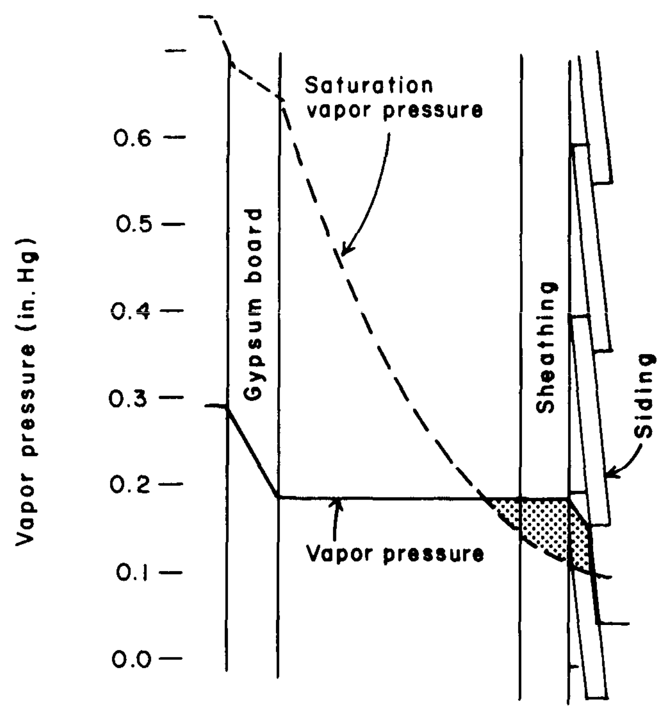

Figure 9-2 – Example of wall vapor pressure profile, without condensation. Indoor conditions: 70 °F, 40 percent RH. Outdoor conditions: 20 °F, 50 percent RH. (ML88 5339)

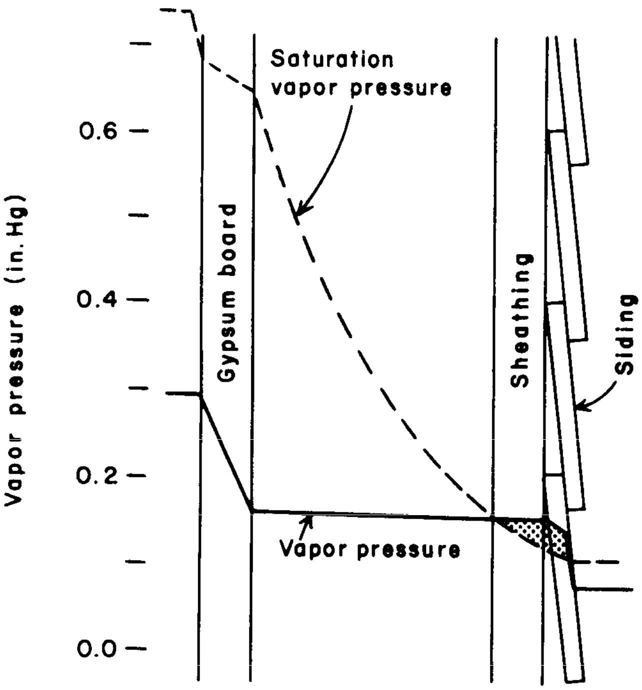

Figure 9-3 – Example of wall vapor pressure profile, assuming condensation at inside surface of sheathing. Indoor conditions: 70 °F, 40 percent RH. Outdoor conditions: 20 °F, 50 percent RH. (ML88 5340)

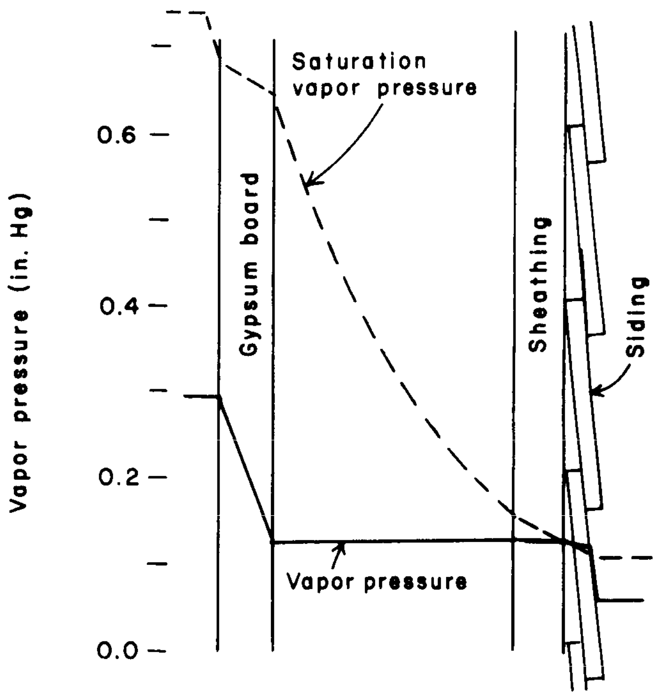

Figure 9-4 –Example of wall vapor pressure profile, assuming condensation in siding. Indoor conditions: 70 °F, 40 percent RH. Outdoor conditions: 20 °F, 50 percent RH. (ML88 5341)

Kieper Method

Several years ago an alternative moisture analysis method was introduced in the United States.[4] Developed in Germany and known as the Kieper method, it has some clear advantages over the traditional moisture profile method, yet has not found widespread acceptance. It allows rapid evaluation of different wall designs under identical environmental conditions. When several transparent overlays are used, response to different environmental conditions also may be quickly determined. The method provides a mechanism for locating the most likely spot for condensation in the wall directly but is not suited for locating more than one such spot. The method is entirely based on diffusion theory, ignoring any air convection effects. At the time of writing, Kieper diagrams or transparent overlays are not commercially available in this country.

[4]The method was presented to CIB W40 working group in a 1976 meeting in Washington, DC, as a draft document titled “A new diagram to evaluate the performance of building construction with a view to water vapor diffusion,” by G. Kieper, W. Caemmerer, and A. Wagner.

A numerical version of the Kieper method is relatively easy to program on computers or programmable calculators and has been successfully implemented by the authors on a TI-59 calculator (TenWolde 1983).

Summary of the Kieper method – First, the position of each layer of material is expressed in terms of thermal (x) and vapor flow (y) coordinates. The x-coordinate of a point in the wall is the R-value of all the materials between that point and the inside, divided by the total R-value of the wall. Similarly, the y-coordinate is defined as a fraction of total Rep-value. This definition of x and y makes temperature a simple linear function of x and vapor pressure a linear function of y. It also allows the definition of a condensation boundary curve in the x,y (Kieper) diagram which is independent of the design of the wall and only depends on indoor and outdoor conditions. Below this curve, condensation conditions may occur. Each wall design can be represented by a curve in the diagram. If any section of this curve falls below the boundary curve for condensation, condensation occurs. The location is assumed to be the point of maximum potential moisture accumulation, which can be easily determined with the help of several auxiliary curves which represent different assumed moisture accumulation rates.

Example: The environmental conditions used in the first example (70 °F, 40 pet RH indoor; 20 °F, 50 pet RH outdoor) translate into the condensation boundary curve and auxiliary curves shown in figure 9-5. The wall design described in table 9-1 again serves as an example. The x and y coordinates can be calculated from the data in table 9-1 and are shown in table 9-2.

The wall curve is plotted in figure 9-5. Using the auxiliary curves, it is clear that the point of maximum accumulation potential is the interface between sheathing and siding (x = 0.93, y = 0.47) with the paint layer (x = 0.99, y = 0.56) as a close second. The diagram does not tell us if saturation conditions occur simultaneously at both points. Assuming condensation at the surface of the siding only, the rate of moisture accumulation may be easily estimated by using the value of the closest auxiliary curve (m_cR_v= 0.2):

$$m_c = 0.2/2.26 = 0.09 \text{ grain/hr-ft}^2$$

This agrees with the previously calculated total rate, 0.111 grain/hr-ft^2.

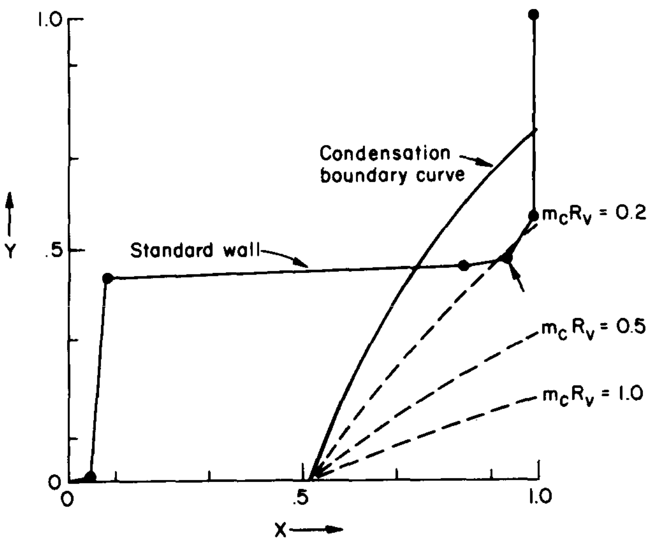

Figure 9-5 – Kieper diagram with curve for example of wall design. Indoor conditions: 70 °F, 40 percent RH. Outdoor conditions: 20 °F, 50 percent RH. (ML88 0020)

Deficiencies of Wall Design Methods

Convection Effects

Several attempts have been made to account for convection effects, either by incorporating convection in existing diffusion methods (TenWolde 1983), or by calculating the effects independently (Burch et al. 1979, Stewart 1979). However, each of these attempts violated one or more of the following principles:

1. The magnitude and direction of moisture flow by convection, unlike diffusion, is independent of vapor pressure gradients.

Table 9-1- Thermal resistance and vapor flow resistance of insulated frame wall, example design

Wall design	R-value	Rep-value
	(hr·ft²·°F/Btu)	(hr·ft²·in Hg/grain)
Inside surface (still air)	0.68	0
Gypsum board, 0.5 in, primed and painted	0.45	[1]1
3.5-in R-11 blanket insulation	11	0.03
Sheathing, 0.5 in, asphalt impregnated insulating board	1.32	0.03
Wood siding	0.81	0.2
Exterior paint, 3 coats	0	[1]1
Outside surface (15 mi/hr wind)	0.17	0
Total	14.43	2.26

[1]Estimated approximate value.

Table 9-2- Example wall; x, y coordinates for Kieper diagram

Location of interface	x coordinate	y coordinate
Indoor air—surface air film	0	0
Surface air film—gypsum board	0.05	0
Gypsum board—insulation	0.08	0.44
Insulation—sheathing	0.84	0.46
Sheathing—siding	0.93	0.47
Siding—paint layer	0.99	0.56
Paint layer—surface air film	0.99	1.0
Surface air film—outdoor air	1.0	1.0

2. Diffusion and convection effects are not independent because moisture convection changes the vapor pressure gradient in the wall.

3. Convection may significantly affect temperatures in the wall, changing the saturation vapor pressure profile.

Latent Heat Effects

When condensation occurs, heat is released at the rate of 0.15 Btu per grain of vapor condensing. This raises the temperature, consequently slowing down the rate of moisture accumulation. The net effect depends on the rate of moisture accumulation, the location in the wall, and the thermal resistance of the wall. A method incorporating this effect is being developed at the Forest Products Laboratory. Preliminary results show that the effect on moisture accumulation is generally small.

Perm Ratings

All methods rely heavily on values for vapor flow resistance of building materials. Data are only available for selected materials, and a perm rating is often given as a range. Materials generally were tested under a limited number of conditions and actual performance may therefore differ substantially from the listed values, especially when vapor pressures approach saturation levels. Perm ratings are discussed in greater detail elsewhere in this paper.

Transient Conditions

Current methods assume steady-state conditions. In reality, however, temperatures, relative humidities, and air pressures are perpetually changing. The resulting evaporation and condensation cycles have been demonstrated greatly to affect the apparent transient thermal behavior (Bomberg and Shirtliffe 1978, Joy 1957, Solvason 1956). Moisture redistribution resulting from changing temperature conditions has also been observed in wood-frame walls (Duff 1971). To model transient conditions one would have to take the effect of this redistribution into account.

NBS Attic Model

Current guidelines on minimum attic ventilation as given in the ASHRAE Handbook of Fundamentals (ASHRAE 1977) and the HUD Minimum Property Standards (1973) were developed 30 years ago. The recent increase in ceiling insulation requirements has raised the question of the adequacy of these standards. To find the answer, Burch and Luna (1980) developed a computer model simulating condensation phenomena in attics. The program is designed to calculate the minimum ventilation rate required to prevent condensation on the underside of the roof sheathing. The program solves a heat and moisture balance for the attic under static conditions. The effects of heat conduction, vapor diffusion, and air convection are included in the balances. Temperatures are calculated at three locations in the attic. Radiant heat exchange between the underside of the roof and the attic floor, as well as solar gains and radiant heat loss to the sky, are accounted for. The air in the attic is assumed to be perfectly mixed.

The critical ventilation rate is found by setting the water vapor pressure of the attic air equal to saturation pressure at the temperature of the underside of the roof and solving the moisture balance for the attic. The model is not capable of predicting moisture accumulation rates. In the current version of the program, outdoor humidity is assumed to be 75 percent, but other values could be used with only a minor adaptation of the program.

Princeton Attic Model

A second attic ventilation model is being developed at Princeton University (Ford 1980). This model is based on the NBS model but incorporates the following additional features:

a. Separate thermal calculations for the end wall and soffit regions, and

b. Influence of wind on the temperature of the exterior surface of the roof.

This model, like the NBS model, solves the balance equations for saturation conditions on the inside surface of the roof sheathing. The model does not calculate moisture accumulation rates, nor does it consider the effect of wind on attic ventilation. Preliminary results seem to differ substantially from results obtained with the NBS model.

Design Theory Summary

There are four moisture design methods available, two for the design of walls and two to determine proper ventilation rates for attics. The wall design methods have a limited usefulness because they are exclusively based on diffusion theory. All methods assume static conditions. The attic models do not calculate moisture accumulation but determine the minimum ventilation rates at which no condensation occurs. The Princeton attic model is still being developed.

Input Data

Climatic

The primary input data for all design methods are average indoor and outdoor temperature and RH. The attic models require additional data for average solar radiation and cloud cover, and the Princeton attic model also needs input data for average windspeed. Climatic data for many locations in the United States may be found in the National Atlas (U.S. Department of the Interior 1970).

Perm Rating

Input data for thermal and vapor flow resistances of the materials in the walls or roofs and ceilings are required for applying design procedures. Reasonably reliable data are available for thermal resistance, but vapor flow resistance data do not exist or are inexact for many structural materials or constructions. An extensive discussion on the subject of perm ratings can be found in the ASHRAE Handbook of Fundamentals (ASHRAE 1977), chapter 20.

Vapor flow resistance or the inverse, permeance, is a function of temperature and RH. A perm, the unit of permeance, is defined as 1 grain/hour-square-foot-inch of mercury vapor pressure difference. The corresponding unit of permeability is the perm-inch, the permeance of 1-inch thickness. Average values determined by the wet- or dry-cup method are most commonly used (ASTM 1980, ASHRAE 1977). When the dry-cup method is employed, the specimen is sealed over the top of a cup containing a desiccant and placed in a controlled atmosphere (usually 50 pct RH). The cup is weighed periodically to determine the rate of vapor transfer. With the wet-cup method the cup contains water instead of a desiccant. Ambient RH and temperature during the test should always be stated with the test results. The dry-cup method is used when the material is expected to be in an environment with low RH. For high RH the wet-cup method is used. Generally, the wet-cup method results in higher perm values, especially for hydroscopic materials such as wood (ASHRAE 1977, Edenholm 1945). Of course, actual performance of any material layer in a building component may very easily depart from listed perm values resulting from variations in material properties and actual RH's and temperatures that are different from those maintained during the perm tests (Joy 1951).

Air Leakage

Air leakage is not considered in the currently available wall design methods, but air leakage to the attic is included in the attic simulation models.

Actual air exchange rates may be measured directly by the tracer gas method. A tracer gas (e.g. SF_6) is released and the concentration measured over a period of time. The rate of decay in concentration is a measure of the air change rate.

An alternative measurement, fan pressurization or depressurization, does not yield air change rates but rather a measure of construction air tightness. Air pressure differentials are artificially created across walls or other components and the airflow is measured. These pressure differentials are far greater than those actually experienced under natural conditions. For this among many reasons, it is difficult to correlate pressurization and tracer gas results (Hunt 1980). A recent computer model that calculates infiltration from pressurization measurements, windspeed, and indoor-outdoor temperatures has been shown to predict actual infiltration with an uncertainty of 30 percent (Blomsterberg and Harrje 1979).

Other Variables

The attic simulation models require a number of data on the dimensions of the attic (surface area of the ceiling, roof, soffit regions, and attic end walls, and the volume of the attic). These values are needed to determine radiant heat and heat conduction losses and gains in the attic.

Field Performance

The critical test of any design method is field performance. Although design for moisture control has been more empirical than quantitative, the concepts and theories discussed above have had a major influence. General observations and field studies have revealed some critical variables, and specific surveys have indicated the extent of moisture damage.

One of the most critical variables for prevention of moisture problems is indoor RH (TenWolde and Suleski 1984). Where major cold weather condensation occurs, indoor RH is frequently high. Problems of mildew indoors and paint failures outdoors often occur only on outside walls of bathrooms or kitchens where indoor humidities are highest.

The amount of concrete used in construction also has a major effect on indoor moisture the first year after a building is constructed. Large quantities of water are used in concrete foundation walls and slabs. Excess water is released to the air as the concrete cures during the first few months. If the building is completed in the fall, humidity control may be a particular problem the first winter. The building should be frequently opened for ventilation until humidity levels are reduced. The problem is often eliminated during subsequent seasons.

Air leakage into structural spaces is the major mode of moisture movement into concealed spaces. It is critical to limit air leaks at all joints, around stacks and floors, and through openings such as electrical outlets.

Penetrations in the vapor retarder are also critical variables for moisture control (Sherwood 1983). Punctures, tears, and other discontinuities allow moisture passage by diffusion and in some cases may allow air leakage. Vapor retarders should be as complete as possible.

Moisture storage capacity is an important variable in reducing the effects of moisture accumulation. Recognizing this effect, Joy (1951) proposed to make the permeance requirement for vapor retarders directly dependent on the moisture storage capacity.

Outdoor temperature is a variable that cannot be controlled, but it has a major influence on field performance of buildings. Condensation occurs only on materials with temperatures below the dewpoint temperature of adjacent air. The potential for condensation problems is greatest at lowest temperatures.

Surveys to detect moisture damage have been made for buildings retrofitted with wall insulation, but there are no published reports of surveys of recently constructed buildings. One survey was conducted in Portland, Oregon, where temperatures are mild, but humid conditions might prevent drying if condensation did occur (Oregon DOE 1979). There were no indications of moisture damage in the wall cavities from condensation in the 96 retrofitted houses evaluated. Researchers concluded that the results of the survey should apply to the western portion of the Pacific Northwest but are not sure that the results can be extended to colder climates. The surveys also showed that continuous vapor retarders are still beneficial in newly constructed houses to keep insulation dry and to reduce infiltration losses.

Another field survey was conducted by the National Bureau of Standards (Weidt et al. 1980) and included evaluation of houses in Minnesota, Connecticut, Virginia, Kentucky, Ohio, and Washington, DC. Observations from a total of 39 houses showed no evidence of major problems associated with retrofitting.

Special Considerations

The primary emphasis of this paper is on new construction of a somewhat conventional nature, and the major concern is for cold weather conditions because that is where damage from condensation is the most frequent. However, certain special considerations deserve our attention. Of particular interest are moisture control in earth-sheltered structures, and the effects of air-conditioning and retrofit for energy conservation.

Retrofit

Moisture control is more difficult to add than to build in at the time of construction, but some preventative or remedial measures can be added. In most retrofits it is not feasible to reduce air leakage to a level that would result in excessively high RH's (Sherwood 1978). However, the added insulation makes outside surfaces colder and thus increases the risk of condensation. Attic ventilation can often be added or increased to carry off moisture entering the attic by air leakage and by diffusion through the ceiling. Walls are more dependent upon vapor retarders for moisture control. Most older houses have several coats of oil-base paint on the walls and this gives some resistance to water vapor transfer. Vapor retarder paints can be applied for added resistance (Sherwood 1978, Sherwood and Peters 1977), especially on walls exposed to high humidities, as in bathrooms. Even with this vapor protection, air leakage at baseboards, electrical outlets, and around windows carried moist air into the wall cavity. Eliminating this air leakage is more critical to water vapor control than are vapor retarders.

Preventative or remedial measures dictated by retrofit technology for moisture control are:

1. Eliminate, as much as possible, air leakage from indoors into walls and attics.

2. Add vapor retarder paint to walls of bathrooms and other high-humidity areas.

3. Keep indoor humidity below 40 percent during winter and even lower when outdoor temperatures are 10 °F or lower.

Recent surveys of moisture in retrofitted houses are discussed in a previous section (Oregon DOE 1979, Weidt et al. 1980). Based on information from these surveys, condensation problems may exist and an understanding of moisture flow is needed to solve them; however, there appears no danger of large-scale decay causing collapse of our retrofitted building stock.

Earth-Sheltered Structures

The low air exchange rate in earth-sheltered structures presents a particular problem of moisture buildup resulting in excessively high indoor humidities. Mechanical dehumidification may be the only method practical during summer that can reduce humidity to about 50 percent. Mechanical ventilation is a more practical method of reducing humidity during winter, and an air-to-air heat exchanger can be used to prevent major heat losses during ventilation.

Exposed walls and roofs of the structure require the same moisture protection as a conventional building. Below grade, the vapor pressure differential is not as large because of soil moisture and cold side temperatures that are generally higher than outdoors. However, vapor retarders are still commonly used (Underground Space Center, University of Minnesota 1979). The more critical matter is to prevent soil moisture from entering the building. This is accomplished by waterproof coatings and good drainage away from the building.

Air-Conditioning

Condensation problems resulting from air-conditioning have been observed in the hot, humid area along the South Atlantic and gulf coast. A survey conducted by Verrall (1962) for the U.S. Navy included examination of buildings in 10 cities in coastal States between Texas and South Carolina. He concluded that damage from condensation was not general, but did occur under certain conditions. Problems that were evident were associated with damp crawl spaces or walls and ceilings adjacent to showers or hot, humid kitchens. A study conducted by Duff (1971) in the relatively warm climate of northern Georgia revealed a total absence of condensation in an air-conditioned test structure. This indicates the low potential for warm weather condensation outside of the hot, humid coastal areas.

Verrall concluded from his study that there are three general approaches needed to control condensation in air-conditioned buildings:

1. Prevent dewpoint temperatures by maintaining moderate indoor temperatures (no lower than 75 °F).

2. Prevent high humidity in crawl spaces by good drainage, the application of a vapor retarder soil cover, and appropriate ventilation.

3. Install vapor retarders on the warm side of walls between air-conditioned areas and high-humidity areas such as shower rooms or hot, humid kitchens.

Studies conducted in southern Mississippi (Sherwood 1985) and Texas (TenWolde and Mei 1986) showed condensation did occur in some types of walls during the air-conditioning season; however, walls dried at the end of the season, and no damage resulted. Some resistance to moisture in the form of closed-cell foam sheathing was found to be helpful in preventing high levels of moisture in the wall cavity.

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Chapter 10
Noise Control

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. The research has helped us understand how sound behaves in rooms and how sound is transmitted between rooms in buildings. Further, experimental measurements, conducted as a result of the research, have defined standardized measurement methods to quantify the acoustical properties of building materials and construction. Based upon these standardized measurement methods, extensive data compilations are now available for design use. However, much of the available technology and design data are knowledge common only to specialists in building acoustics. In the eyes of the layman, the technology may be obscured by the terminology used to discuss it.

The incorporation acoustical design in building construction has long been recognized as an aspect of total design, affecting design criteria. In the United States, building codes are now being implemented that incorporate quantitative acoustical criteria. Also, as multifamily housing becomes more commonplace, designers and builders are increasingly challenged to provide adequate acoustical performance. This chapter discusses the technology now available to solve acoustical problems.

First, however, a distinction must be made between two often confused aspects of building acoustics: sound absorption and sound transmission.

1. Sound absorption refers to the ability of a material or surface of a room to absorb sound within that room. Sound absorption in no way implies that the material or surface will hinder or attenuate the transmission of sound through it.

2. Sound transmission refers to the ability of a material or a wall of a building to allow sound to propagate through the material. One goal of building acoustics is the design of walls, floors, and ceilings to hinder or attenuate sound as it propagates through the building.

Noise insulation design is concerned only with the sound transmission properties of the building construction. The present discussion is, therefore, restricted to characterization of the sound transmission properties of light-frame construction.

Background

Historically, structural mass was one of the first physical parameters related to noise insulation of building construction (Chrisler and Snyder 1929). Increasing mass increases noise insulation. This works but is only one approach. Light-frame construction offers the designer several parameters that may be varied to achieve specific noise insulation requirements.

Noise Insulation or Noise Isolation

It is important to distinguish between the two terms "noise insulation" and "noise isolation." Noise or sound *insulation* is a property of a structural component such as a wall or a floor-ceiling assembly, specifically its capacity to prevent sound from transmitting through the assembly. This chapter is concerned with the noise insulation characteristics of light-frame construction.

Noise insulation is the characterization of a complete construction comprising walls, ceiling, floor, vents, etc., and noise *isolation* is the capacity of the complete construction to attenuate sound as it propagates from the source into the receiving room. The degree of noise *isolation* achieved in any room within a building depends, in part, upon the noise *insulation* of the structural components enclosing the room. It also depends on sound entering the room through vents, air gaps, and cracks, and the extent to which the room is furnished with sound-absorbing items such as carpets, drapes, and furniture.

Building codes may specify acoustical performance as either noise insulation criteria for the components used or noise isolation criteria for the complete construction. In either case, it is necessary to design and to build for a specified degree of noise insulation. (In the case of noise isolation criteria, the design process is followed by performance testing after the construction is finished.) Before technical aspects of noise insulation design can be discussed, it is necessary to introduce some basic terminology.

Basic Terminology

The standard definition of terms relating to acoustics is readily available (ASTM 1980d). This section briefly describes the basic terminology required to begin the technical presentation. More complete treatments of both the terminology and the physical description of sound waves may be found, for example, in the works of Berendt et al. (1967) or Beranek (1971).

Sound Pressure Level

The sound pressure level, L, is defined as:

$$L = 10 \log_{10} (p^2_{rms}/p^2_{ref}), \text{ dB (re. } p_{ref}) \quad (10\text{-}1)$$

where p_{rms} is the root mean square acoustic pressure
$p_{ref} \equiv 20\ \mu\text{Pa}$ (approximately 2×10^{-10} atmospheres at standard sea level conditions)

The root mean square or rms sound pressure of most sound fields varies with frequency. Hence, the sound pressure level varies with frequency. The variation of sound pressure level with frequency is called a sound pressure level spectrum. Frequency is measured in units of Hertz and is abbreviated Hz.

Octave and 1/3-Octave Bands

This is another description of the frequency content of sound. Two frequencies are said to be one octave apart if their ratio is 2. For example, 250 Hz and 500 Hz are one octave apart in frequency. The octave and 1/3-octave bands divide the frequency scale into intervals or bandwidths. Each interval is denoted by its center frequency. Both the center frequencies and the bandwidths are standardized (ANSI 1966). As the nomenclature implies, three contiguous 1/3-octave bands comprise one octave band.

Acoustics data are usually presented in 1/3-octave bands. The resulting sound pressure level spectrum is then called a "1/3-octave sound pressure level spectrum" or simply a l/3-octave spectrum. For noise *insulation* design of buildings, one is usually concerned with the frequency range between 100 and 5,000 Hz.

Frequency-Weighted Sound Levels

To understand or interpret noise *isolation* criteria, it is necessary to use frequency-weighted sound levels. These are single-number sound levels that characterize an entire sound pressure level spectrum. The frequency weighings used in acoustics are standardized (ANSI 1976).

The most commonly used frequency weighting is the "A-weighting." The resulting measurement is the "A-weighted sound level." A-weighted sound levels are denoted by dBA, although one still encounters the older notation dB(A). A-weighted sound levels are important since the frequency weighting used attempts to reproduce the frequency weighting of the human ear.

Building Codes and Design Criteria

Schultz (1980b) has presented a comprehensive and philosophical overview of noise control as related to building acoustics in the 1980's. He has concluded that:

1. Building codes should address the issue of noise isolation.

2. Existing traditional building construction methods meet acoustical needs if properly used.

3. Construction quality control is a necessity.

4. Noise isolation provisions in building codes must be enforced to be effective.

Acoustical criteria are becoming more commonplace in U.S. building codes. Unfortunately, not all building codes incorporating acoustical criteria provide the attributes suggested by Schultz. During the past 5 years, the number of municipalities incorporating quantitative acoustical criteria in their building codes has increased. In 1975, the number was 22 municipalities in 11 states (Bragdon 1975). In 1980, the number had increased to 64 municipalities in 20 states (Bragdon 1980). These building codes generally specify acoustical criteria in one of two ways: noise insulation criteria or noise isolation criteria. As in Schultz (1980b), the use of noise *isolation* criteria appears to be preferred. The differences between these two categories of noise control criteria define the design process required to meet the building code specifications.

Noise Insulation Criteria

Noise insulation criteria specify the performance of components such as a wall or floor-ceiling assembly. This type of specification eases the burden of design, since field verification or performance testing of the completed building is not required. The performance testing is often too costly for routine building code enforcement (Schultz 1979). The HUD Minimum Property Standards for Multifamily Housing are an example of this type of design criteria (U.S. Department of Housing and Urban Development 1973).

Noise Isolation Criteria

Noise isolation criteria specify the performance of the completed building or envelope surrounding a room. This type of specification places the burden of achieving the criteria on the design and construction of all components, required ventilation, and their interconnection. Simplified field measurement procedures, using A-weighted sound levels, have been developed so that building code enforcement is more easily achieved (Schultz 1973a, ASTM 1980i). This approach is taken so that building codes incorporating acoustical criteria actually provide the occupant with a stated degree of noise isolation (Schultz 1973 b). A model noise control code developed for the U.S. Environmental Protection Agency is an example of a specification of noise isolation criteria (Miller and Schultz 1978, Harris et al. 1981).

The Design Burden

Noise isolation criteria place a burden on the designer beyond a direct specification of the noise insulation properties of the walls, floors, glazing, and doors. General guidance is provided for relating noise isolation and noise insulation criteria (Miller and Schultz 1978, Pallett et al. 1978, Weber et al. 1981). A general rule is that noise insulation criteria are 3 to 5 dB greater than the comparable noise isolation criteria. Such general rules are subject to considerable variation. However, the basic point is that noise *insulation* specification is the basis for designing a building to achieve a noise *isolation* criterion. The remainder of the chapter will focus upon the design of light-frame wall and floor-ceiling construction to achieve a specified level of noise insulation performance.

Airborne Noise Insulation

Airborne noise insulation is concerned with a structure's ability to attenuate sound incident upon and transmitting through the structure. The incident sound waves cause the structure to vibrate. The structural vibrations result in the sound being reradiated on the opposite side of the structure. Airborne noise insulation is a property of the structure. However, the characteristics of the incident sound field must be simulated for measurements, or modeled for prediction, in order to determine the noise insulation performance of the actual structure.

Sound transmission loss (TL) is the quantity used to characterize airborne noise insulation. TL is measured in decibels or dB. The sound TL is a function of frequency. A larger value of TL denotes better noise insulation.

In the following sections the sound transmission loss characteristics of light-frame construction are presented by comparing theoretical predictions to laboratory measurements. In taking this approach, only the comparisons are discussed. The theoretical prediction methods are included under analysis. The reader may then focus on the comparisons, recognizing that the necessary theory is available for reference and use. The aim is to emphasize the capability of the theory to predict the measured performance.

Thin-Panel Noise Insulation

The characterization of the air-borne noise insulation of light-frame construction begins with thin-panel sound TL. Thin-panel characteristics are then used to account for structural details of the frame construction. This is possible because the main sound-attenuating mechanism for frame construction is attributed to the mechanical properties of the panels covering the framework.

Figure 10-1 illustrates the general sound TL characteristics of a *thin* panel of homogeneous material. The vertical axis is the TL (units of decibels, dB) on a linear scale. The horizontal axis is frequency (expressed in Hertz, Hz) and is a logarithmic scale. The thin-panel sound TL is characterized by frequency regions as indicated. Region 1 is characterized by resonant vibration of the panel excited by the incident sound field. For common building materials this frequency region is usually so low that it is unimportant to building acoustics. The frequencies above this range are a more important consideration.

Region 2 of figure 10-1 is referred to as the "mass law" region. For this frequency range, the thin-panel sound TL is very closely approximated by a linear function of the logarithm of the frequency (see eq. (10-11a). The theoretical slope of this curve is 6 dB for each doubling of frequency or 6 dB per octave. Increasing the panel weight theoretically increaies the value of TL by 6 dB

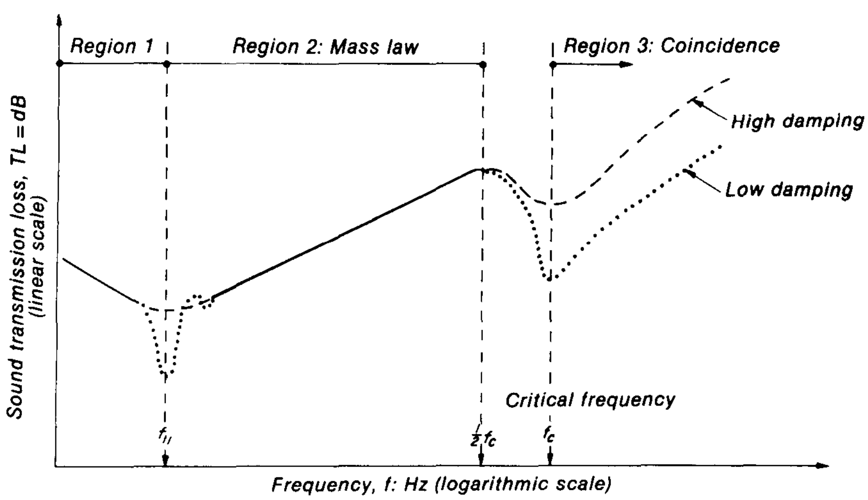

Figure 10-1 – Sound transmission loss characteristics of a thin ***panel. (M151 850)*** for each doubling of weight over the entire frequency range of Region 2. The 6-dB increase in TL for a doubling of either weight or frequency is called the mass law. The upper frequency limit of this region is approximately 0.5 f_c.

Region 3 of figure 10-1 begins at a frequency called the critical frequency, f_c. The critical frequency is a characteristic of the panel material and the panel bending stiffness. At the critical frequency, the panel sound TL decreases dramatically from the mass law line. For *thin* homogeneous panels, the critical frequency is inversely proportional to the panel thickness and may be estimated using equations (10-9) or (10-10). Increasing panel thickness, and hence weight, decreases the critical frequency. As a design objective, however, the critical frequency should be as high as possible. As a result, the selection of panel thickness is a compromise between increasing TL in the mass law region and decreasing the critical frequency.

Frequencies greater than the critical frequency are called coincidence frequencies. Physically, the incident sound field "coincides" spatially with bending waves in the panel. The thin-panel sound TL in this frequency range may be estimated using equation (10-1lb).

These results apply to *thin* homogeneous panels. If the bending wavelengths of the panel vibration are less than six times the panel thickness, the above characterization does not apply, and thick-panel theory must be used (Mindlin 1951, Sharp 1973, Sharp et al. 1980). For lightweight building materials such as gypsum board, the bending wavelengths are large compared to the thickness so that the panels may be considered to be thin over the frequency range important to noise insulation. For the same frequency range, more massive construction such as concrete and brick behaves as a thick panel, and this characterization does not apply (Sharp et al. 1980). The net effect is that concrete and brick do not exhibit sound TL values as large as one might expect based upon their mass and thin-panel theory. This is one reason that light-frame construction is capable of providing noise insulation comparable to that provided by more massive construction.

Other structural forms that do not conform to the mass law for thin homogeneous panels are sandwich panels and orthotropic materials such as plywood. It is beyond the scope of this chapter to present the basis for the differences (Beranek 1971, Jones 1981). However, the reader can understand that differences are to be expected. Sandwich panels are characterized by both the bending and shear stiffness of the face sheets and core material. Orthotropic materials, such as plywood, are characterized by the bending stiffness in mutually orthogonal directions. One cannot expect, therefore, that a theory based upon a thin homogeneous material will apply either to sandwich construction or to orthotropic materials.

To evaluate the application of theory to practical forms of light-frame construction, it is necessary to compare the predictions to measurements of noise insulation. The following section describes the laboratory measurement of sound transmission loss.

Laboratory Measurement

The laboratory measurement of sound TL is conducted using standardized methods (ASTM 1980e, International Organization for Standardization 1978a). The structure is mounted in an opening between two rooms such that the only sound transmission path is through the structure. One room contains a sound source generating a specified sound pressure spectrum. This room is called the source room. The other room is called the receiving room. The sound fields in each room are characterized by measuring the sound pressure levels at several locations within each room. These data are averaged to yield a single sound pressure level for each room. The measurements are conducted for a minimum of 16 contiguous 1/3-octave bands with center frequencies from 125 to 4,000 Hz. These center frequencies and the filter band widths are standardized (ANSI 1966).

At each center frequency, the sound TL is calculated using the expression:

$$\mathrm{TL} = \bar{L}_1 - \bar{L}_2 + 10 \log(S/A_2), \text{ dB} \qquad (10\text{-}2)$$

where $\bar{L}_1$ and $\bar{L}_2$ are the space-time average sound pressure levels in the source and receiving rooms, respectively

S is the surface area of the test specimen

A2 is the sound absorption in the receiving room

Note that laboratory sound TL tests are conducted under idealized conditions (ASTM 1980e, International Organization for Standardization 1978a). These conditions attempt to simulate a diffuse incident sound field and to limit the sound transmission between the rooms to the surface area of the test specimen. Under laboratory test conditions, variations of sound TL occur when identical specimens are tested in different laboratories. These differences may be as large as 8 dB for a given 1/3-octave band frequency and can be attributed to several different causes (Jones 1979, Sharp et al. 1980). However, laboratory data generally confirm the *shape* of the TL curve as indicated by figure 10-1.

Sound Transmission Class Rating

Several methods have been developed to characterize the shape of the TL curve and to quantify this shape by a single number. One such rating is the sound transmission class or STC rating. In terms of the STC rating, interlaboratory variations may be as large as 5 or 6 STC points (Jones 1979).

Figure 10-2 presents a typical plot of sound TL data for a laboratory test specimen. The points represent the sound TL as determined using standard test methods.

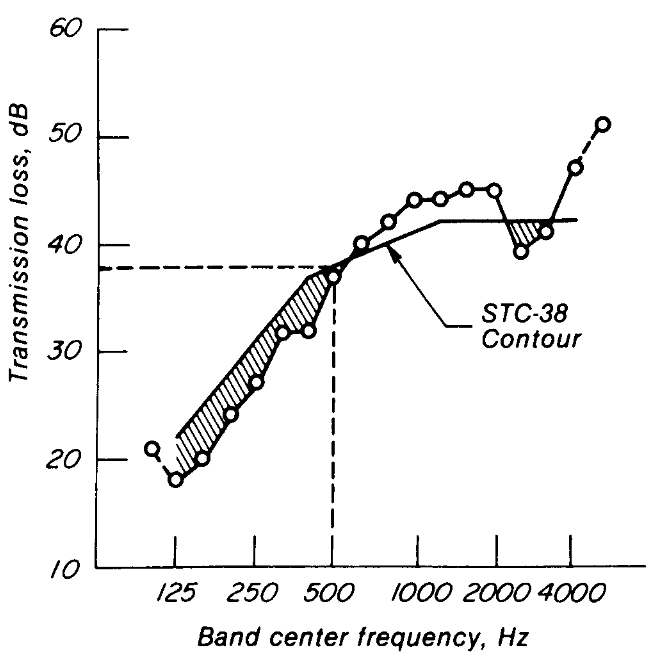

Figure 10-2 –An example of the sound transmission class contour fitted to a sound transmission loss curve. (M151 506)

The shape of the TL curve is characterized by increasing sound TL between 125 and 1,000 Hz. Between 1,000 and 2,000 Hz, the curve levels off and suddenly decreases at 2,500 Hz. Above 2,500 Hz, the sound TL begins to increase. Comparing figures 10-1 and 10–2, it is seen that the frequency range between 125 and 1,000 Hz corresponds to the mass law region; 2,500 Hz is the 1/3-octave band containing the critical frequency; and the range above 2,500 Hz is the coincidence region.

The 16 data points represent a quantity of data that is difficult to comprehend. As a result, single-number rating procedures have been developed to rate the sound TL or noise insulation of a structure. In the United States this number is the STC rating (ASTM 1980c).

The STC rating attempts to accomplish two objectives: to characterize the airborne sound TL data by a single number and to provide a single number that correlates with occupant's subjective response to intruding noise. The rating is a relative scale based on the idealized transmission loss curve of a 9-inch-thick plastered brick wall that is assumed to provide occupants with an adequate degree of sound insulation (Yaniv and Flynn 1978).

The STC contour shown in figure 10-2 comprises three straight-line segments. The method used to determine the STC rating is specified and involves fitting the STC contour to the measured sound TL data according to definite rules (ASTM 1980c). This procedure allows the measured TL data to fall below the STC contour by a specified amount. This is indicated by the shaded region in figure 10-2.

The STC rating is determined by the sound TL value corresponding to the value of the fitted STC rating contour at 500 Hz. This procedure is indicated by the dashed lines in figure 10-2. The higher the value of the STC rating, the better the degree of airborne noise insulation *and* occupant satisfaction. A 5-point difference between STC ratings for different structures is generally considered to be a noticeable difference (Berendt and Corliss 1976). Table 10-1 lists the STC rating and describes the corresponding structure for several typical wood-frame walls. Also listed in the table is an indication of the privacy afforded by the structure, in terms of the intrusiveness of speech sounds (Berendt and Corliss 1976).

Table 10-1 – Sound transmission class (STC) ratings for typical wood-frame walls (ASTM 1980a)

STC rating	Privacy afforded	Wall structure
25	Normal speech easily understood	1/4-inch wood panels nailed on each side of 2 by 4 studs.
30	Normal speech audible but not intelligible	3/8-inch gypsum wallboard nailed to one side of 2 by 4 studs.
35	Loud speech audible and fairly understandable	5/8-inch gypsum wallboard nailed to both sides of 2 by 4 studs.
40	Loud speech audible but not intelligible	Two layers of 5/8-inch gypsum wallboard nailed to both sides of 2 by 4 studs.
45	Loud speech barely audible	Two sets of 2 by 3 studs staggered 8 inches on centers fastened to 2 by 4 base and head plates with two layers of 5/8-inch gypsum wallboard nailed on the outer edge of each set of studs.
50	Shouting barely audible	2 by 4 wood studs with resilient channels nailed horizontally to both sides with 5/8-inch gypsum wallboard screwed to channels on each side.
55	Shouting not audible	Double row of 2 by 4 studs 16 inches on centers fastened to separate plates spaced 1 inch apart. Two layers of 5/8-inch gypsum wallboard screwed 12 inches on center to the studs. A 3-1/2-inch-thick sound-attenuation blanket is installed in one stud cavity.

The STC rating is discussed here to emphasize that it is determined from laboratory measurements of the sound TL of a structure. The rating procedure has been criticized (Sharp et al. 1980, Yaniv and Flynn 1978); however, the vast quantity of sound TL data and corresponding STC data make their application the most viable approach to noise insulation design (Berendt et al. 1967, DuPree 1980). As an architectural and engineering design tool for characterizing the airborne noise insulation of structures, the STC rating is the most widely used rating in the United States today.

The STC rating represents one approach for ranking the airborne noise insulation of building construction. At first, one may have difficulty in developing a sense of the significance of the STC rating as it corresponds to different forms of building construction. One approach is to relate the STC rating to the surface weight for various building materials and types of construction. Such an empirical relationship is indicated in figure 10–3 by the broad-shaded line. The relationship applies only to homogeneous construction forms such as hardboard and gypsum board panels and concrete block and concrete walls. More important, however, are the discrepancies between the empirical result and the points corresponding to various configurations of light-frame constructions. Figure 10-3 emphasizes that light-frame construction can provide airborne noise insulation, based upon the STC rating, equal to that provided by more massive forms of building construction such as concrete block and concrete walls.

To understand the application of STC ratings, which are based on laboratory measurements, to the design of buildings, it is necessary to recognize the differences between the laboratory and the field environments. Significant differences are presented in the following section.

Field Measurement

The airborne noise insulation of structures must be determined in the field to ensure that design performance is achieved. For field data, a clear distinction between noise insulation and noise isolation must be made. The conditions encountered in typical field installations are very different from those present in the laboratory. Many of these differences are discussed in detail in the literature and summarized by Sharp et al. (1980).

One of the more important differences is the presence of flanking sound transmission paths in field installations. A flanking path represents an, alternative

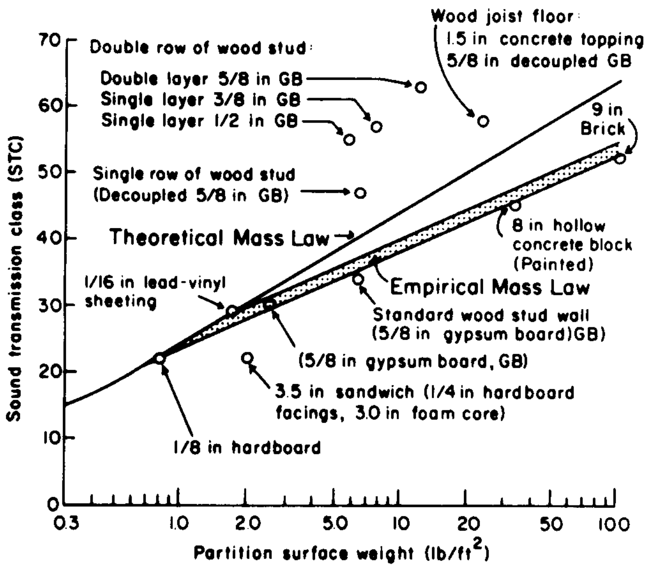

Figure 10-3 – Graph of theoretical and empirical field incidence mass laws expressed as sound transmission class versus panel or partition surface weight, w. Examples of typical constructions are also shown. Shaded area is ±1 dB with respect to STC = 14.5 log w + 25 and indicates approximate nature of relationship. (ML88 0021)

path for the sound propagation, other than through the wall or floor-ceiling partition. Since the airborne noise insulation is based upon the acoustical energy transmitted through the partition, the presence of flanking sound transmission effectively represents a degradation of the noise insulation performance of a partition. These flanking paths may be summarized as follows:

1. Air leaks in buildings – pipe and duct penetrations and perimeters of walls, floors, doors, and windows.

2. Airborne transmission paths – ventilation ducts, ceiling plenums, doors, and common corridors.

3. Structureborne paths – coupled vibration of the walls, floor, and ceiling that result in reradiated sound.

Examples of design techniques to prevent air leaks and airborne sound transmissions are available (ASTM 1980g, ASTM 1980h, Berendt and Corliss 1976). Structureborne sound transmission is discussed in the following section. Finally, good workmanship and quality control during construction are of vital importance to ensure that a structure performs to its full noise insulation potential (Schultz 1980b).

Because of the possibility of flanking sound transmission in field installations, two quantities are used to measure field performance: field transmission loss (FTL) and noise reduction (NR). FTL is a measure of the sound TL or *noise insulation* of a structure under field conditions (ASTM 1980i). The measurement of FTL requires that all flanking sound transmission be eliminated so that the data describe the performance of the wall or floor-ceiling assembly being tested. The conduct of these tests is time consuming and expensive (Schultz 1979). NR is a measure of the *noise isolation* including all sound propagation paths between two rooms. To restate these definitions: FTL is a measure of the test specimen performance in situ; NR is a measure of the entire building enclosure performance (Sharp et al. 1980).

Single-Number Rating

The measurement of FTL and NR is conducted in a series of 1/3-octave bands just as required for the laboratory measurement of TL. Similarly, single-number ratings for field data are determined based upon the STC rating contour (ASTM 1980c). For FTL data, the single-number rating is called the Field Sound Transmission Class (FSTC). For NR data, the single-number rating is called the Noise Isolation Class (NIC). These ratings only apply for partitions separating rooms indoors (ASTM 1980h). Under field conditions, the partition may separate rooms within a building or the partition may be an exterior wall. The FTL is defined differently for these two conditions (ASTM 1980e).

Indoor-to-indoor – The theoretical basis for the measurement of indoor-to-indoor FTL assumes that the sound fields in each room are diffuse. The test specimen separates the source room from the receiving room and all flanking sound transmission paths have been eliminated. The field sound TL is based upon measurement of the average sound pressure levels in the two rooms and is given by:

$$\text{FTL} = \bar{L}_1 - \bar{L}_2 + 10 \log(S/A_2), \text{ dB} \quad \text{(l0-3)}$$

where $\bar{L}_1$ is the average sound pressure level in the source room
$\bar{L}_2$ is the average sound pressure level in the receiving room
S is the area of the test partition
A_2 is the sound absorption in the receiving room

The relationships used to derive TL in the laboratory and the FTL in the field are functionally identical and emphasize that FTL data are an attempt to simulate laboratory-like conditions in the field.

Outdoor-to-indoor – The field measurement of outdoor-to-indoor sound TL is defined in terms of an incident plane wave on the exterior surface of the test specimen and a diffuse sound field in the receiving room. These are idealized conditions that are simulated during a field test using standard measurement methods (ASTM 1980i, International Organization for Standardization 1978b). For these conditions, the field sound TL is given by the expression:

$$\text{FTL} = L_1 - \bar{L}_2 + 10 \log(S \cdot \cos\theta/A_2) + 6 \text{ dB}, \quad \text{(10-4)}$$

where L_1 is the incident sound pressure level at the location of the test partition on the building surface (i.e., the partition is physically absent and L_1 can only be measured indirectly)
L_2 is the average sound pressure level in the receiving room
θ is the angle that the incident sound makes with the normal to the test partition
S and A_2 are defined as for the indoor-to-indoor measurement

The exterior sound field is generated by a loudspeaker with the axis oriented at the angle θ relative to the normal to the plane of the test partition. The angle θ must be stated for the measurement. Currently, two standard field measurement methods are in use (ASTM 1980i, Internation Organization for Standardization 1978b). ASTM is developing a measurement method similar to the 140/V method of the International Organization for Standardization.

Whereas laboratory TL data are extensively compiled, FTL data are not so readily available. This is undoubtedly because of the expense of conducting field measurements.

Laboratory-Field Measurement Comparison

As previously mentioned, when specimens of identical construction are tested in different laboratories, differences between the sound transmission loss and the STC rating are observed (Sharp et al. 1980, Jones 1979). These differences may be significant (more than 8 dB for TL and 5 points for STC). A complete discussion of this discrepancy, including possible reasons for the differences, is presented by Sharp et al. (1980).

Similarly, differences are observed between transmission losses measured in the laboratory and field. Several researchers have reported comparisons of laboratory and field measurements. The data are for indoor-to-indoor space separations and are summarized here for wood-frame construction. The comparison is between the STC rating (laboratory) and the FSTC rating (field). As will be seen, the field ratings are usually lower than the laboratory ratings. The laboratory and field comparisons are summarized as follows:

1. Berendt et al. (1967), indicate a degradation of 4 to 5 points in the STC rating for construction with typical or normal workmanship. With special attention given to the construction, the degradation may be reduced to 1 or 2 points in STC.

2. Heebink and Grantham (1971) indicate a degradation of 3-1/2 STC points. By correcting air leakage and flanking conditions the degradation was reduced to 2-1/2 STC points.

3. Jones (1975) has reported degradations of O to 8 STC points for wood-frame construction on a wood joist floor.

For design guidance, it is common practice to select a structure with a laboratory STC rating from 3 to 5 points above the field requirement to allow for these differences.

Prediction Methods

Prediction of the sound TL of wood-frame construction is a necessary design tool. Predictions may be used to design for a specific TL characteristic or to interpret differences between laboratory and field measurements. A summary of prediction methods applicable to wood-frame construction is presented in a later section. This section presents comparisons between the predictions and laboratory measurements.

The predictions depend upon the thin panels covering the framework. The mass and stiffness of the framework are not parameters that are specifically included in the methods described here. Details concerning the prediction methods are provided under Analysis Methods. The predictions generally apply below the critical frequency (Region 2 in fig. 10-1) and are discussed in the order of the structural configuration.

Single thin panel – Figure 10-4 (Sharp 1973) presents a comparison between prediction and measurement for a single panel of 5/8-inch gypsum board. The critical frequency is approximately 2,500 Hz. The prediction between 1,250 Hz (0.5 f_c) and 2,500 Hz (f_c) is a straight line connecting the two curves at these frequencies. The agreement is reasonable over the entire frequency range. Beranek provides an alternative procedure for this type of structure (Beranek 1971).

Double thin panels – Figure 10-5 presents a comparison between prediction and measurement for double thin panels with a 4-inch cavity depth. Fiberglass batts were installed in the cavity for the measurement data. The hardboard density is given in table 10-2. The cavity resonance frequency, f_o, and the cavity standing wave frequency, f_ℓ, are defined under the heading "Analysis Methods." The characteristic shape of this curve is quite different from that of a single thin panel. In particular, the rapid rise of the TL curve above f_o allows double panel configurations to exhibit STC ratings comparable to more massive construction such as concrete (Sharp 1973, Sharp et al. 1980). This conclusion is evident by noting the STC ratings of double row of wood stud walls indicated in figure 10-3.

Figure 10-6 presents an alternative use of the prediction methods. In this case the measured TL data for each panel are used in the functional relationships. The measured data are presented in table 10-2.

Connected double thin panels – Figure 10-7 presents a comparison of prediction and measurement for a single row of stud wood-frame wall having 2- by 4-inch studs spaced on 24-inch centers. The gypsum board panels are directly attached to the studs. One panel is 5/8 inch thick and the other panel is 3/8 inch thick.

These comparisons indicate very good agreement between theory and measurement. Another technique to increase the airborne noise insulation of wood-frame construction is to attach the panels to the studs using metal channels or clips. The result is to decouple the panel motion from the studs through the resilience of the attachment. As indicated in figure 10-3, rather dramatic improvement of the STC rating is achieved using this technique for a single row of wood stud wall with 5/8-inch gypsum board panels. However, the consideration of resiliently mounted panels must be based upon additional comparisons of theory and experiment. The theory is available and only awaits the necessary comparison (Sharp 1978).

Outdoor-to-indoor predictions – The prediction of outdoor-to-indoor noise isolation and insulation is an extremely important and difficult task. Methods are available for application to building design (Lewis 1974, Pallett et al. 1978). However, such predictions are highly site-dependent and should be made by an acoustical consultant. The difficulty arises in attempting to describe the incident sound field on the building exterior.

Traffic noise barriers – Highway traffic noise is an important environmental consideration. Light-frame construction, in addition to the obvious application to buildings, is becoming an important construction method also for highway noise barriers (May 1978). It is beyond the scope of this paper to consider design of barriers with respect to diffraction of sound around the barrier. Diffraction effects determine the height and length of the barrier for the specific site. To be effective, however, the noise barrier construction must attenuate the sound incident upon the barrier from the highway. The aim is to provide a light-frame construction that attenuates noise propagating through the structure and is competitive with more massive structures in noise reduction and cost (Simpson 1976).

As will be discussed in the section on Analysis Methods, highway traffic noise may be considered as a line noise source. (Figure 10-8 illustrates a line source

Table 10-2– Measured values of transmission loss (dB) for a number of conventional building materials (Cremer et al. 1973)

Building material	Surface weight, lb/ft^2	Critical frequency, Hz[1]	One-third-octave band center frequency, Hz																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
			Transmission loss, dB																	
1/4-in gypsum board	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 gypsum board	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 gypsum board	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 gypsum board	2.6	2,500	14.5	16.5	18.5	20.5	22.5	24.5	26.5	28	29.5	31	32	33.5	34	30.5	25.5	29	33	35.5
Lamination[2] of 1/3 in and 1/4-in gypsum board	2.0	5,000	13	15	17	19	20	22	24	26	27	29	31	32	34	35	36	37	37	33
Lamination[2] of 1/2 in and 1/2-in gypsum board	4.0	3,150	19	21	23	25	27	28	29	31	32	33	34	35.5	36.5	37	36.5	33.5	36	41
Lamination[3] of 1/2 in and 5/8-in gypsum board	4.6	2,500	21	23	25	27	29	31	33	33.5	35	35.5	35	35.5	36	35	32	34	36.5	40
Lamination[3] of 5/8 in, 1/2-in, and 5/8-in board	7.2	2,000 2,500	23	25	27	29	31	33	35	34	35	35	36	38	40	39	39	41	43	47
1/8-in hardboard	0.7	10,000	7	7	9	10.5	12.5	14	18	19	21	22.5	23.5	26	27.5	29	32	34.5	36.5	36.5
1/4-in hardboard	1.4	5,000	10	12	14	15	17	20	21.5	23	25	27	29	32	33.5	35	36	36.5	37	35
2-in reinforced[4] concrete	24	630	34	35	36	38	37	36	38	39	41	43	46	49	51	52	54	56	58	59
4-in reinforced[4] concrete	48	315	39	42	42	42	42	43	43	46	50	53	54	55	57	59	60	64	66	68
6-in reinforced[4] concrete	72	200	39	39	42	42	42	46	48	50	53.5	55.5	58	60	62	64	64	66	68	70
1/2-in plywood[5]	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 on center.

[3]Spot laminations – 24 in on center.

[4]Assuming a density of concrete of 144 lb/ft^3. This will vary according to the aggregate.

[5]From FPL files.

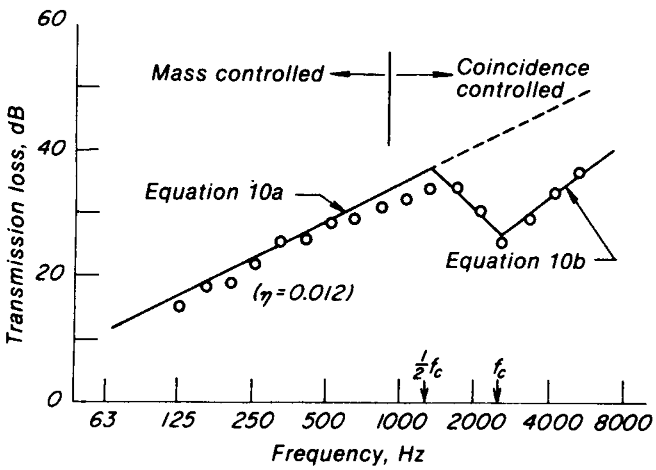

Figure 10-4 –Measured values (o) and calculated curves of the transmission loss of 5/8-inch gypsum board (21). (M151507)

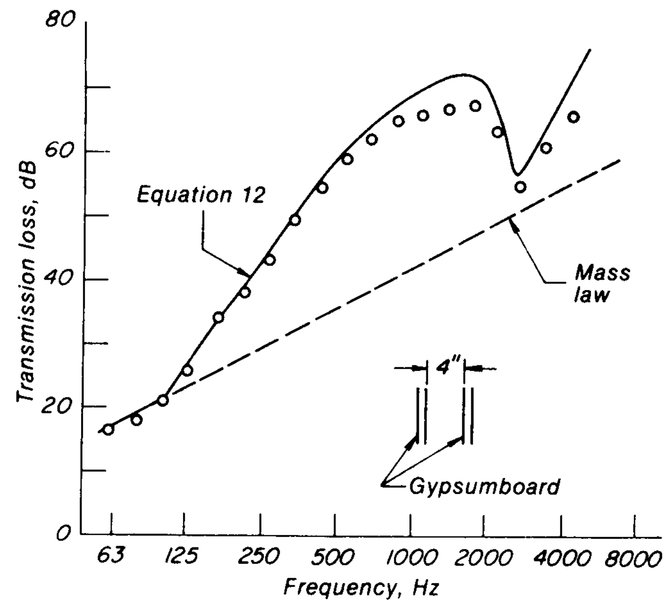

Figure 10-6– Measured values (o) for individual panels and calculated curves of the transmission loss of 5/8-inch gypsum board. Fiberglass batts in the cavity for measured data. (M151 508)

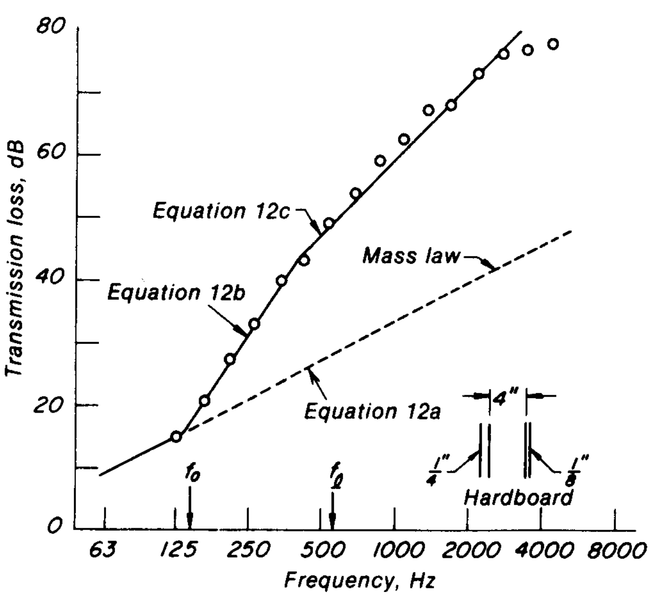

Figure 10-5 -Measured values (o) of the transmission loss of a double panel compared to curves calculatedly the approximate method. Fiberglass batts in the cavity for measured data. (M151 509)

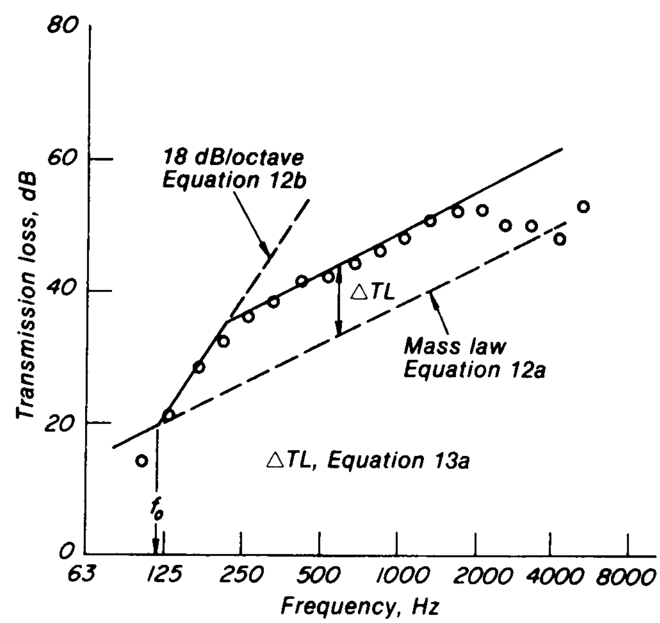

Figure 10-7–Measured values (o) and predicted curves of transmission loss for a double-panel construction of 5/8- and 3/8-inch gypsum board with wooden line studs, 24 inches on center, and fiberglass batts in the cavity. (M151 510)

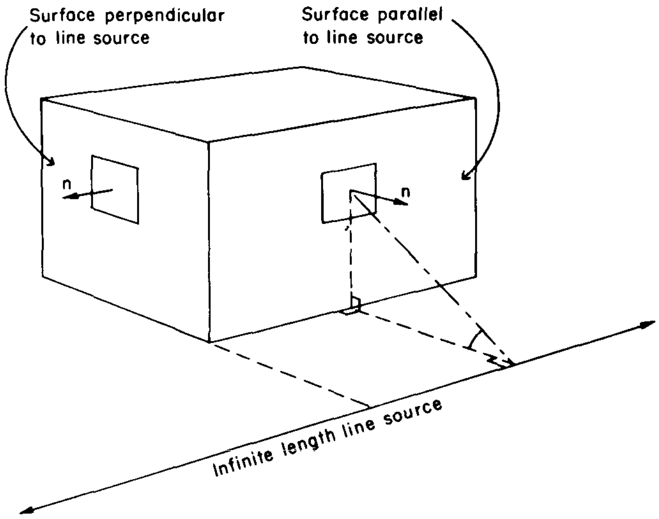

Figure 10-8 – Geometry for surface orientation relative to line source. (ML88 0022)

(highway) geometry relative to a smooth building surface. Two mass law relationships will be presented.) One relationship applies to the surface parallel to the line source and the other applies to the surface perpendicular to the line source. These are two commonly encountered alignments that apply both to buildings and to noise barriers. Relationships are available for general orientation of the surface relative to the line source (Rudder 1983). The methods presented in Analysis Methods have been used to interpret field measurements and may be used for preliminary design purposes (Lewis 1974).

Available Data Sources

Compilations of sound transmission loss data are available for design use. These compilations cover a wide range of structural configurations and materials including light-frame construction. Available compilations include: 1

1. Berendt et al. (1967) – Octave and 1/3-octave TL data, STC ratings, and IIC ratings.

2. Heeden (1980). – 1/3-octave TL data, STC ratings, and IIC ratings.

[1]The Impact Insulation Class of IIC rating refers to impact noise insulation of floor-ceiling assemblies as presented later.

3. California Office of Noise Control – STC and IIC ratings (DuPree 1980).

4. Sabine et al. (1975) – 1/3-octave TL data, STC data, and thermal performance data for exterior walls, doors, and windows.

5. Marsh (1971). – l/3-octave TL data for glass.

6. Quirt (1981). – 1/3-octave TL data and STC data for glass.

These data may be used to determine bounds on the STC ratings of structures. For example, the California data compilation lists 317 interior frame wall designs (194 wood stud and 123 metal stud configurations). These data were tabulated into the number of designs in each 5-point STC interval from STC 25 to 65. The percentage distribution of these data is given in table 10-3. Figure 10-9 presents the distribution data of table 10-3. Representative wood-frame construction, typical of the construction required to achieve an STC rating within the various intervals, is also indicated in figure 10–9. As seen in the table, the designs cover a wide range of STC ratings. Further, over 65 percent of these designs exhibit STC ratings above 45. To satisfy building code requirements, the designer usually has to select or specify STC ratings above 45.

These data support Schultz's (1980b) contention that traditional construction (such as light-frame

Table 10-3 – Percentage distribution of light-frame construction designs (DuPree 1980)

STC interval[1]	Wood stud designs	Metal stud designs	All designs
		Pct	
25–30	1.3	0.6	1.9
30–25	2.2	1.0	3.2
35–40	9.8	6.6	16.4
40–45	6.0	6.6	12.6
45–50	14.8	12.0	26.8
50–55	15.5	9.2	24.7
55–60	8.8	2.5	11.3
60–65	2.8	0.3	3.1
All STC	61.2	38.8	100.0

[1]Sound transmission class (STC) rating system (International Organization for Standardization 1978a) is used, and the interval includes the lower limit and excludes the upper limit.

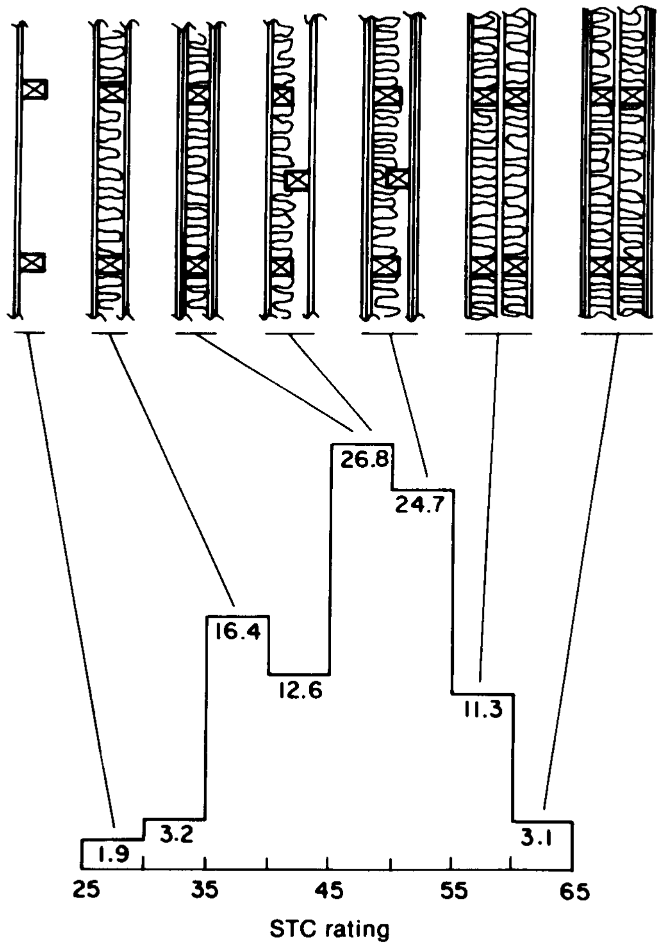

Figure 10-9 – Representative wood-frame construction and percentage distribution of designs with sound transmission class (STC) rating from California data compilation (DuPree 1980); see also table 2. (M151 512)

construction) can provide the required noise isolation. Of course, this requires that flanking sound transmission is controlled. One form of flanking sound transmission, structureborne noise, is described in the next section.

Structureborne Noise

The mechanism for structureborne noise is the propagation of bending waves through the structure resulting in sound being radiated from all the surfaces of the receiving room. This propagation results from the coupling of the walls with the floor and ceiling at the structural connections. The presence of structureborne flanking sound transmission is one of the possible reasons for FTL values being lower than would be expected from laboratory measurements of TL. Two state-of-the-art reviews have been prepared describing the complexity of the problem and identifying research needs to quantify structureborne noise (Sharp et al. 1980, Ungar 1980). Structureborne noise propagation and radiation have been investigated theoretically and are described in textbooks on noise control (Beranek 1971, Cremer et al. 1973). With the current state of the art, however, the problem can only be approximately taken into account during design of conventional wood-frame construction (Ungar 1980).

Field measurements of structureborne flanking sound transmission indicate that it can represent a limiting condition – especially when designing for high levels of airborne sound transmission loss (Jones 1975). Experience in Europe indicates that the theory can be applied to design problems provided that empirical data obtained from field measurements are available (Gerretsen 1979). Unfortunately, European construction is not similar to that in the United States, and the European design methods do not generally apply. The incorporation of structureborne noise as a quantitative design consideration must await the development and verification of U.S. based research results.

Impact Noise Insulation

Impact noise is noise generated by footsteps or dropped objects that is transmitted through a floor-ceiling assembly to the room below. Impact noise is a design consideration in multifamily dwellings for the floor-ceiling assembly separating living units. The design or selection of floor-ceiling construction on the basis of impact noise insulation is a distinct consideration in addition to the airborne noise insulation requirements. Simply stated, good airborne noise insulation performance does not necessarily imply good impact noise insulation performance. A recent state-of-the-art review of impact noise testing and noise insulation rating provides an in-depth discussion of the complex nature of this noise insulation problem (Schultz 1980a).

Historically, impact noise testing has utilized a standard tapping machine. This standard tapping machine provides noise insulation data that are reproducible under laboratory and field conditions for similar floor-ceiling construction. The problem is that the occupant's subjective rating of the impact noise insulation does not correlate well with the insulation rating obtained using the standard tapping machine. The result is that occupant satisfaction cannot be guaranteed even if the construction exhibits a high impact noise insulation rating.

The impact noise insulation of a floor-ceiling assembly may be determined using three possible methods (ASTM 1980a, ASTM 1980b, Schultz 1980a). All of the methods involve laboratory measurements. The standard method uses the standard tapping machine and rates the impact noise insulation using a single-number classification called the Impact Insulation Class or HC (ASTM 1980 f). The IIC rating is similar in concept to the airborne noise rating using the STC. Both ratings are obtained by fitting a grading curve to a plot of 1/3-octave band sound pressure level data. The grading curve for determining the IIC rating is different, however, from the grading curve used to determine the STC rating.

A higher value of IIC rating is intended to imply improved impact noise insulation. However, as mentioned above, increasing the IIC rating does not necessarily result in increased occupant satisfaction (Schultz 1980a). To improve this situation, two tentative laboratory test methods have been proposed (ASTM 1980a, ASTM 1980b). One method utilizes a modified tapping machine, and the other method utilizes a live walker. These two methods have been developed for the purpose of improving the correlation between the rating of a structure's impact noise insulation as determined by physical measurement and an occupant's subjective response to impact noise.

From a practical standpoint, the IIC rating may be specified for acoustical design purposes or as a building code requirement. The IIC ratings are available for many different floor-ceiling constructions and are extensively compiled (DuPree 1980, Heeden 1980). For wood-frame construction, the design will most likely employ either a floating floor or a thin layer of poured concrete over the subflooring-joist system and the finished ceiling. The floor surface will be covered with a soft or resilient carpet and pad. For building codes based upon noise isolation requirements, the consideration of impact noise may be based upon using a specific type of construction without any reference to acoustic criteria (Harris et al. 1978, Miller and Schultz 1978).

The following example is given as an illustration of the importance of the floor covering in determining the IIC rating of a basic construction. The example is selected from the compilation of IIC data prepared by the California Department of Health Services (DuPree 1980). The basic construction comprises a two-layer subfloor on 2- by 10-inch wood joists spaced 16 inches on center. A 5/8-inch plywood subfloor is nailed to the joists, and a 1/4-inch particleboard is glued to the plywood. On the ceiling side of the construction, resilient metal channels are attached to the joists on 24-inch centers, and 1/2-inch gypsum board is fastened with screws to the resilient channels. A 3-inch-thick sound attenuation blanket is installed in the cavity between the joists. The basic construction exhibits an STC rating of 51 and an HC rating of 49.

Alternative floor coverings are installed on the basic construction, and the impact noise tests are conducted. These alternative floor coverings do not change the STC rating of 51. However, the IIC ratings change over a range of 20 points, as indicated in table 10-4. This example illustrates that it is possible to alter the IIC rating significantly (over 20 dB) without altering the airborne noise insulation (STC rating). From the design standpoint, one should first establish the airborne noise insulation required of the floor-ceiling assembly and then select the floor covering to obtain the appropriate IIC rating.

Table 10-4 – Variation of IIC rating[1] with floor covering for example construction (see text for description)

No floor covering (basic construction)	49
1/2-inch wood parquet flooring	50
1/16-inch vinyl	47
Cushioned vinyl	51
50-ounce carpet on 30-ounce foam-rubber pad	58
65-ounce carpet on 30-ounce foam-rubber pad	71
76-ounce carpet on 50-ounce hair pad	70

[1]Impact insulation class (ASTM 1980f)

Energy Conservation and Noise Insulation

Design techniques used to increase the noise insulation of building construction also generally reduce energy losses. Noise insulation is not, by itself, a good indicator of energy efficiency (Sharp et al. 1980). However, the steps taken to insulate a building from exterior noise are the same steps taken to reduce energy losses: first, eliminate air leaks; second, modify windows and doors; and third, modify the basic structural elements. The literature contains both laboratory data and economic models describing design methods for evaluating the thermal transmittance, the noise insulation of exterior walls, and the cost of energy-saving modifications (Davy and Skale 1977, Sabine et al. 1975, Weber et al. 1981). The discussion here will be an overview of the design considerations.

Air Infiltration

Gaps, cracks, and vents represent paths by which air infiltration occurs in buildings. These paths also represent the main cause of noise insulation reduction in buildings. The gaps and cracks may be the result of poor construction quality control. Vents, however, are required to exchange the air inside a building with fresh outside air. The energy loss occurs when the conditioned inside air is exchanged with outside air. The outside air must be reconditioned, and the cost of this reconditioning is the cost of the energy lost by uncontrolled air infiltration.

The first step in soundproofing a building or designing for exterior noise control is to ensure that all gaps and cracks are sealed and that vents are provided with acoustic baffles. However, this approach may require that controlled air ventilation be provided by some kind of system. Hence, the operating cost of the ventilation system must be included along with the initial capital costs associated with developing a cost/benefit analysis for energy conservation and noise control.

The benefits that may accrue from this procedure can be determined only for the specific building being analyzed. However, the degradation of the noise insulation as a result of cracks can be quantified. For example, an empirical relationship has been developed between the STC rating of a sealed window and the STC rating of the same window when air leaks have not been controlled (Sabine et al. 1975). The air leaks are quantified by the leakage rate, V, at a pressure differential of 0.3 inch of water. The result is:

$$R = R_o - 10 \log[1 + 0.00229(\dot{V}/S) \cdot 10^{R_o/10}] \qquad (10\text{-}5)$$

where R_o is the sealed window STC
V is the leakage rate at 0.3 in of water, cfm
S is the window area, ft^2

Thermal Transmittance

Acoustical and thermal energy transfer through walls, doors, and windows are governed by very different physical principles. As a result, one would not expect noise insulation and thermal transmittance to be highly correlated. Available experimental data have been obtained and compared (Sabine et al. 1975). These data exhibit considerable scatter; however, the overall trend of the data is important to remember – good noise insulation performance (high STC) usually implies good thermal performance (low thermal transmittance). These data are based upon a comparison of windows, doors, and walls. The conclusion, then, is useful only from an overall design standpoint.

Wood-Frame Construction

For wood-frame construction, as a single component, a different conclusion may be reached from these data. Two examples are given by Sabine et al. (1975) that illustrate the variation of airborne noise insulation and the thermal-transmittance. These examples are basically of wood-frame construction with exterior wood siding and 1/2-inch gypsum board interior finish. In the first example, cavity insulation was added and the STC rating increased less than 3 points; however, the air-to-air U-value decreased from 0.2 to 0.07 Btu $ft^2/°F$. This illustrates that the thermal transmittance may be changed significantly with very little change in the airborne noise insulation. In the second example, the interior gypsum board is mounted on resilient channels. In this case, the U-value for the construction was unchanged, but the STC rating increased 8 points. This illustrates that the airborne noise insulation may be changed significantly with very little change in the thermal transmittance. These examples emphasize the design potential of light-frame construction to meet both thermal transmittance and airborne noise insulation requirements by individually varying the construction details to achieve the design objective.

Fire Ratings and Noise Insulation

The degree of synergy present between noise reduction and energy conservation is a sharp contrast to the apparent lack of a quantitative relationship between noise reduction and the fire resistance properties of frame construction. For a fire rating of 1 to 3 hours, the STC ratings for frame construction can vary between 30 and 60.

Although an explicit relationship cannot be established, it is possible to determine bounds on the fire rating (expressed in hours) and the noise insulation (expressed as an STC rating) for conventional frame construction. Based upon data reported in the literature, a tabulation of STC rating and the fire rating was developed (Gypsum Association 1978, National Gypsum Co. 1981). The tabulation comprises 261 specific frame construction designs. The designs were conventional construction typical of interior walls, exterior walls, chase walls, shaft walls, and floor-ceiling assemblies. The data were sorted into STC intervals for each fire rating. The result is presented in table 10–5 as a percentage distribution of the designs that exhibit a given tire rating and have STC ratings within the indicated interval. For example, 6.2 percent of the designs provide an STC rating of 40 to 45 with a fire rating of 2 hours. This result is totally empirical. However, table 10-5 does provide an indication of the capability of frame construction to meet both a noise insulation specification and a fire-rating specification.

Table 10-5 – Percentage distribution of frame construction designs: Sound transmission class (STC) rating and fire rating

STC interval[1]	Frame construction design distribution, percent					
	Fire rating, hours					All
	3/4	1	2	3	4	
25-30	0	0	0	0	0	0
30-35	0.4	3.5	1.9	0.4	0	6.2
35-40	0	14.6	3.8	0.7	0	19.1
40-45	0	10.4	6.2	1.5	0.7	18.8
45-50	0.4	14.6	10.7	2.7	1.5	29.9
50-55	0	9.6	8.1	0.7	0.4	18.8
55-60	0	2.3	4.2	0	0	6.5
60-65	0	0.7	0	0	0	0.7
All	0.8	55.7	34.9	6.0	2.6	100.0

[1]The STC interval includes the lower limit and excludes the upper limit. Data from Gypsum Association (1978) and National Gypsum Co. (1981).

From a qualitative standpoint, there is an apparent synergy between noise insulation design and fire safety design. For example, increasing the gypsum board thickness and varying the cavity depth between panels influences both the fire rating and the sound transmission characteristics of light-frame construction. In the design of light-frame walls and floor-ceiling assemblies, one should consider this synergy so that the final construction emphasizes the dual objective of achieving a desired fire rating and level of noise insulation. Further, by requiring fire/draft stopping in concealed spaces, the result is to control both fire and smoke spread and to avoid potential flanking sound transmission paths. This qualitative synergy is most evident when incorporating draft stopping in attics and concealed floor-ceiling assemblies. By sealing all possible leaks and cracks to prevent passage of hot gases and smoke, one is also improving the acoustic integrity of the design. The basic point is that fire/draft stopping requirements may be integrated with the acoustical requirements so that both design objectives are achieved using a common construction.

Analysis Methods

Design-oriented methods for predicting the sound transmission loss of light-frame construction are presented below, followed by data that may be used with the prediction methods.

The first section defines the sound transmission loss of a structure as a measure of noise insulation. The next three sections are devoted to prediction methods. The prediction methods are classified according to the nature of the incident sound field and subclassified according to the structural configuration.

Sound Transmission Loss

The sound TL of a partition is defined in terms of the sound fields on either side of the partition and is a function of frequency. The sound TL is the ratio, expressed on the decibel scale, of the airborne sound power incident on the partition to the sound power transmitted by the partition and radiated on the other side (ASTM 1980d). The sound TL is expressed as:

$$TL = 10 \log(W_1/W_2) \text{ dB} \qquad (10\text{-}6)$$

where W_1 is the incident sound power, watts
W_2 is the transmitted sound power, watts

This definition is necessary in order to establish the sound TL as a property of the partition. Further, the definition emphasizes that the noise insulation performance of a partition depends upon the incident sound field.

The definition of equation (10-6) forms the basis for both the measurement and the prediction of the partition sound TL. From a measurement standpoint, it is necessary to develop a relationship between the sound power and the more easily measured sound pressure or sound pressure level. The relationship is based on theory and depends upon the nature of the sound field. As a result, measurement of the sound TL is based upon the functional form:

$$TL = L_1 - L_2 + \text{Normalization Terms} \qquad (10\text{-}7)$$

where L_1 is the incident sound pressure level, in dB
L_2 is the sound pressure level in the receiving space, in dB

The quantity expressed as “Normalization Terms” indicated in equation (10–7) represents mathematical functions relating the sound power to the sound pressure on each side of the partition. The explicit form of these functions depends upon the theoretical models used for this relationship.

From the standpoint of predicting the sound TL of a structure, equation (10-6) forms the basis of several theoretical models (Beranek 1971, Sharp et al. 1980). These models incorporate a theoretical description of the incident sound field and predict the transmitted sound field. The prediction methods may then be classified according to the incident sound field. This allows the following discussion of noise insulation of light-frame construction for both indoor-to-indoor and outdoor-to-indoor conditions.

Diffuse Sound Fields

Sound fields may be described in terms of the propagation directions of the sound waves at each point within the field. Simply stated, in a diffuse sound field, there is an equal probability of sound arriving from any direction at each point within the field. A diffuse sound field is an idealization. Perfect diffusion is approached in laboratory reverberation chambers at high frequencies or in cases where both the source room and the receiving room are large and contain little sound-absorbing material. The concept of a diffuse sound field is also used to approximate the conditions in typical rooms in buildings. The sound TL prediction methods presented in this section are based on the assumption that a diffuse incident sound field exists. These methods then apply to laboratory conditions and, as an approximation, to partitions separating adjacent rooms in buildings.

Single Thin Panel

The structure is a single thin panel of homogeneous material supported at its edges. The design equations apply to specific ranges of frequency based upon the mass and bending stiffness of the panel. The frequency range is defined by the panel fundamental resonance frequency, f_{11}, and the panel critical frequency, f_C. The general curve of sound transmission is presented in figure 10-1.

Fundamental resonance frequency, f_{11} – The panel fundamental frequency is the lowest resonance frequency of the panel. The incident sound field at this frequency excites the fundamental panel vibration mode, and the panel sound TL is low. For a rectangular panel with simply supported edges, the fundamental frequency may be estimated using the relationship:

$$f_{11} = 2.57\sqrt{D/\omega}\ [1/a^2 + 1/b^2]\ \text{Hz} \qquad (10\text{-}8)$$

where D is the panel bending stiffness, lb-in
ω is the panel surface weight, lb/ft²
a,b are the panel length and width, ft

Properties of a few common building materials are presented in table 10-6. For these common materials and typical dimensions of building construction, the panel fundamental frequency is so low that it can usually be ignored for sound TL problems. However, the panel fundamental frequency represents the lower frequency limit for which the prediction methods apply.

Critical frequency, f_c – As described above, the incident sound field excites panel vibrations at the resonance frequencies of the panel. This is a matching of the excitation frequency with the panel natural frequencies. Similarly, at high frequencies, the spatial wavelengths of the exciting sound field match with the structural geometry and excite panel response. The spatial matching of the sound field with the structural geometry is called coincidence. The lowest frequency for which this effect occurs is called the critical frequency, f_c. At each frequency greater than the critical frequency, coincidence occurs. The sound TL of the panel is rapidly decreased at the critical frequency just as it is decreased at the fundamental resonance frequency, f_{11}.

The critical frequency, f_c, of a thin homogeneous panel may be estimated either on a theoretical basis or on an empirical basis. Theoretically, the critical frequency may be estimated using the expression:

$$f_c = 1.24 \cdot 10^5\sqrt{\omega/D}\ \text{Hz} \qquad (10\text{-}9)$$

where ω is the panel surface weight, lb\ft²
D is the panel bending stiffness, lb·in.

Empirically, the critical frequency may be estimated using a relationship of the form:

$$f_c = \text{constant}/\omega\ \text{Hz} \qquad (10\text{-}10)$$

where the constant is empirically determined for the panel material. The dimensions associated with the constant are: Hz·lb/ft².

Examination of equation (10-9) indicates that the panel critical frequency is inversely proportional to the panel thickness (ω is proportional to the thickness and D is proportional to the thickness cubed). Hence, increasing the panel thickness (and the surface weight, ω) decreases the panel critical frequency. As a design objective, it is generally best to keep the panel critical frequency as high as possible to increase the sound TL of the panel over the frequency range between f_{11} and f_c.

Design equations – For a diffuse incident sound field, an estimate of the sound TL of a single thin panel may be determined theoretically (Beranek 1971, Sharp et al. 1980). The above discussion concentrated on the definition of the frequency ranges for which these theoretical results apply, and that a diffuse incident sound field is, at best, a laboratory condition. To account for nonideal sound fields, the theory also provides an estimate (Beranek 1971, Sharp et al. 1980). For sound fields typical of laboratory conditions, the sound TL of a single thin panel may be estimated using the expressions:

$$TL\omega = 20\log(\omega f) - 34.0\ \text{dB}\ (f_{11} < f < \tfrac{1}{2} f_c) \qquad (10\text{-}11a)$$

and

$$TL = TL_\omega + 10\log(\eta f/f_c) + 10\log[1 - (f_c/f)] + 3.6\ \text{dB}\ (f > f_c) \qquad (10\text{-}11b)$$

where f is frequency, Hz
q is the panel loss factor

Discussion – Equations (10-11a) and (10-11 b) may be applied for the frequency ranges indicated. From these results, it is seen that below the panel critical frequency, the sound TL increases at a rate of 6 dB for each doubling of either panel surface weight or the frequency (20 log(2) = 6). This result is commonly called the mass law, and the result applies to thin panels. Hence, the mass law does not imply massive structures – the only way to increase the panel mass, for a given material, is to increase the panel thickness. Above the critical frequency, the panel sound TL is determined using equation (10-11a). The discussion in the main text indicates the accuracy that may be achieved using these results (fig. 10-4).

Double Thin Panels

A double panel structure consists of two thin panels separated by an airspace of constant depth. The panels are connected only at their edges; and sound absorption material, such as glass fiber, is installed in the cavity. The sound absorption material is at least 2 inches thick and extends over the entire surface area of the panels. The design equations apply to specific frequency ranges as described below. The general shape of the theoretical sound TL as a function of frequency is presented in figure 10-10.

Cavity resonance frequency, f_o – The cavity fundamental resonance frequency corresponds to the mechanical resonance of the thin panels with the air enclosed within the cavity. This resonance frequency may be estimated using:

$$f_o = 321/\sqrt{\omega_e d} \text{ Hz} \qquad (10\text{-}12a)$$

where $\omega_e = 2\omega_1\omega_2/W$, lb/ft^2
$W = \omega_1 + \omega_2$, lb/ft^2
d is the cavity depth, in.

As a design objective, the cavity depth is usually established so that f_o has a prescribed value. The

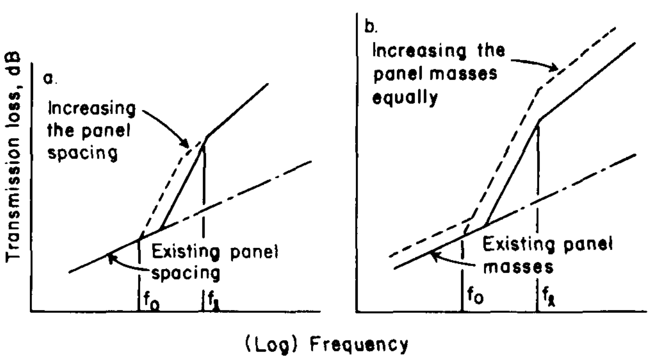

Figure 10-10 – The effect on the transmission loss of an ideal double panel of varying (a) panel spacing and (b) panel mass. (ML88 0023)

parameters ω_1 and ω_2 are the surface weights of each panel.

Cavity standing wave frequency, f_λ – This frequency corresponds to an acoustic standing wave between the parallel panels. The wavelength is twice the cavity depth at this frequency. This frequency may be estimated using:

$$f_\ell = 2158/d \text{ Hz} \qquad (10\text{-}12b)$$

where d is the cavity depth, in. The function of sound absorption material in the cavity is to damp out the harmonics of the standing wave. A full discussion of the benefits of cavity sound absorption is presented by Sharp (1973) and Sharp et al. (1980).

Design equations – For a diffuse incident sound field, the sound transmission loss of a double thin-panel construction may be estimated using the following equations:

$$TL = 20 \log(Wf) - 34.0 \quad \text{dB} \quad (f < f_o) \qquad (10\text{-}13a)$$

$$TL = TL_{\omega 1} + TL_{\omega 2} + 20 \log(fd) - 60.7 \quad \text{dB} \quad (f_o \leq f \leq f_\ell) \qquad (10\text{-}13b)$$

$$TL = TL_\omega + TL_\omega + 6.0 \quad \text{dB} \quad (f_\ell \leq f \leq \tfrac{1}{2} f_c) \qquad (10\text{-}13c)$$

The parameters used in the above equations are defined in equation (10–12a). The terms $TL_{\omega 1}$, and $TL_{\omega 2}$, are the sound TL functions for the individual panels as given by equation (10-11a).

Discussion – The general shapes of the functions given above are illustrated in figure 10–10. The above results indicate that at low frequencies, the double-panel construction behaves as a single panel with a surface weight equal to the total surface weight of the construction. This is seen by comparing equation (10-13a) to equation (10-11a). In the frequency interval between f_o and f_ℓ, the sound TL increases rapidly with frequency. This characteristic is utilized in design by selecting the cavity depth, d, to fix the value of f_o at the desired value. At frequencies above the cavity fundamental standing wave frequency, f_ℓ, the sound TL still increases with frequency. The rate of increase, however, is less than that for the frequency range between f_o and f_ℓ.

Another use of equation (10-13a) is possible if measured TL data for the individual panels are available. The measured TL data are substituted into equations (10-13a) through (10-13c) and the resulting value of TL plotted at the measurement frequencies. A smooth curve is drawn through these points. This method is not restricted by the upper limit denoted by the critical frequency f_c. Figure 10-6 illustrates an example of this prediction method.

Connected Double Thin Panels

In order to provide necessary structural stiffness, a framework must be used to support the two surface panels. The thin panels are parallel with one panel directly attached to the framework. Sound absorption material is assumed to be in the cavity as described above. The second panel is attached to the framework as described below. The method of attachment affects the sound TL of the structure.

Design equations – The prediction method is based upon use of equations (10-13a) and (10-13c). These equations are used to establish the curves indicated in figure 10-11. The solid line in figure 10-11 is the

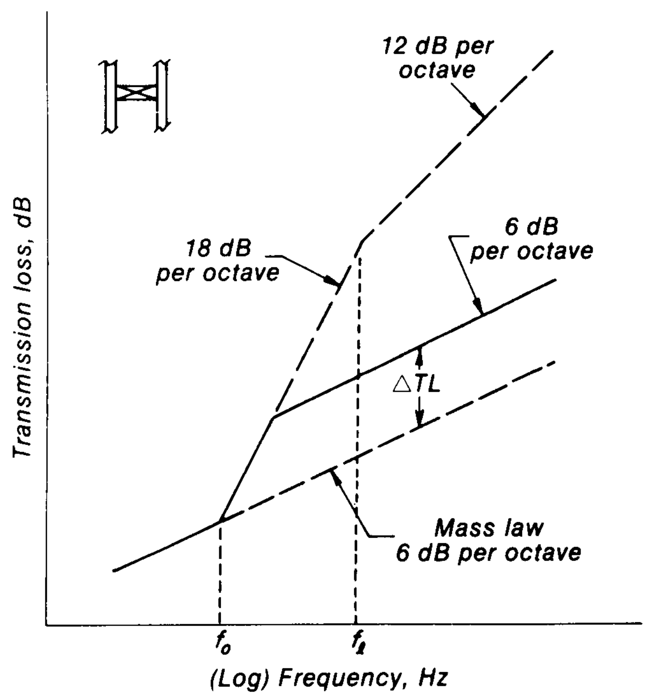

Figure 10-11 – General form for the transmission loss of a double panel with connections between the panels. (M151 516)

predicted TL of the structure. The dashed lines represent the extensions of the predictions using equations (10-13a) and (10-13b). The value of WTL, indicated in figure 10-11, is determined using the following expressions:

Direct Attachment

$$\Delta TL = 10 \log(f_c) + 10 \log(S/n\ell) + 20 \log(\omega_1/W) - 23.6 \text{ dB } (f \le \tfrac{1}{2} f_c) \quad (10\text{-}14a)$$

Point Attachment

$$\Delta TL = 20 \log(f_c) + 10 \log(S/n) + 20 \log(\omega_1/W) - 55.2 \text{ dB } (f \le \tfrac{1}{2} f_c) \quad (10\text{-}14b)$$

where S is the panel surface area, ft^2
ℓ is the length of a single stud, ft
n is the number of point attachments or studs
$W = \Omega_1 + \omega_2$, lb/ft^2

In using equation (10-14a), f_c is the highest critical frequency of the two panels, and ω_1 is the surface weight of the other panel. In using equation (10-14b), f_c is the critical frequency of the panel supported by the point attachments, and ω_1 is the surface weight of the other panel.

The use of the terms "direct attachment" and "point attachment" require clarification. For a direct attachment, the panel may be attached to the studs at points; however, the panel is in direct contact along the entire length of the stud (Sharp 1973). From a theoretical aspect, the point attachment must allow the panel to contact the stud only at a point along the stud length. That is, the panel must be separated from the stud by a small spacer. The panel is then attached using a nail or screw through the spacer to the stud.

Discussion – If the above instructions are closely followed, this prediction method can be extended to include any combination of either point or direct attachment desired (Sharp 1978). The experimental verification is limited to a few designs; however, it appears to be the best available prediction method at this time (Jones 1978).

Directional Sound Fields

This section presents design-oriented methods for predicting the sound TL of structures exposed to incident sound waves arriving from a restricted direction. The direction of the sound wave is defined by an angle of incidence, θ, measured from the normal to the panel. Directional sound waves are most typically encountered from outdoor environmental noise sources. Hence, these methods may be used – with judgment – to estimate the sound attenuation of exterior walls of buildings.

Point Noise Source

A point noise source may be used to approximate many environmental noise sources provided that the distance from the source to the measurement location is large, relative to the source dimensions (Beranek 1971). At large distances, the spherical sound waves spread into plane waves. These plane waves arrive at the panel at an angle of incidence 13.

Normal incidence – If the plane waves arrive parallel to the plane of the panel, the sound is said to arrive at normal incidence (θ = O). For this condition, the sound TL of the thin panel is given by the expression:

$$TL_o = 20 \log(\omega f) - 20.9 \text{ dB} \quad (f \leq \tfrac{1}{2} f_c) \qquad (10\text{-}15)$$

where ω is the panel surface weight, lb/ft^2
f is the frequency of the sound, Hz
f_c is the critical frequency (eq. (10-9))

The above result should be used for prediction for frequencies such that $TL_o > 15$ dB. Methods are available for predicting the sound TL above the critical frequency (Bragdon 1975).

Incidence at angle, θ – For plane sound waves that arrive at the panel at an angle of incidence θ, the panel sound TL is estimated using:

$$TL(\theta) = TL_o + 20 \log(\cos\theta) \text{ dB} \qquad (10\text{-}16)$$

where TL_o is given by equation (10-15). This result is valid for incidence angles in the range $0° \leq \theta \leq 60°$ (Beranek 1971).

Discussion – If these approximations are used for outdoor-to-indoor noise isolation design, the noise source must be fixed in location relative to the plane of the panel.

Line Noise Source

A line noise source is quite commonly used to model highway traffic noise (Barry and Reagan 1978, May 1978). Attenuation of highway traffic noise is a major problem both for highway agencies and builders developing land adjacent to highways. The noise attenuation is a major design consideration in the construction of both highway noise barriers and exterior walls of buildings. This section describes one approach to estimate the noise insulation of such structures. The sound TL depends upon the orientation of the plane of the panel relative to the line source as illustrated in figure 10-8.

Perpendicular line source – For a single infinite-length line source with an orientation perpendicular (normal) to the plane of the panel, the expression for the sound TL is given by:

$$TL_{\omega ine} = TL_o - 10 \log [TL_o + 6] + 9.4 \text{ dB} \qquad (10\text{-}17)$$

where TL_o is given by equation (10-15).

Parallel line source – For a single infinite-length line source with an orientation parallel to the plane of the panel, the expression for the sound TL is given by:

$$TL_{\omega ine} = TL(\Gamma) 10 \log [TL(\Gamma) + 6] + 9.4 \text{ dB} \qquad (10\text{-}18)$$

where $TL(\Gamma)$ is given by equation (10-16) evaluated at the incidence angle Γ illustrated in figure 10-8.

Discussion – The expressions given in equations (10-17) and (10-18) should be used for tentative guidance. Field test data have been reported; however, the application for detail design of frame construction must await field evaluation (Lewis 1974, Rudder 1983).

Data for Common Building Materials

Data that may be used in connection with the prediction methods are presented in tables 10-2 and 10-6.

Units and Constants

Acoustics uses the SI system of measurement (Beranek 1971). In this system mass, length, and time have the units of kilogram (kg), meter (m), and seconds (s). All of the equations in this chapter have been converted to the mixed English units of pounds (lb) for weight, feet (ft) and inches (in) for length, and seconds (s) for time. Further, the characteristic resistance of air (ρc) has been taken as 83.2 lb/ft2·s, and the speed of sound has been taken as 1,130 ft/s. The gravitational constant used is 386.4 in/s^2.

Table 10-6 – Data for common building materials (abridged from ASTM 1980b and Gypsum Association 1978)

Building material	Density[1]	ωf_c	Loss factor[2]
	lb/ft³	*Hz·lb/ft²*	η
Concrete	150	9,000	0.005-0.02
Brick	120-140	7,000-12,000	0.01
Glass	156	7,800	0.001-0.01
Gypsum board	48	6,300	0.01-0.03

[1]Density of concrete will vary depending upon aggregate used.
[2]Loss factor for glass is very sensitive to edge-mounting conditions.

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