SANDWICH PANELS FOR BUILDING CONSTRUCTION

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SANDWICH PANELS FOR BUILDING CONSTRUCTION

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Summary

Sandwich panels consisting of thin facings bonded to thick, light-weight cores have been developed for many uses, including aircraft and buildings. This report summarizes research at the Forest Products Laboratory on the use of sandwich panels in housing and other buildings.

Sandwich cores include honeycombs of paper or other thin sheet materials of various configurations, foamed resins, or other materials. Paper honeycombs can be treated with resin to increase their strength and resistance to moisture. Techniques for fabricating paper-honeycomb cores are well developed. Facing materials include plywood, wood-fiber boards, cement-asbestos boards, reinforced plastics or laminates, and various metals. Phenol, resorcinol, or melamine glues are widely used for bonding facings to cores of wood or wood-base materials, while other adhesives or techniques may be required with metals or plastics.

This report gives formulas for calculating the strength and stiffness of sandwich panels and illustrates their use. Structural tests have confirmed the validity of the formulas and demonstrated the excellent structural properties of sandwich panels. While high moisture content and aging may adversely affect these properties, sandwiches can be made structurally adequate after those effects are taken into account. A sandwich exposure unit enclosing a heated space at Madison, Wisconsin, remains in good condition after 11 years of exposure.

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

Since sandwich panels have large surface areas, changes of dimension or warping that accompany climatic changes must be taken into account. The bowing and cupping of full-size panels were studied, both under steady-state conditions and in service exposure. A formula for calculating bow was verified by observations of bow up to about 1/4 inch in plywood-faced wall panels 8 feet long.

Sandwich panels have heat-insulating properties in accordance with their thickness and the materials used. Insulating properties of honeycomb core can be improved by filling the core with foamed plastic or certain granular materials. Heat flow at joints and fastenings may be a serious problem with constructions in which metal parts are used. Sandwiches with perforated facings give sound absorption comparable to that in many existing acoustical materials. Sandwiches, because of their structural dependence on the bonding of thin materials, are vulnerable to fire but the use of a paper-honeycomb core in a panel does not particularly increase the fire hazard. Decay and termite resistance offer no problems different from those involving the same materials when used more conventionally.

Sandwich panels in buildings must be structurally adequate, have the necessary insulating qualities, and be economical to make and use. Room design should be related to a convenient module of panel width, such as 3 or 4 feet, or panels of room size should be made. One of the most critical problems is that of developing joints or fastenings that transmit the loads safely and keep joints tight with seasonal changes of weather. Experience with the sandwich exposure unit at the Forest Products Laboratory has shown that a usable structure can be made and that erection of a building of sandwich construction is quick and easy.

Introduction

A structural sandwich is a layered construction formed by bonding two thin facings to each side of a thick lightweight core. Principal stresses under load are carried by the facings, which are generally high in density and strength. A strong and durable adhesive between core and facings is required. A sandwich has great strength and stiffness for its weight. For building uses, such desirable features as impermeable facings that act as moisture barriers and the incorporation of thermal insulation or fire resistance in the cores are readily attained. The wide range of possible facings permits an unlimited choice of decorative effects.

Structural sandwiches made of layers of dissimilar materials have long been used. General recognition of the structural properties of sandwiches and development of the principles for making use of those properties, however, did not occur until the time of World War II, when durable adhesives became available for bonding the parts together. An outstanding example of that time was the Mosquito Bomber (fig. 1), an airplane of sandwich construction consisting of thin birch plywood facings on a thick balsa-wood core. Rapid development for aircraft uses occurred as the high ratio of strength and stiffness to the weight of the sandwich became generally known. Experiments were made with a great variety of core and facing materials.

It was soon apparent that the qualities in aircraft sandwich panels would be useful also in housing or other building construction. Early experimental work in this direction began at the Forest Products Laboratory as World War II ended. An exposure unit at the Laboratory has been under continuous service test since 1947. A rapid increase in the use of the hollow-core flush door, a structural sandwich, occurred at about the same time. More recently, there has been increasing use of sandwich in curtain wall constructions in large buildings. Curved panels have been employed to form a vaulted roof in a school building in Tacoma, Washington. Today, the sandwich panel is widely recognized as a versatile and useful structural element.

Structural sandwiches have had a great variety of uses. Core materials have included honeycomb constructions of paper, thin wood, metal, and glass fabric, as well as cellular cellulose acetate, foamed rubber, or plastic. Facings have included plywood, hardboard, asbestos board, sheet metals, and plastic laminates. Sandwich constructions for ship hulls have been investigated. Miscellaneous uses include tanks, trailers, shipping containers, pallets, and furniture.

A major building use of sandwich panels is presently for curtain-wall construction in large commercial buildings. Porcelain-enameled steel or aluminum facings on cores of paper honeycomb or foamed glass are popular for such applications. The porcelain surface offers a wide choice in color or texture and gives a permanent finish. This construction with textured aluminum faces was used in an automobile manufacturing plant at Indianapolis. Sandwich panels with porcelain-enameled steel facings used in another manufacturer's technical center near Detroit are shown in figure 2. Sandwich-type construction has also been employed for banks in Detroit, Manhattan office buildings, and numerous other buildings. Many of these panels are, of course, curtain-wall type rather than load-bearing units.

Sandwich panels as structural units in houses have been used experimentally. Experimental sandwich-type homes were built in the late 1940's by developers of sandwich in Massachusetts, Virginia, and California. Figure 3 shows the experimental sandwich unit erected at the Forest Products Laboratory in 1947 and still under test. Several desirable features of sandwich for housing construction have long been recognized. A thermal insulating core can be combined with thin facings to make a strong and stiff wall or roof unit. Such units are light in weight, a factor of particular advantage for the transportation of prefabricated houses. Interior partitions can be faced with various materials, such as decorative plywood.

The hollow-core flush door presently constitutes the most widespread use of sandwich in housing. Figure 4 illustrates four types of hollow-core construction. A Forest Products Laboratory report (12)[2] summarizes the construction and use of hollow-core flush doors. Such doors are light in weight and have ample strength and stiffness. Most are made for interior use.

While much research has been done on structural sandwiches, few reports have been published on sandwich for building construction. The purpose of this report is to summarize the published and unpublished information in a general publication on construction and use of sandwich in buildings. This publication is intended to be a source of information for makers and users of sandwich panels and others who may be interested. While much of the information is technical in nature, it is presented in a form designed to be usable by anyone in the building industry.

Principal emphasis is given in this report to the research of the Forest Products Laboratory on structural load-bearing sandwiches of wood or wood-base materials and intended for residential or similar light building construction. Examples of other uses of sandwich have already been cited. Much of the basic information given, however, is applicable to sandwiches made of any suitable material and used in any type of building.

Construction of Sandwich Panels

Factors Affecting Design

The two principal structural functions of the core of a sandwich are (1) to hold the facings straight and parallel, and (2) to transmit shear stresses between the facings in the same manner as the web functions in an I-beam. The core is light in weight, and its thickness imparts strength and stiffness to the sandwich through the resulting spacing of the facings. Relatively thin facings of dense material carry the principal stresses, deriving their

[2] Underlined numbers in parentheses refer to literature cited at the end of this report.

stability from the lateral support given by the thick core. This mutual interaction is made possible by bonding the facings to the core with a strong and durable adhesive.

A sandwich panel for building use must be durable. Facings, core, and adhesive must remain strong under conditions of use which may include severe moisture exposure, decay, or insect attack. This may involve preservative treatment as conditions warrant.

Heat insulation, fire resistance, and resistance to moisture are properties that influence the design of the core. Facings must be thick enough and strong enough to resist puncture. Light weight may be important, though generally less so in buildings than in vehicles.

Cost may be the critical factor in sandwich design. Facings should be no heavier than required to carry the loads. Cores of lighter weight are generally lower in cost, but they must be structurally adequate. Resin treatment of honeycomb paper cores is essential for providing resistance to moisture, but the resin content should be no higher than is necessary to do the job. Most building uses require a weatherproof adhesive, but lower priced adhesives of limited moisture resistance may have value in some interior uses.

Core Materials

Sandwich cores are generally made of cellular configurations of a sheet material, such as paper, cloth, mineral fabric, or metal, or of foamed or expanded materials. From considerations of availability and economics, resin-treated paper honeycomb has had much study (10). Polystyrene or other foams currently show promise of large-scale development. This report deals mainly with paper-honeycomb cores (10).

Paper-Honeycomb Cores

Kraft-base papers are suitable for making honeycomb cores. Weights of 30 to 125 pounds per 3,000 square feet have been used. A 50-pound paper was the basis of much of the research at the Forest Products Laboratory, although it appears that a 30-pound paper can make a satisfactory sandwich for building use. Honeycombs with relatively large cells require heavier papers. Paper of light weight may be hard to handle while being corrugated or during fabrication of the core. It appears that any of the ordinary chemical pulps are suitable for making core papers. For applications where maximum permanence is not a factor, a high-yield semichemical pulp may be acceptable or even preferable. Since the core material in a sandwich panel is protected from ultraviolet light, which is a major factor in deterioration, the permanence of such pulps may not be critical. Reclaimed paper may also provide suitable fiber for sandwich cores.

Paper honeycomb cores need resin treatment to get adequate moisture resistance and wet strength. Phenolic or polyester resins have been used. A treatment with 15 percent of a water-soluble, phenol-formaldehyde resin has been found to give suitable wet strength (9). A resin content greater than about 15 percent does not produce a gain in strength commensurate with the increased quantity and the cost of the resin required. There is evidence that as little as 5 percent of water-soluble resin gives adequate wet strength. Alcohol-soluble resins have also been used; they appear to coat the fibers, whereas water-soluble resins penetrate them (9, 10). Resin may be added to the paper in a separate impregnating machine, or quantities of 15 percent or less may be applied when the paper is manufactured (10). It is possible to add resin during paper manufacture by:

1. Applying it at the paper-machine size press or similar device.
2. Blending the fiber and resin in water suspension in the beater and retaining this resin in the sheet during papermaking.
3. Continuous addition of liquid resin at the machine headbox.

Tensile tests of untreated papers have shown that they have practically no wet strength. Papers impregnated with 5 to 15 percent of phenolic resin retained one-half to two-thirds of their dry tensile strength when wet (9).

Aging effects on a 50-pound kraft paper treated with 5 to 15 percent of resin were tested in tension after 72 hours' exposure to steam at 208° F. (9). Losses of tensile strength ranged from 0 to 18 percent, averaging about 8 percent.

Many configurations of paper honeycomb core are possible, but expanded and corrugated types presently appear to be the most important. Expanded types are available commercially in large quantities and are easily shipped for long distances when compressed. Corrugated types utilize the same corrugated papers that are extensively used in the packaging industry.

In the expanded type of core, sheets of paper are laid up and coated with parallel strips of adhesive. The adhesive strips on successive sheets are positioned at midpoint between the strips of the preceding and the succeeding sheet. After the adhesive is cured, the core blanks are cut into strips of a width equal to the desired thickness of the core. Guillotine-type cutters used for this purpose can be operated to a width tolerance of 0.01 inch or less. The core may then be expanded for placement in the sandwich or shipped in its compressed form. Special machines have been designed to mechanize the bonding and expansion of this type of core. Figure 5 shows the hexagonal cells typical of expanded core. This core has good structural properties, but the arrangement of any core with cells perpendicular to the facings may give rise to problems of insulation or fire hazards.

Much research has been done at the Forest Products Laboratory on the corrugated-paper honeycomb core. In this type, the cell or flute is made by hot-forming resin-treated paper between fluted rolls on equipment of the type used in making corrugated container board. The corrugated sheet, with or without flat interleaving sheets, can be assembled in many ways. Figure 6 shows the PNL type with flat interleaves(P standing for all flutes parallel, N for paper normal to facings, and L for interleaves), while figure 7 shows the XN type with corrugations at right angles in adjacent sheets (X for crossed flutes, and N for paper normal to the facings). Both types have good structural properties. A third type, XF, is identical with XN but is placed in the sandwich with all flutes parallel to the facings (X for crossed flutes, and F for paper flatwise). This is little used, because of its lack of strength and rigidity perpendicular to the facings. Work at the Forest Products Laboratory has shown that corrugated cores can be made with equipment and techniques that are widely available.

The weight of paper honeycomb cores varies with the weight of paper, the amount of resin added to the paper, and the size of the cells. Cores with larger cells require heavier paper, and thus may weigh nearly as much as cores with small cells. Corrugated cores have been mostly in the range of 2 to 5 pounds per cubic foot. Expanded cores have been made with densities from 1 to 6 pounds per cubic foot; values below about 2 pounds per cubic foot, however, are generally for untreated cores.

Paper for corrugated-type honeycomb cores may be corrugated on fluted rolls of the type common in the box industry. The A-size flute, 1/3 inch wide and about 3/16 inch deep, was used in corrugated cores at the Forest Products Laboratory. Larger flutes with heavier papers may be desirable. The PNL type (fig. 6) is made by laying up corrugated and flat sheets alternately and bonding them into blocks of considerable thickness, almost exactly as is now done in making blocks for insulation or cushioning in packaging. Resin treatment stiffens the corrugated sheets and makes them easier to handle. Corrugating machines are available in which a flat sheet and a corrugated sheet are bonded together to make a single-faced board; a number of such boards are then stacked to make PNL blocks of the desired thickness. Fabrication of the XN type of core is similar, except that all sheets are corrugated and adjacent sheets are laid so that flute directions are at right angles. After bonding, the stack of sheets is cut into strips equal in width to the thickness of the core desired for the sandwich panel. Figure 8 shows the cutting of the core on a bandsaw; circular saws may also be used. Cutting within a tolerance of 0.015 inch in thickness has been found to be satisfactory for cores of this type 2 inches or more in thickness. These operations are relatively simple by hand, but production of large volumes of core would require that they be mechanized.

Most of the early work on corrugated-paper cores involved the use of costly adhesives to bond the paper sheets within the core. Since the bond between individual sheets is not critical to the structural properties of sandwich panels with XN or PNL cores, experiments have been made with cheaper adhesives. Comparative tests were made on panels with 1/4-inch plywood facings having XN-type cores in which the flutes were bonded with (a) phenolic resin, (b) urea resin, (c) sodium silicate, and (d) no adhesive. The presence or nature of the adhesive within the core appeared to have only a slight effect on the shear strength of panels tested in either the dry or the wet condition, provided that the corrugations were perpendicular to the facings. While it is not practical to assemble a core and fabricate a sandwich panel without a sheet-to-sheet adhesive, the tests showed that lower-cost adhesives can be used for this purpose (9). Where corrugations are parallel to the facings, shear strength depends upon the glue bond within the core.

Other Honeycomb Cores

Aluminum honeycomb cores of both the expanded and the corrugated types have been used extensively in aircraft construction, and to a lesser extent in some of the larger buildings. Their cost appears to preclude them from general building use. Aluminum honeycomb cores are now commercially produced in a wide range of densities and mechanical properties (6). Expanded aluminum cores are thermally conductive because of the continuity of metal from facing to facing. Another problem with aluminum and some other metal cores is the difficulty in getting satisfactory bonding to the facings with a low-cost adhesive.

A considerable number of other materials have been used in honeycomb cores, some only experimetally. These include strips of veneer, impregnated glass cloth (7), vegetable fabrics, glass fiber, and foams of isocyanate, polystyrene, or other plastics. Foamed cores have been used in hollow-core flush doors.

Table 1 gives some mechanical properties of typical core materials. Properties indicated include those that are important in building sandwich design.

Strength values are based on the gross area of the expanded core. The table shows that the heavier cores have the higher strength properties.

Facings

One of the advantages of the sandwich panel is the great latitude it provides in the choice of facings and the possibility of using thin sheet materials because of the nearly continuous lateral support afforded by the core. The stiffness, stability, and to a large extent the strength, of the sandwich are determined by the characteristics of the facings. A wide variety of materials are suitable. The choice among these involves a number of considerations. There must be enough strength and stiffness to meet structural requirements for the completed sandwich. A reasonable degree of puncture resistance is necessary. Considerations of fire resistance, thermal insulation, or vapor permeability are influenced by the core as well as the facing. The expansion characteristics of the facings largely control the stability of the size and shape of sandwich panels. Cost and availability are important considerations.

Some of the materials suitable for sandwich facings are plywood and veneer, with or without resin-treated paper overlays; hardboards or other wood-fiber or particle boards; cement-asbestos board; fiber-reinforced plastics or laminates, including resin-impregnated glass cloth; metals, such as aluminum, magnesium, enameled steel, or stainless steel; and combinations of wood and metal.

Plywood is a versatile facing material, and the performance of panels with plywood facings can now be well predicted. It has good dimensional stability and structural properties and can be dependably bonded to the core with proven adhesives. When exposed to outdoor conditions, some plywoods, such as Douglas-fir, may show face checking and raising of the grain. This may be largely eliminated by the use of a resin-treated paper overlay sheet bonded to the outer face of the sandwich panel to produce a smooth surface and a uniform base for painting. Since the facing is securely bonded to the core of the sandwich panel, a two-ply veneer facing, with or without an overlay, can be used, as in flush doors. Although each facing is unbalanced, the panel as a whole is in balance.

Sandwich facings for wall panels in the Forest Products Laboratory exposure test unit (13) included: 1/4-inch, three-ply Douglas-fir of exterior type, Sound-2-Sides grade, some with a resin-treated paper overlay on one face; two-ply Douglas-fir of 1/10-inch veneers with the grain of the veneers at right angles and a resin-treated paper overlay on one side; 1/8-inch Douglas-fir veneer with resin-treated paper overlays on both sides; 1/8-inch or 1/4-inch hardboard;

1/4-inch cement-asbestos board; 1/8-inch hardboard with a thin porcelainized steel sheet bonded to the outer side; and 0.02-inch clad aluminum. Floor panels were faced with 3/8-inch, five-ply Douglas-fir plywood of Exterior type and Sound-2-Sides grade.

Resin-impregnated facings of glass cloth or metal in great variety have been used extensively on sandwiches for aircraft or in the construction of large buildings. Aluminum facings may be in the cost range available for housing or other small buildings. A considerable number of Forest Products Laboratory reports (14) have been issued on plastic laminates and on various sandwich constructions with plastic or metal facings. Proceedings of the Porcelain Enamel Institute include papers on properties and various applications of enameled steel sandwich facings.

Table 2 gives properties of a number of sandwich facing materials. Materials of a considerable range in weight, strength, and stiffness are listed. Those that show a large loss of strength and stiffness when soaked, or a linear expansion greater than 0.25 percent, are questionable for exterior use. The three-ply plywood shown in table 2 was of exterior type. Other exterior-type plywoods may be expected to be comparable in moisture content and absorption, while strength, stiffness, and linear expansion may vary with the species and the construction. A Forest Products Laboratory publication (8) indicates means of calculating the strength properties of any construction of plywood.

Fabrication

Fabrication of cores has already been discussed. Honeycomb cores are available commercially, so that assembly of a sandwich panel often begins with blocks of the completed core.

Durable bonds of paper honeycomb cores to wood or wood-base facings are obtainable with phenol, resorcinol, melamine, or similar resin glues. Urea resin or casein glues will give good strength and durability in interior service where exposure conditions are mild. The allowable assembly time may be a critical factor where sandwich panels are complicated in layup. Most of the sandwich panels made at the Forest Products Laboratory were bonded with an acid-catalyzed intermediate-temperature-setting phenolic-resin adhesive applied at about 22 grams per square foot of surface. Adhesives may be applied with rubber rolls to either core or facing, or both, but it was found that with a resin spread of 22 grams per square foot, application was necessary only to the facings. The intermediate-temperature-setting resin was allowed to stand 3 to 20 hours after application, so that the solvent of the resin could evaporate before the panels were assembled and pressed.

The following tabulation indicates a number of bonding techniques that are possible with paper-honeycomb cores and wood or wood-base facings about 1/4 inch thick:

Equipment	Resin Adhesive	Pressing Conditions
Hot press	Phenol, melamine, or fortified urea	10 to 30 minutes at 240° to 320° F.
Cold press	Resorcinol or phenol-resorcinol	6 hours at 75° F.
Vacuum bag (cold)	Resorcinol or phenol-resorcinol	6 hours at 75° F.
Vacuum bag (hot)	Resorcinol, phenol-resorcinol or fortified urea	15 minutes at 210° F.
High-frequency press	Resorcinol, phenol-resorcinol or fortified urea	2 to 5 minutes at 210° F.

Pressure must be adequate to insure contact of the surfaces to be joined, but must be carefully controlled to avoid crushing of the core. A limited amount of crushing of corrugated-paper honeycomb cores may be permissible to insure full contact of core and facing; 2 to 3 percent compression of the thickness of the core is possible without serious damage. Pressures of 15 to 25 pounds per square inch for 40 minutes at 230° F. were found satisfactory with the corrugated-paper honeycomb cores and the acid catalyzed, intermediate-temperature-setting phenolic resin used at the Forest Products Laboratory. Lower pressures may be needed with expanded paper cores or cores of low density. Where the panel has a wood frame, as in a flush door, pressures may be increased appropriately. Conventional plywood presses may not provide the close control required in the low range of pressures used, and special presses may be desirable for sandwich panels. Because the required pressure is low, simple and perhaps less costly presses could be used. Pressing of sandwich panels with dissimilar facings in hot presses has been found difficult because of unequal dimensional movement of the facings in response to moisture or thermal changes.

Bonding of cores and facings of metals, glass-fiber laminates, or other materials involves a variety of problems. The process requires proper surface preparation of materials and the use of recently developed special resin adhesives for bonding metal to metal, metal to wood, glass fiber to glass fiber, or a host of other possible combinations. Many of these adhesives cure only at high temperatures. Welding or brazing is sometimes used with metals. Most of the development has been related to aircraft sandwiches, but much of it applies to the large variety of materials used in curtain-wall sandwiches in large buildings. The techniques for fabricating such sandwiches have been reported (15). Various reports in the proceedings of the Porcelain Enamel Institute refer to the fabrication of enameled steel facings, such as are often used in large buildings.

Sandwich panels generally require final edge trimming to size. Honeycomb-paper or other wood or wood-base materials may be sawed, planed, or milled with ordinary woodworking machinery. Metals or other hard materials usually require special cutting tools. Edge trimming is often accompanied by routing or shaping to receive splines or other fastening devices.

Insertion of fasteners, utilities, or service fixtures in sandwich panels sometimes causes problems. With edge fasteners, the problem involves tying together thin facing materials, which may be highly stressed. Splines or other edge inserts for this purpose should be matched to the core with respect to dimensional change from moisture or temperature. Pipes or conduits up to 5/8 inch in diameter have been successfully pressed into paper-honeycomb cores without previous routing of grooves to receive them (fig. 9). If the cores are not too thin, larger inserts may be pressed into place.

Structural Properties of Panels

Formulas for Calculation

The bending stiffness of a flat sandwich panel with facings of equal thickness is given by the formula:

$$D = E_f \frac{b(h^3 - c^3)}{12} + E_c \frac{bc^3}{12} \qquad (1)$$

where D is stiffness in pounds-(inches)^2, E_f and E_c are moduli of elasticity of the facings and of the core, respectively, in pounds per square inch, b is the width and h is the thickness of the panel in inches, and c is the thickness of the core in inches. Since most sandwich cores for building construction are light in weight and low in stiffness, the last term of (1) can usually be omitted.

The shear stiffness of the core is given by the formula:

$$N = G_c \frac{(h + c)b}{2} \tag{2}$$

where N is stiffness in pounds and G_c is the shear modulus of the core in pounds per square inch.

The deflection of a uniformly loaded sandwich panel simply supported at its ends is given by the formula:

$$w = \frac{5 Wa^3}{384D} + \frac{Wa}{8N} \tag{3}$$

where w is the midspan deflection in inches, W is the total load in pounds, and a is the length of span in inches. With a long span in relation to the thickness of the panel the deflection due to shear is negligible and the last term of (3) may be omitted.

The stresses produced by bending of a sandwich panel with equal facings are given by the formulas:

$$F = \frac{2M}{f(h + c)b} \tag{4}$$

and

$$S = \frac{2V}{(h + c)b} \tag{5}$$

where F is the average compressive or tensile stress in the facing and S is the shear stress in the core, in pounds per square inch, M is the bending moment in inch-pounds, V is the shear load in pounds (2V = W in a simply supported panel under uniform load), b is the width and h is the thickness of the panel in inches, c is the thickness of the core in inches, and f is the thickness of one facing in inches.

Edgewise compressive loads cause compressive stress in the facings or may cause a long panel to bend or buckle. The compressive stress in the facings is given by the formula:

$$C = \frac{P}{2fb} \tag{6}$$

where C is compressive stress in pounds per square inch and P is the edgewise compressive load in pounds.

The load that will cause the panel to bend or buckle is given by the formula:

$$P = \frac{\pi^2 D}{a^2 \left(1 + \frac{\pi^2 D}{a^2 N}\right)} \qquad (7)$$

with units as previously defined.

Formulas (1) to (7) are suitable for sandwich panels with thin facings of equal thickness. More exact analyses have been made for sandwiches with facings of different thicknesses, for moderately thick facings, or for heavy-duty sandwiches with facings that may wrinkle into or away from the core (15).

Example of Structural Design

A typical problem in sandwich design is that of calculating a sandwich wall panel 8 feet long and 4 feet wide that will carry a horizontal load of 15 pounds per square foot and a vertical load of 500 pounds per lineal foot. Common practice requires that deflection under the horizontal load must not exceed 1/360 of the span. The facings will be Douglas-fir plywood with an allowable stress of 1,600 pounds per square inch on those plies with grain parallel to the stress, and an effective modulus of elasticity of 900,000 pounds per square inch parallel to the face grain. The paper honeycomb core has an allowable shear stress of 10 pounds per square inch and a shear modulus of 6,000 pounds per square inch.

Since the stiffness requirement may govern the design, the panel will be calculated on that basis and then checked against the allowable stresses. A facing thickness of 1/4 inch will be assumed for the plywood to assure adequate resistance to puncture or impact. In 1/4-inch sanded plywood, the combined thickness of the two plies parallel to the direction of stress is 0.14 inch.

Since the solution of the complete formula (3) for h or c is difficult, an approximation will first be made by dropping the last term. Then, putting the deflection requirement in formula (3):

$$\frac{a}{360} = \frac{5\ Wa^3}{384\ D} \text{ or } D = \frac{75}{16}\ Wa^2$$

$W = 15 \times 4 \times 8 = 480$ pounds, and $a = 12 \times 8 = 96$ inches.

$$D = 20.7 \times 10^6$$

Then in formula (1), again dropping the last term,

$$h^3 - c^3 = \frac{12 \times 20.7 \times 10^6}{48 \times 900,000} = 5.75$$

With the thickness of each facing denoted by f,

$$h = c + 2f \text{ and } h^3 - c^3 = 6c^2 f + 12cf^2 + 8f^3$$

When $f = 1/4$:

$$3/2\, c^2 + 3/4\, c + 1/8 = 5.75 \text{ and } c = 1.70 \text{ inches.}$$

Use $c = 1.75$ making the total thickness of the panel 2-1/4 inches.

Now check on the effect of core shear deformation on the deflection of the panel, From formula (2):

$$N = \frac{6,000 \times 4 \times 48}{2} = 5.76 \times 10^5 \text{ pounds}$$

And from formula (1), omitting the last term:

$$D = \frac{900,000 \times 48 \times (11.39 - 5.36)}{12} = 21.7 \times 10^6$$

Then, from the formula (3), using all terms:

$$w = \frac{5 \times 480 \times 96^3}{384 \times 21.7 \times 10^6} + \frac{480 \times 96}{8 \times 5.76 \times 10^5} = 0.255$$

$$+ 0.010 = 0.265 \text{ inch}$$

This shows that deflection of this panel due to core shear deformation is small and that the total deflection of 0.265 inch is 1/362 of the span.

While the remainder of these design computations are based on a panel thickness of 2-1/4 inches, it may be noted here that a greater thickness of wall may be required for thermal insulation (pages 24-25), installation of fittings or utilities, or other reasons not related to strength. A moderate increase in thickness of the panel will substantially increase its strength and stiffness against the horizontal loads.

The shear stress in the core of the panel due to horizontal load, as calculated from formula (5), is:

$$S = \frac{4 \times 8 \times 15}{4 \times 48} = 2.5 \text{ pounds per square inch}$$

which is well within the allowable shear stress.

In calculating stresses in the facings, it is assumed that only those plies that have grain parallel to the direction of stress are effective. The effective thickness of each 1/4-inch facing is thus 0.14 inch.

The compressive (or tensile) stress in the facings due to horizontal load, as calculated from formula (4) and $M = \frac{WL}{8}$, is

$$F = \frac{2 \times 5,760}{0.14 \times 4 \times 48} = 428 \text{ pounds per square inch}$$

The compressive stress in the facings due to vertical load, as derived from formula (6), is:

$$C = \frac{500 \times 4}{2 \times 0.14 \times 48} = 149 \text{ pounds per square inch}$$

The sum of the stresses from horizontal and vertical loads occurs in the compression facing of the panel and is equal to 428 + 149 = 577 pounds per square inch, well below the allowable value of 1,600 pounds per square inch.

A check of the buckling load on the panel is made by formula (7), as follows:

$$\frac{\pi^2 D}{a^2 N} = \frac{9.87 \times 21.7 \times 10^6}{96^2 \times 5.76 \times 10^5} = \frac{214 \times 10^6}{5,310 \times 10^6} = 0.040$$

Then from formula (7):

$$P = \frac{214 \times 10^6}{96^2 \times 1.040} = 22,300 \text{ pounds}$$

The stress corresponding to this buckling load, as derived with formula (6) is:

$$C = \frac{22,300}{2 \times 0.14 \times 48} = 1,660 \text{ pounds per square inch}$$

This buckling stress is well in excess of the calculated total stress of 577 pounds per square inch. It is a good safety practice, however, to keep the total stress down to about one-third of the buckling stress.

Structural Tests

Table 3 gives results of bending tests on sandwich building panels, both new and after service periods of 16 months or 8 years. Static bending tests consisted of applying uniformly distributed or quarter-point load slowly to the panels. Impact bending tests were run by dropping a 60-pound sandbag. These panels were of the types used in the Forest Products Laboratory exposure test unit. Figure 10 shows one of the plywood-faced panels tested to failure after 16 months of service in the exposure unit.

Concentrated loads of 50 to 200 pounds on an area 1 inch in diameter caused less deflection of the aluminum-faced panels described in table 3 than that under design load in static bending. Permanent denting of the 1/50-inch facings occurred at loads ranging from 190 to 290 pounds. Tests made with a falling 2-inch steel ball on specimens of similar panels caused dents 0.01 to 0.03 inch deep from drops of 4 inches. Dents of equal depth were more noticeable in smooth, bright sheets of metal than in materials like fiberboard, with a dull finish or texture.

Edgewise compressive loads up to 500 pounds per lineal foot caused negligible deformation and no damage to plywood- and aluminum-faced panels 8 feet long. Three aluminum-faced panels failed by buckling of a facing at loads of 2,300 to 3,100 pounds per lineal foot. A 1- by 8-foot panel faced with 1/4-inch plywood developed a load of 19,000 pounds at failure.

Three aluminum-faced panels like those described in table 3 were tested under an edgewise racking load. There was no structural failure at twice the design load of 60 pounds per lineal foot of width. Ultimate strengths were from 250 to 640 pounds per lineal foot when the panels were fastened and restrained in a manner like that to be expected in service.

Factors Affecting Structural Properties

Moisture and temperature are important agents affecting the structural properties of sandwiches made of wood or wood-base materials. They may have an immediate effect on the facings or the core, and they are major factors in producing aging effects on facings, core, or adhesive bond.

Facings of wood or wood-base material are hygroscopic; that is, they take on or give off water vapor until they are in equilibrium with the surrounding atmosphere. With an increase of moisture, the dimensions are increased, while structural properties are generally reduced. This can and often does happen to a building. Since the properties of sandwich are largely controlled by the facings, these effects are important.

Table 2 shows the moisture effects, both on dimension (columns 7 and 8) and on strength and stiffness (columns 12, 14, and 16), of a number of facing materials. Plywood expands by 0.1 to 0.2 percent of its original length and loses about 18 percent of its strength and stiffness when soaked. Shock resistance is little affected. Hardboards and insulating boards have more expansion than plywood. The reductions of strength and stiffness follow the same order.

Moisture also affects the strength of the paper core. Honeycomb cores A and B in table 1 were tested for compressive and shear strength when dry and when wet. The wet values were about 30 percent in compression and about 45 percent in shear, compared to the dry values given in table 1 (9).

Temperature effects on strength are generally not important in sandwiches for building construction. Most wood materials have 0.33 to 0.5 percent decrease or increase of strength for each 1° F. increase or decrease of temperature (16). Adhesives that become plastic at high temperatures should be used with care where there is a possibility of high tempereratures in service. On the other hand, thermosetting adhesives that have not been fully cured may become hardened and strengthened by exposure to high temperature; this was shown in tests of sandwich specimens with phenol-resin-treated paper honeycomb cores bonded to aluminum facings.

A number of paper-honeycomb cores treated with phenolic or polyester resins were tested before and after 6 cycles of accelerated aging consisting of the following operations in each cycle: immersion in water at 120° F. for 1 hour; spraying with wet steam at 200° F. for 3 hours; storage at 10° F. for 20 hours; heating in dry air at 210° F. for 3 hours; spraying with wet steam at 200° F. for 3 hours; and heating in dry air at 210° F. for 18 hours. Some 72 core constructions were tested, mostly designs intended for marine use. A few representative results are summarized in table 4. Strength was found to be reduced about 20 percent, stiffness about the same amount, and shock resistance generally very little. Because of the limited number of tests, the results show some inconsistency and are considered to be conclusive only in a general way.

Sandwich panel specimens 3 by 36 inches in size, with paper-honeycomb cores 1 inch thick and a variety of wood facings similar to those in the Forest Products Laboratory exposure unit, were subjected to the same accelerated aging cycles. Bending tests were made before and after aging to determine if the strength properties were changed. The reduction of shear stress developed in the cores of the aged specimens was about 20 to 30 percent. The reduction of stiffness was about 20 percent. No visual defects or warping were observed in the aged specimens. Similar tests of sandwich panels 2 inches thick and consisting of expanded paper honeycomb cores and aluminum faces showed a 28 percent average reduction in bending strength after accelerated aging. In similar tests, sandwich made with facings of porcelainized steel bonded to 1/8-inch hardboard lost about three-quarters of their bending strength. In another similar series, compression and shear strength of the expanded paper honeycomb cores were but little reduced by aging.

Small specimens of a commercially manufactured 2-inch sandwich with resin-treated paper-honeycomb core and aluminum faces were tested in tension perpendicular to the faces after a variety of aging exposures. The exposures and the results of the tests are summarized in table 5. The tests showed appreciable softening of the adhesive bonding the cores to the facings when exposed to a temperature of 180° F. The adhesive bond also was seriously affected when soaked in water for 48 hours. Exposure to high humidity or to cyclic conditions had less severe effects.

Table 3 gives test values on full-size sandwich panels removed from the Forest Products Laboratory exposure unit after exposure in the walls of a building heated during cold weather. The wood-faced panels showed no reduction of bending strength or stiffness after 16 months of service. The aluminum-faced panels showed no loss of stiffness and, while they lost about 30 percent of their bending strength after 8 years of service, the strength remaining was still about 7 times the design strength. It was estimated that this loss of bending strength showed that the adhesive bond of the core to the facings was reduced to about 30 percent of its original value.

Table 4 shows that the resin-treated paper core is not greatly affected by aging, while test data given in tables 3 and 5 indicate that the bond of the core to the metal facings may be seriously deteriorated. These tests were made on panels fabricated some years ago, and adhesives and processes for bonding wood or paper to metal have been substantially improved since that time.

Other Properties of Panels

Dimensional Stability

Sandwich panels have large surface areas that may change appreciably in dimension with variations of temperature or moisture content. When used in exterior walls of buildings, the two facings are generally exposed to different conditions and thus assume different dimensions; the resultant imbalance causes bowing or cupping. Defects in materials or manufacture can cause warping or twisting. Tests have shown that the change in dimension of a sandwich panel with equal facings and exposed to the same condition on both sides is practically the same as that of a free facing.

Dimensional changes with temperature are important in metal facings, while in wood-base facings they are largely overshadowed by the effects of moisture change (table 2). Representative values for the thermal coefficient of expansion in some common facing materials are as follows:

Material	Dimension change 10^{-6} per °F.
Douglas-fir wood	
Parallel to grain	2
Perpendicular to grain	19
Douglas-fir plywood	3
Treated hardboard	11
Cement-asbestos board	4
Aluminum	14
Steel	7
Glass	5

The formula for deflection or bowing of a sandwich panel caused by differential expansion between the two facings is

$$w = \frac{ka^2}{8h} \tag{8}$$

where $\underline{w}$ is the deflection in inches, $\underline{a}$ is the length of the panel, $\underline{h}$ is the thickness of the sandwich, and $\underline{k}$ is the differential expansion of the facings in ratio to their length.

Assume an aluminum-faced wall panel 8 feet long and 2 inches thick and a temperature difference of 13° F. between the two facings. From the above tabulation, $\underline{k}$ = (14 x 13) millionths = 0.000182. Then,

$$w = \frac{0.000182 \times 96 \times 96}{8 \times 2} = 0.105 \text{ inch.}$$

The effect of severe temperature differences was shown by laboratory tests on six sandwich panels, 20 by 72 inches in area and 3 inches thick. The core was paper honeycomb, and the facings were various combinations of Douglas-fir veneers and plywood, mostly with paper overlay and one with aluminum paint on the warm side. The panels were built into a wall between two rooms, one at 70° F. and the other a refrigerated room at -20° F. Bowing due to temperature occurred immediately; it was toward the warm side and was observed to range from practically nothing up to 0.06 inch in the various panels. With contuinuing exposure, the bow was reduced because of expansion in the facings on the cold side due to absorption of moisture.

Tests of smaller panels placed near the floor in the same wall showed about 5 percent of moisture in the facing on the warm side, 4 percent in the core, 5 percent in the facing on the cold side, and an additional 5 percent as frost crystals on the inner surface of the cold facing. Bow of the panels was not measured. The low moisture content in the cold facings was due in part to incomplete air circulation in the cold room and in part to the resistance of paper overlays and finishes to the transmission of water vapor through the facings on the warm side of some of the panels.

Observations of panels in the exposure unit at the Forest Products Laboratory gave a more complete picture of bowing under service conditions. The unit consisted of 17 test panels 8 feet long in the north and south walls and 10 test panels 14 feet long in the roof of an enclosure of a heated space at Madison, Wis. (13). The panels had paper-honeycomb cores and a variety of facings consisting of plywood and veneer, aluminum, hardboard, cement-asbestos board, and a hardboard-steel combination. Bow was caused by a difference in the expansion of the outside and inside facings that resulted from temperature or moisture differences, or both. Observations over a period of about 9 years have been analyzed.

The bow was found to follow a cyclic pattern, panels generally showing about the same values in the same seasons, year after year. Monthly averages throughout the years of observation showed similar cycles within each group of plywood- and veneer-faced panels, aluminum-faced panels or hardboard-faced panels. Plywood- and veneer-faced wall panels 3 inches thick reached a general maximum outward bow of 0.25 inch and roof panels 4-1/2 inches thick about 0.3 inch in late winter, becoming nearly straight in summer. Figure 11 shows the average bow of plywood- and veneer-faced wall panels by months. Aluminum-faced wall panels 2 inches thick bowed inward about 0.1 inch in winter and were essentially straight in summer. Aluminum-faced roof panels 3 inches thick were straight in winter and bowed outward (upward) about 0.1 inch in summer. Hardboard-faced wall panels 3 inches thick showed the most bow, nearly 0.5 inch in late winter. Wall panels 3 inches thick with facings of 1/8-inch hardboard bonded to a thin porcelainized steel sheet bowed a maximum of 0.1 inch.

Winter bow in panels faced with wood materials was due to differences in the moisture content of the outside and inside facings. The temperature was lower and the relative humidity thus higher on the outside, so that the outer facing reached a higher moisture content toward the end of winter. Thermal contraction of the outer facing tended to reduce the amount of bow, but was overshadowed by the expansion due to the higher moisture content. Calculations by formula (8) from the observed amount of bow, with correction for temperature, indicated a maximum moisture content difference between outside and inside facings of about 8 percent. Direct observations of moisture content were not made, but moisture content values of about 18 percent in the outside facings and 10 percent in the inside facings seem reasonable.

The effects of temperature were shown in wood-faced panels, but were more clearly seen in the aluminum-faced panels, which underwent no change of dimension because of moisture. For example, it was observed in the wood panels that a sudden drop of the outside temperature caused a temporary decrease of the outward bow, while long-continued low temperature increased the bow. In the aluminum-faced panels, the thermal contraction of the facings and the amount of bow were proportional to the temperature difference between the two facings. Bow was toward the warm side. Thus, in winter, panels on the south wall bowed less than those on the north wall, except on cloudy days, when the two were nearly equal. Aluminum-faced roof panels were nearly straight in winter and bowed upward in summer, showing the strong solar effect on the outer facings. The response to temperature changes was quick, and significant differences were detected between morning and afternoon. In some instances, the aluminum-faced roof panels were observed to respond to transient clouds that obscured the sun for a matter of only minutes.

Formula (8) shows that the bow is proportional to the square of the length and inversely proportional to the thickness. Thus, if the bow of an 8-foot plywood-faced panel in winter is 1/4 inch, that of a 16-foot panel of the same thickness would be 1 inch. Longer panels, applied with their length horizontal, would bow still more. In such long panels, however, the bow can be largely restrained without excessive stress on the facings by means of suitable fastenings at midlength to other structural elements.

Two panels of door size, with inner facings of hardboard and outer facings of aluminum, were observed for several years on the same exposure unit. The bow differed by only about 1/10 inch between winter and summer. Winter bow appeared to be reduced by the partial balance between the thermal contraction of the outer facing and the reduced dimension due to low moisture content in the inner facing. Obviously, the performance of such a sandwich in service will depend much upon the moisture and temperature condition at which it is fabricated.

The bowing of hollow-core flush doors 1-5/8 inches thick exposed to a moisture differential on the two sides has been examined by test (12). With an atmosphere of 90 percent relative humidity on one side and 25 percent on the other side of a door with plywood faces, the doors became bowed lengthwise 1/4 to 1/2 inch and became cupped crosswise about 1/20 inch. They were thus dished or concave. The temperature was nearly the same on both sides. When the humidity differential was removed, the doors recovered from most of the bow and cup. Where one of the long edges of the door was restrained by three hinges and a stop, that edge bowed half as much as the free edge.

Thermal Properties

The heat transmission coefficient of a sandwich panel is a complex summation that may be represented by the equation:

$$U = \frac{1}{f_o} + \frac{1}{(t/k)} + \frac{1}{f_i} + E$$

in which U is the overall time rate of heat flow through the sandwich, f_o and f_i are surface coefficients for the outside and inside facings, values of t and k represent the thickness and the associated heat conductivity coefficient for each element of the panel, and E is a radiation coefficient based on emissivity values of the radiating surfaces. Since these coefficients are only partly known, the calculation of this formula is difficult and uncertain, and reliance is placed mainly on U-values observed in conductivity tests.

Heat conductivity coefficients observed in the standard guarded-hot-plate test (1) on a number of representative paper-honeycomb cores 1 inch thick are shown in table 6. The coefficients are in terms of British thermal units per hour per square foot per degree F., the lower values indicating better insulating properties. The values range from 0.31 to 0.59. Cores of similar type showed an increase of the conductivity coefficients with higher density. The range among types of construction with unfilled cores was 0.45 to 0.59, while cores with air spaces filled with insulating material had coefficients of 0.31 to 0.40. All of these cores were of types having flutes perpendicular to the facings of the panel. Other tests of unfilled cores with all flutes parallel to the facings gave conductivity coefficients from 0.29 to 0.36; such cores, however, have low shear strength and stiffness.

A number of experiments were made on the filling of the air spaces in the cores, either with foamed-in-place phenolic resins (fig. 12) or with granular fill materials. A foamed resin reduced the conductivity coefficient of the PN core from 0.58 to 0.40. Filling with a granulated silica aerogel material instead of the foamed resin reduced the coefficient to 0.37. While the filling of the spaces in complex honeycomb structures causes manufacturing problems, these results show that substantial improvement of heat insulation is possible.

Test data furnished by manufacturers of a number of commercial products have indicated that very low conductivity coefficients are attainable with certain foamed plastics. These can be made as efficient insulators and with the strength and rigidity necessary in a sandwich core. The conductivity of honeycomb or foamed cores may also be reduced by incorporating reflective insulation.

A limited number of thermal-conductivity tests of sandwich panel constructions have been made at the Forest Products Laboratory, generally at temperatures of about 70° F. on the warm side and about -20° F. on the cold side. A guarded-hot-box method similar to the present standard method (3) was used. A 3-inch panel with XN-type (fig. 7) paper-honeycomb core and 1/4-inch Douglas-fir plywood facings showed an observed U value of

0.150. A 2-inch wall section with expanded core (fig. 5) and aluminum facings and containing a panel joint gave a U value of 0.259, approximately the same as for an uninsulated frame wall of conventional construction. Combinations of steel exterior walls separated by air spaces from liner sandwich panels with a 1-3/8-inch paper-honeycomb core and 1/8-inch hardboard facings gave observed U values of 0.166 to 0.199.

Panels made with a commercial expanded paper-honeycomb core and 0.02-inch aluminum facings are reported to have U values of 0.425 in 1-inch thickness, 0.275 in 2-inch thickness, 0.210 in 3-inch thickness, and 0.173 in 4-inch thickness. These values are reduced to about one-half if the cells of the core are filled with foamed resin.

Maximum allowable U values for outside walls of dwellings, as given in the performance standards of the Federal Housing Administration, range from about 0.20 in the northern States to about 0.40 in the southern States. For comfort and freedom from condensation the values should be reduced by nearly one-half from these maximums. The effectiveness of insulation and its functions in houses are discussed fully in a Forest Products Laboratory publication (11). The test values indicate that sandwiches with unfilled cores may be required to have greater thickness for insulation than for strength or stiffness in exterior walls or roofs in cold climates.

If sandwich panels are used for exterior walls or roofs in cold climates, temperatures of the indoor surfaces of the sandwich may drop low enough to cause objectionable condensation of water vapor from the interior air. The problem is most acute with sandwiches having metal facings and heat-conductive cores, and at joints or around openings.

A variety of sandwich-panel joint types were tested at the Forest Products Laboratory for heat conductivity from a temperature of 73° F. in still air on the warm (indoor) side to -10° F. with moving air on the cold (outdoor) side. The panels were 3 inches thick, with XN-type (fig. 7) paper-honeycomb cores and 1/4-inch plywood or 0.02-inch aluminum facings. Under these conditions, the plywood-faced panel had surface temperature on the warm side of 66.4° F., and dropped to 66.0° F. at a joint with a plywood-fiberboard spline. These surface temperatures would require a relative humidity of nearly 90 percent indoors to cause condensation of water vapor.

The aluminum-faced panel had surface temperature of 57.5° F. on the warm side, 36.2° F. on the warm side of a joint with continuous metal from outside to inside, and intermediate values with other joints designed so that the continuity of the metal was interrupted from cold side to warm side. With a facing temperature of 57.5° F., condensation would occur at an indoor relative humidity of 65 percent, and with a temperature of 36.2° F. at a relative humidity of 30 percent.

Some construction details around openings gave warm-side surface temperatures below 32° F., which would permit condensation with indoor humidities below 25 percent. One door opening construction showed a warm-side surface temperature of 18° F. The wide range of results observed in these tests emphasizes the importance of care in design details at sandwich joints and openings to reduce condensation problems in cold weather. With metal facings, a break in the continuity of metal from outer to inner surface of the joint is essential.

A few aluminum-faced sandwich panels were exposed to summer sunshine at Madison, Wis., and surface and core temperatures were recorded. A red-painted panel reached a temperature of 151° F. on its upper surface, unpainted or white-painted panels being somewhat cooler. Temperatures of the cores and those at the lower surface were lower. Calculations from the observed data indicated that the upper surface temperature at Madison could occasionally reach higher values than those observed. A maximum temperature of 171° F. was reached in a sandwich with black facings exposed sunshine at Phoenix, Arizona.

Acoustical Properties

It is hard to make a simple evaluation of the acoustical properties of structural materials. Sound originating in space reaches a wall, where part of it is reflected back from the surface and part is absorbed. The absorbed portion may be partly reflected from the farther surface and partly transmitted beyond. The portion reflected back into the original space may be partly absorbed and partly relfected by other objects, with the reflected part again reaching the wall. There are thus reflection and absorption, both of which influence sound transmission. The problem is complicated by the variation of these properties with the frequency or period of vibration of the sound.

Sound-absorption tests were made by the National Bureau of Standards "box test" on a number of sandwich panels at a sound frequency of 500 cycles per second. A 1-1/4-inch panel with paper-honeycomb core and 1/8-inch hardboard faces had an absorption coefficient of 0.04, about the same as that of an unpainted brick wall. Variation of the arrangement of the flutes of the core had little effect. Perforation of the facing nearest the source of sound permitted much more absorption, with coefficients in the range of 0.50 to 0.70, comparable to many of the commercial acoustical materials. This was true with perforated facings of hardboard, plywood, or aluminum.

A few tests of sound transmission through various wall constructions in the laboratory of a manufacturer of paper honeycomb cores indicated the following transmission losses in decibels at a sound frequency of 512 cycles per second:

Material	Sound transmission loss decibels
2-inch sandwich with aluminum facings	27
Plywood facings on 1- by 3-inch studs	26
2-3/4-inch sandwich with steel facings	36
Wood studs, lathed and plastered	43
8-inch brick wall, plastered	48

The materials are listed in increasing order of weight per square foot. It is of interest that the brick wall, which was low in sound absorption, effectively reduced sound transmission because of its heavy mass and its reflective qualities.

Fire Behavior

The performance of a structural element, such as a sandwich panel in a fire, may be considered under two categories, fire resistance and flame spread. Fire resistance is the resistance to penetration through the thickness of the panel by a fire of specified standard intensity. Flame spread is observable either on the surface of the panel or within the core. Tests of both categories of performance have been made at the Forest Products Laboratory. A further consideration in sandwich panels is that their structural properties depend largely upon the facings and the bond of the facings to the core. If either should fail, the structural value is lost, regardless of whether fire penetration or flame spread has occurred. While fire tests of sandwich panels under structural load have not been made, some observations in connection with other tests throw light on this question.

Fire-resistance tests of sandwich panels were made by a method similar to the ASTM standard method (2), in which one side of a panel is exposed to a fire of specified increasing intensity and the time to failure is noted. Sandwiches 3 inches thick with paper-honeycomb cores and 1/4-inch painted plywood facings failed in 15 to 19 minutes by charring through the exposed face and the core. The higher resistances were shown by panels with the flutes of the cores parallel to the facings. With facings of 1/8-inch plywood and paper overlay on paper-honeycomb cores with unobstructed flutes running from face to face, the fire resistance was about 13 minutes. Application of a froth-producing coating to the core material increased the resistance to about 40 minutes. In other tests, panels with steel or cement-asbestos board facings on paper-honeycomb cores with flutes running from face to face showed fire resistances of 6 to 17 minutes, which were approximately doubled by introducing a cement-asbestos separator midway in the core, making in effect a double sandwich. Filling of the cores with foamed resin further improved the fire resistance. Two 2-inch-thick aluminum-faced panels failed in about 5 minutes, by which time considerable melting of the facings had occurred.

In all of these tests, there was failure of the exposed facing or of its bond to the core some time before final failure at the times indicated above. This indicates that the failure of panels under structural loads would occur from loss of strength before it occurred from penetration of fire. Facings of greater thickness and insulating value and bonding adhesives with more heat resistance would improve the fire resistance of sandwich panels. Where the hazard of exposure to fire is high, it may be desirable to apply a relatively thick, nonstressed insulating cover over the thinner stressed facing of the sandwich panel.

Flame spread on combustible facings of sandwich panels is a surface effect, similar to that in the same materials in general uses. Flame spread characteristics are conveniently determined by the small-tunnel test developed at the Forest Products Laboratory (4). Representative values by that test are as follows:

Material	Flame-spread index
Asbestos wallboard	0
Douglas-fir plywood, 3/8-inch, exterior type	112-114
Douglas-fir plywood, impregnated with fire-retardant	17-21
Douglas-fir plywood, with fire-retardant coating	79-84
Hardboard, untreated	89-97
Lauan plywood, 1/4 inch	111-113
Red oak lumber, 3/4 inch	100

Flame spread in resin-impregnated paper-honeycomb cores was investigated by a test method illustrated in figure 13. The exposure time was 4 minutes, and observations were made of the spread and persistence of flame in the core. In cores having all flutes perpendicular to the facings (figs. 5 and 6), only slight flame spread occurred. Burning was restricted to the honeycomb material in contact with the flame. When the igniting flame was removed, flaming stopped immediately while glow persisted 1 or 2 minutes longer. In the case of the cross-corrugated core (fig. 7) in which half of the flutes were parallel to the facings, there were open channels for rapid vertical flame spread, and in a core with flutes parallel to the facings both lengthwise and crosswise of the panel, flame spread was rapid in both directions. These test panels had open edges (fig. 13), and draft and flame spread in flutes parallel to the facings could have been reduced by barrier sheets covering the edges.

Although resin-treated paper core is not in itself highly resistant to fire, its use between sandwich facings does not seem to be hazardous. Thin facings and their adhesive bonds to the core appear to be the critical points in the fire resistance of sandwich panels.

Decay and Termite Resistance

Problems of decay and insect resistance are basically the same in structural sandwiches as in other structural elements using wood. Design and construction details that minimize the entrance of moisture or permit its ready escape will help keep moisture content low and thus reduce the hazards of decay or insect attack in wood or wood-base materials. Application of these principles to house construction is discussed in a U. S. Department of Agriculture bulletin (17).

Measures to prevent entrance of outside moisture include keeping wood construction away from soil or damp masonry, roof overhangs to reduce wetting of walls from rain, and avoidance of leaks. Joints between sandwich panels, and particularly horizontal joints, need flashing, calking, or use of water-repellent preservatives to assure watertightness. Accumulation of water vapor originating in the house in cold weather should be controlled as in good conventional construction, by suitable vapor barriers on the warm side and avoidance of vapor barriers on the cold side. Lastly, whatever the measures used, periodic careful inspections are necessary to make sure that conditions favorable to decay or insect attack upon vulnerable materials do not develop in service.

Wood or wood-base materials used for sandwich facings or cores can be protected by preservative treatment. If plywood or hardboard facings are given preservative treatment, care should be taken that the treatment is of a type that will leave a surface suitable for bonding to the core. Where moisture conditions are severe, only exterior-type adhesives should be used to bond cores to facings. Such adhesives have more resistance to decay than does the wood that they bond.

The decay resistance of paper used for honeycomb cores for sandwiches was studied at the Forest Products Laboratory. Table 7 shows percentages of tensile strength remaining in untreated and treated papers after 2 months' exposure to two decay fungi (9). Fungus No. 617 was a brown-rotter (*Lenzites trabea*) which attacks cellulose only, and fungus No. 517 was a white-rotter, which attacks both lignin and cellulose and leaves wood white and spongy. The paper weighed 50 pounds per 3,000 square feet. Other tests showed some tendency toward greater loss of strength in the heavier than in the lighter papers.

The tests showed also (9) that stripes of silicate glue, such as could be applied in forming an expanded honeycomb core, improved the decay resistance, while similar stripes of phenolic glue gave no improvement. Another series of tests made on paper cores treated with 20 to 35 percent of water-soluble phenolic resin showed good resistance to 3 decay fungi, while polyester resins gave less protection. It was found that treatment of the paper with 15 percent of a water-soluble phenol-formaldehyde resin to give wet strength also gave good decay resistance. There was evidence that treatment with as little as 5 percent of resin could give decay resistance if about 2 percent of pentachlorophenol dissolved in ethyl alcohol were added to the resin .

All of the tests indicate that treatment of paper-honeycomb cores for decay resistance offers no serious problems.

Building with Sandwich Panels

Design considerations as applied to sandwich building panels must be based upon the purpose that the panels are intended to serve. Economical use of sandwich in light buildings requires that its properties of strength and stiffness be fully utilized to make a strong and rigid structure. Panels used as curtain walls do not support loads, but need insulating properties and, in larger buildings, a specified fire resistance. Acoustical properties may be important in interior partitions. Decay resistance may need to be provided in construction near the ground. Dimensional stability needs to be considered in all designs. The choice of core and facing materials and bonding adhesives may be affected by any or all of these factors.

Where sandwich panels are used in light buildings, such as houses, low cost is essential. This may dictate the use of low-cost cores, such as paper honeycomb or foamed resin, and facings of widely available sheet materials such as plywood, hardboard, or aluminum. The required thickness may be dictated by strength or stiffness requirements, or, in the colder climates, by insulation needs. Thicker panels are more stable against warping or cupping under severe exposure conditions.

Where panels enclose rooms, an economical relation of room sizes to panel sizes needs consideration. Many facing materials come in 3- or 4-foot widths, and most rooms can be designed around the 3-foot or the 4-foot module. A panel length of 8 feet gives wall panels that are continuous through the height of 1 story. Panels 12 feet or more in length for ceilings or roofs may require extra-long sheets or scarf-jointing and gluing of the sheets of facing material to transmit stresses through the full length. Bow will be greater in the longer panels, unless they are restrained by suitable fastenings.

One of the most critical problems affecting building uses of sandwich is that of suitable joints or fastenings. These must be strong enough and rigid enough to transmit whatever stresses are called for in the design without excessive deformation or slip. Joints must be tight and must resist loss of heat or penetration by fire. They must be reasonably easy to assemble.

Splines of wood or of insulating board faced with plywood are often the most economical means of meeting these requirements in sandwiches with paper-honeycomb cores and plywood or hardboard facings. The panel can be fabricated with projecting facings, or the core can be routed out after fabrication to accommodate the splines. The spline can be glued to one panel at the same time the core is bonded to the facings, if desired. Window and door frames can likewise be formed to spline into the edges of the panels.

Joints of panels with metal facings require special attention for insulation, so that metal is not continuous between outside and inside facings. Where edges of panels rest on concrete, it may be necessary to place an insulating pad between the edges of the facings and the concrete. Gaskets of rubber or neoprene and sealing or calking compounds are helpful in sealing the joints. Since some dimensional change of a panel as large as 4 by 8 feet is unavoidable, the joint sealer should be of an elastic type to accommodate seasonal changes in the opening.

Repair of sandwich construction differs from that of more conventional construction in that the structural properties of sandwich depend much upon the facings. If extensive damage has occurred to a facing, it is necessary to restore the strength as well as the appearance, and to make sure that the repaired facing is adequately bonded to the core. Since satisfactory bonding under field conditions may be difficult, it is usually better to replace than to repair panels that are extensively damaged. The technique of repairing stressed wood or plywood facings where gluing is involved is described in a publication of the Housing and Home Finance Agency (18).

A suggested plan for a 24- by 32-foot sandwich-panel house was worked out at the Forest Products Laboratory (13). A design module of 4-foot width was used. Sandwich panels were 3 inches thick in exterior walls, 4-1/2 inches thick in the roof and an interior bearing partition, and 6 inches thick in the floor. Joints were made with splines of plywood glued to insulating board or of wood. Strapiron clips were suggested for fastening the floor panels to the concrete foundation sill. Partitions met the exterior wall at a panel joint in the wall, with splines both within and on the partition side of the wall panels. Nailing of the edges of panels to the splines was concealed where possible by base, crown, or cove moldings. Special window and door frames were devised to fit between the facings of the wall panels. Figures 14 and 15 show the essential details of the plan.

The sandwich exposure unit at the Forest Products Laboratory (fig. 3) was erected on monolithic concrete footing walls. Construction was begun at one end and carried through to the other, with wall, roof, partition, and floor panels installed as the work progressed. Doors and windows were installed and trim and hardware attached after all panels were up. The superstructure was erected in 2-1/2 days. Since the sandwich panels were light in weight, wall and roof panels for the one-story structure were set in place quickly and easily without the use of mechanical hoisting equipment.

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Table 1.--Mechanical properties of several types of honeycomb cores

Designation	Type[1]	Weight of assembled core	Compressive strength[2]	Shear properties[3]: Shear strength	Shear properties[3]: Modulus of rigidity
(1)	(2)	(3)	(4)	(5)	(6)
		Lb. per cu. ft.	P.s.i.	P.s.i.	1,000 p.s.i.
A	Paper, corrugated	1.64	30	28	....
B	........do..........	2.58	63	74	....
C	Paper, expanded	1.96	45	....	....
D	........do..........	1.76	95	97	10.3
E	........do..........	3.96	360	306	20.6
F	Glass cloth	3.46	286	165	11.9
G	Aluminum	3.05	234	152	29.1
H	.......do..........	4.41	436	244	41.9

[1]Core A, XN type, 30-pound paper, 5 percent phenolic resin; core B, XN type, 50-pound paper, 15 percent phenolic resin; Core C, 60-pound paper, 10 percent phenolic resin; Core D, 60-pound paper, 20 percent phenolic resin; Core E, 125-pound paper, 35 percent phenolic resin; Core F, 112-114 glass cloth, phenolic resin, 1/4-inch cells; Core G, 0.002-inch foil, 3/8-inch cells; Core H, 0.002-inch foil, 1/4-inch cells; all paper cores tested dry; shear in cores D to H inclusive, parallel to core ribbons.

[2]Compression perpendicular to facings of sandwich, core ends laterally supported.

[3]Cores A and B, shear in bending. Cores D, E, F, G, and H, shear between two steel plates.

Table 2.--Average[1] properties of some sandwich facing materials

Material	Thickness	Weight per square foot, dry	Moisture content		Absorption[3]	Linear expansion[4]		Compression and tension parallel to length of sheet						Impact puncture resistance[6]	
			Dry	Soaked[2]		Parallel to length of sheet	Perpendicular to length of sheet	Compression[5]		Tension				Dry	Soaked[2]
								Maximum crushing strength	Modulus of elasticity	Maximum tensile strength		Modulus of elasticity			
										Dry	Soaked[2]	Dry	Soaked[2]		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	In.	Lb.	Percent	Percent	Percent	Percent	Percent	P.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.	1,000 p.s.i.	1,000 p.s.i.	In.-lb.	In.-lb.
Douglas-fir plywood	1/4	0.74	8.0	69.4	28.0	0.10	0.22	5,170	1,280	6,060	4,950	....	959	581	568
Untreated hardboard	1/8	.75	4.8	36.5	11.0	.38	.37	3,420	672	3,460	1,800	669	308	198	212
Do.	1/4	1.40	5.8	37.5	11.3	.23	.27	2,900	700	2,350	1,000	....	224	529	580
Treated hardboard	1/8	.77	5.7	30.7	9.4	.30	.37	5,260	900	4,980	3,020	855	382	206	225
Do.	1/4	1.44	5.5	20.7	3.6	.26	.25	4,620	810	4,260	2,700	....	422	439	527
Finnish hardboard	1/8	.73	7.4	67.1	29.3	.32	.33	3,300	681	4,570	990	679	93	271	252
Laminated paperboard, waterproofed	1/4	.70	9.6	72.9	18.3	.24	1.12	780	313	1,840	250	293	67	231	136
Do.	3/8	.96	9.7	40.1	9.3	.21	1.05	780	317	1,700	420	294	79	344	276
Cement-asbestos board	1/8	1.36	4.2	12.0	9.8	.08	.08	7,130	2,678	2,730	2,060	2,627	2,182	163	148
Do.	1/4	2.46	4.4	....	....	....	....	6,290	2,369	2,440	....	2,312	....	720+	....

[1]Average of 6 specimens from 3 sheets of material from commercial stocks.

[2]Soaked 7 days.

[3]Soaked 24 hours.

[4]Conditioned at 30 percent and then at 97 percent relative humidity.

[5]Compression tests in the dry condition only.

[6]Puncture by a pyramidal steel tup with triangular base 2.45 inches on each side.

Table 3.--Static and impact bending properties of sandwich building panels

Description of panel					Static bending tests			Impact bending[1]
Overall dimensions	Thickness	Facings: Material	Facings: Thickness	Paper honeycomb core type	Design load	Deflection at design load	Load at failure	Height of drop causing failure
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Ft.	In.		In.		P.s.f.	In.	P.s.f.	Ft.
WALL PANELS -- NEW								
4 x 8	3	Plywood	1/4	XN	20	0.168	263	8
4 x 8	3	Plywood	1/4	PN	20	.196	251	....
2 x 8	3	Hardboard	1/4	XN	20	.203	315	....
2 x 8	3	Hardboard	1/8	XN	20	.306	202	....
2 x 8	3	Cement-asbestos board	1/4	XN	20	.093	194	....
2 x 8	3	Insulating board	15/32	XN	20	.871	67	....
3 x 8	2	Aluminum	1/50	Hexagonal	15	.218	214	7
WALL PANELS -- REMOVED FROM SERVICE[2]								
4 x 8	3	Plywood	1/4	XN	20	.100	368	....
4 x 8	3	Overlaid veneer	1/8	XN	20	.134	301	....
3 x 8	2	Aluminum	1/50	Hexagonal	20	.213	140	....
FLOOR PANELS								
3-1/2 x 13-1/2	6	Plywood	3/8	PN	40	.150	308	....
3-1/2 x 13-1/2	6	Plywood	3/8	XN	40	.222	445	10+
ROOF PANELS								
3-1/2 x 14	3	Aluminum	1/50	Hexagonal	15	.646	51	4+

[1]Drop of a 60-pound sandbag.

[2]Plywood and veneer panels tested after 16 months' service, aluminum panels after 8 years' service.

Table 4.--Effect of aging on paper-honeycomb[1] sandwich cores

Treating resin		Ratio of property after aging to property before aging[2]		
		Compression parallel to flutes		
Type	Amount	Static strength	Impact strength	Modulus of elasticity
	Percent	Percent	Percent	Percent
Water-soluble phenolic	20	79	125	107
Do	35	81	80	86
Alcohol-soluble phenolic	20	80	100	70
Do	35	110	100	60
Polyester	20	64	86	223
Do	35	100	70	70

[1]Weight of paper was 90 pounds per 3,000 square feet.

[2]Accelerated aging consisted of 6 cycles of the following: immersion in water at 120° F. for 1 hour; spraying with wet steam at 200° F. for 3 hours; storage at 10° F. for 20 hours; heating in dry air at 210° F. for 3 hours; spraying with wet steam at 200° F. for 3 hours; and heating in dry air at 210° F. for 18 hours.

Table 5.--Average[1] results of tensile tests on specimens of sandwich wall panels[2]

Exposure conditions		Average of four panels		
Exposure	Time or cycles before testing	Tensile strength	Failure in: Glue	Failure in: Paper
		P.s.i.	Percent	Percent
1. Conditioned at 80° F. 65 percent R.H. Tested dry		75	58	42
2. 48 hr. in water at 80° F. Tested wet		44	82	18
3. 1 hour at 180° F. Tested at 180° F.		28	94	6
4. Continuous exposure to 97 percent R.H. at 80° F.	1 week	70	69	31
	2 weeks	85	54	46
	4 weeks	78	58	42
	8 weeks	88	39	61
	12 weeks	69	60	40
	16 weeks	88	46	54
5. 1 cycle -- 2 weeks at 80° F. and 97 percent R.H. 2 weeks at 80° F. and 30 percent R.H. and repeat	1 cycle	91	49	51
	2 cycles	74	59	41
	3 cycles	71	63	37
	4 cycles	95	31	69
	6 cycles	80	34	66
6. 1 cycle -- 1 hour in water at 122° F., 3 hr. in wet steam at 200, F., 20 hr. at 10° F., 3 hr. at 212° F., 3 hr. in wet steam at 200° F. 18 hr. in dry air at 212° F.	1 cycle	49	79	21
	2 cycles	50	91	9
	3 cycles	66	77	23
	4 cycles	38	96	4
	5 cycles	41	86	14
	6 cycles	32	94	6
7. 1 cycle, 24 hours at 158° F., 24 hours at 40° F. and repeat	5 cycles	92	42	58
	10 cycles	82	33	67
	15 cycles	82	57	43
	20 cycles	83	30	70
8. 1 cycle, 2 days in water, 12 days at 80° F., 30 percent R.H. and repeat	1 cycle	88	35	65
	2 cycles	63	59	41
	3 cycles	80	52	48
	4 cycles	83	28	72
	6 cycles	50	53	47

[1]Each value is the average from 10 specimens for each panel subjected to exposures 1, 2, or 3, and from 5 specimens for each panel tested at the end of each period after being subjected to exposures 4, 5, 6, 7, or 8.

[2]The wall panels consisted of 0.020 inch aluminum faces bonded to a 2-inch-thick honeycomb core of resin-treated paper.

Table 6.--Conductivity coefficients (K) in resin-treated paper honeycomb cores 1 inch thick and of various constructions

Core construction[1]	Filler in core	Density	Conductivity coefficient[2]
		Lb. per cu. ft.	(K)
XN	None	2.75	0.45
PN	..do............	2.94	.46
PN	..do............	5.47	.58
PNL	..do............	3.35	.47
PNL	..do............	5.50	.59
PN	Foamed resin	5.36	.40
PN	Fill insulation	4.72	.37

[1]PNL and XN types of core are shown in figures 6 and 7, respectively. PN is similar to PNL except that the flat interleaves are omitted.

[2]British thermal units per hour per square foot per inch of thickness per ° F.

Table 7.--Loss of tensile strength in honeycomb core papers after 2 months' exposure to two decay fungi

Treating resin			Loss of tensile strength[1]		
Type	Content	Added preservative	Fungus No. 617	Fungus No. 517	Average
	Percent		Percent	Percent	Percent
None	....	....	100	100	100
Water-soluble phenolic	5	None	37	33	35
Do....................	5	2 percent pentachlorophenol	2	-2	0
Do....................	10	None	19	21	20
Do....................	15	.....do.......	6	-1	2
Alcohol-soluble phenolic	15	.....do.......	84	99	92

[1]Percentage strength loss with respect to matched control specimens. Each value is an average of 8 test replications.

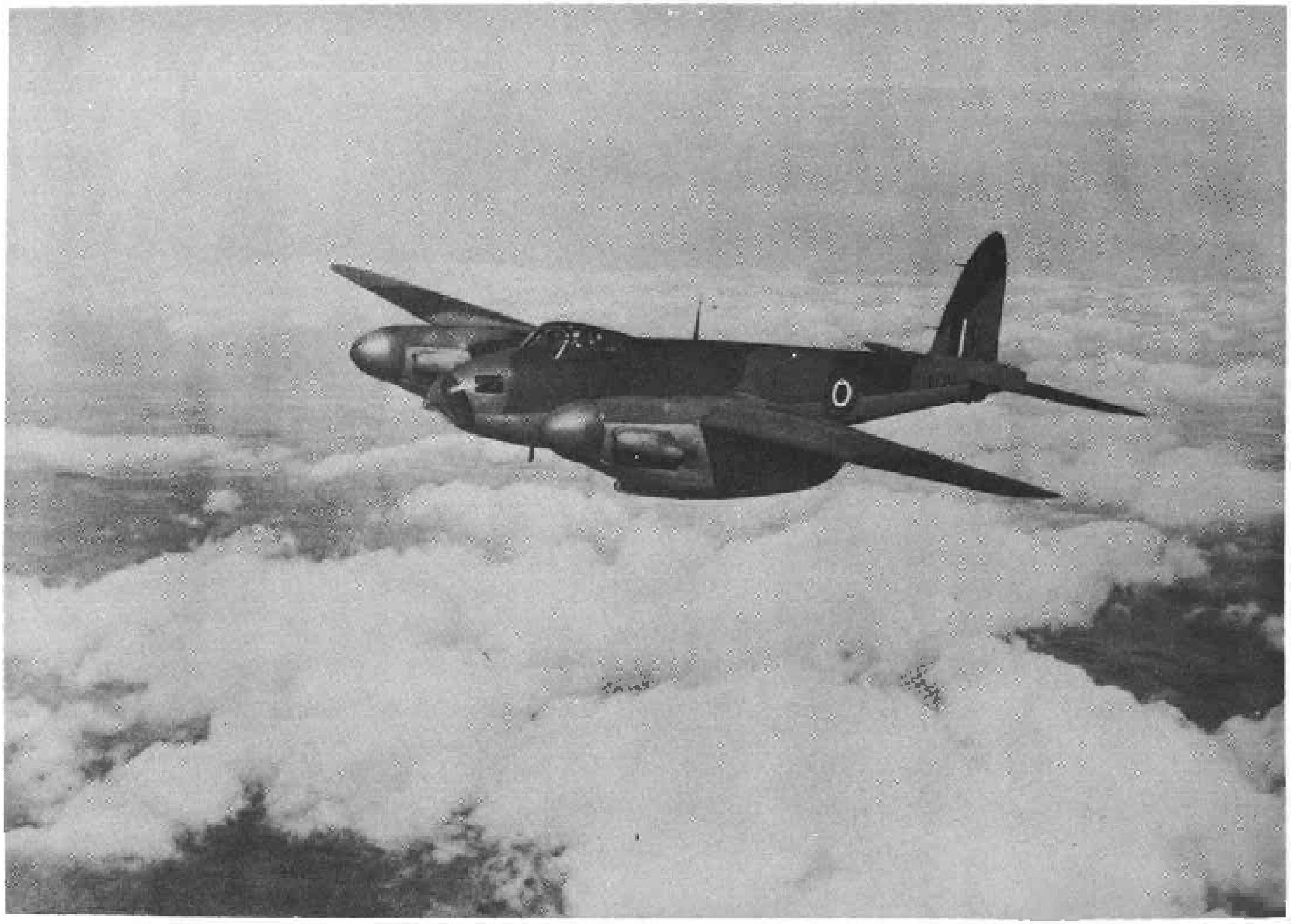

Figure 1. --The Mosquito Bomber, a World War II airplane featuring wood sandwich construction.

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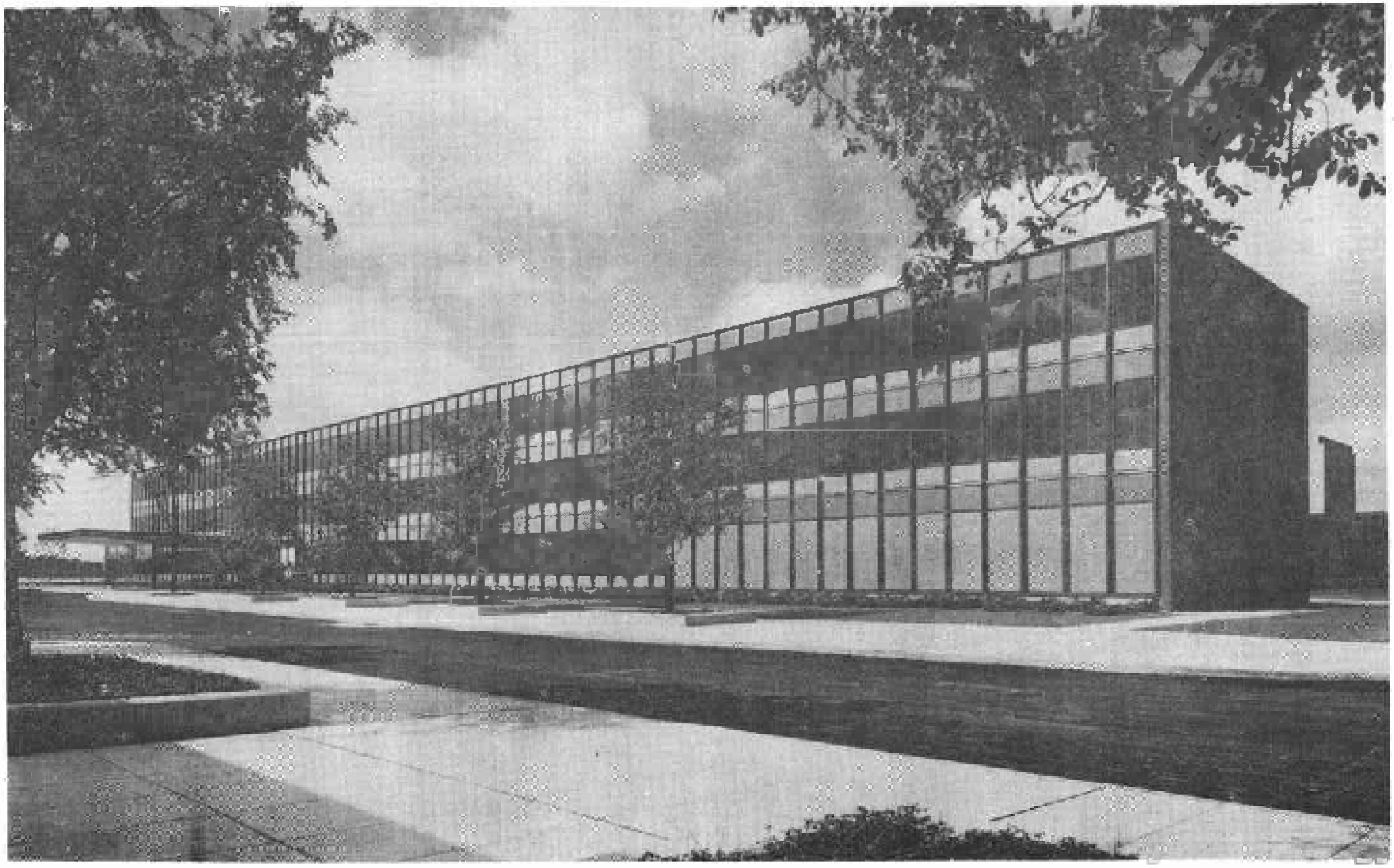

with enameled steel

building. Photo courtesy of General M

Figure 3. --Sandwich exposure unit at the Forest Products Laboratory, Madison, Wis.

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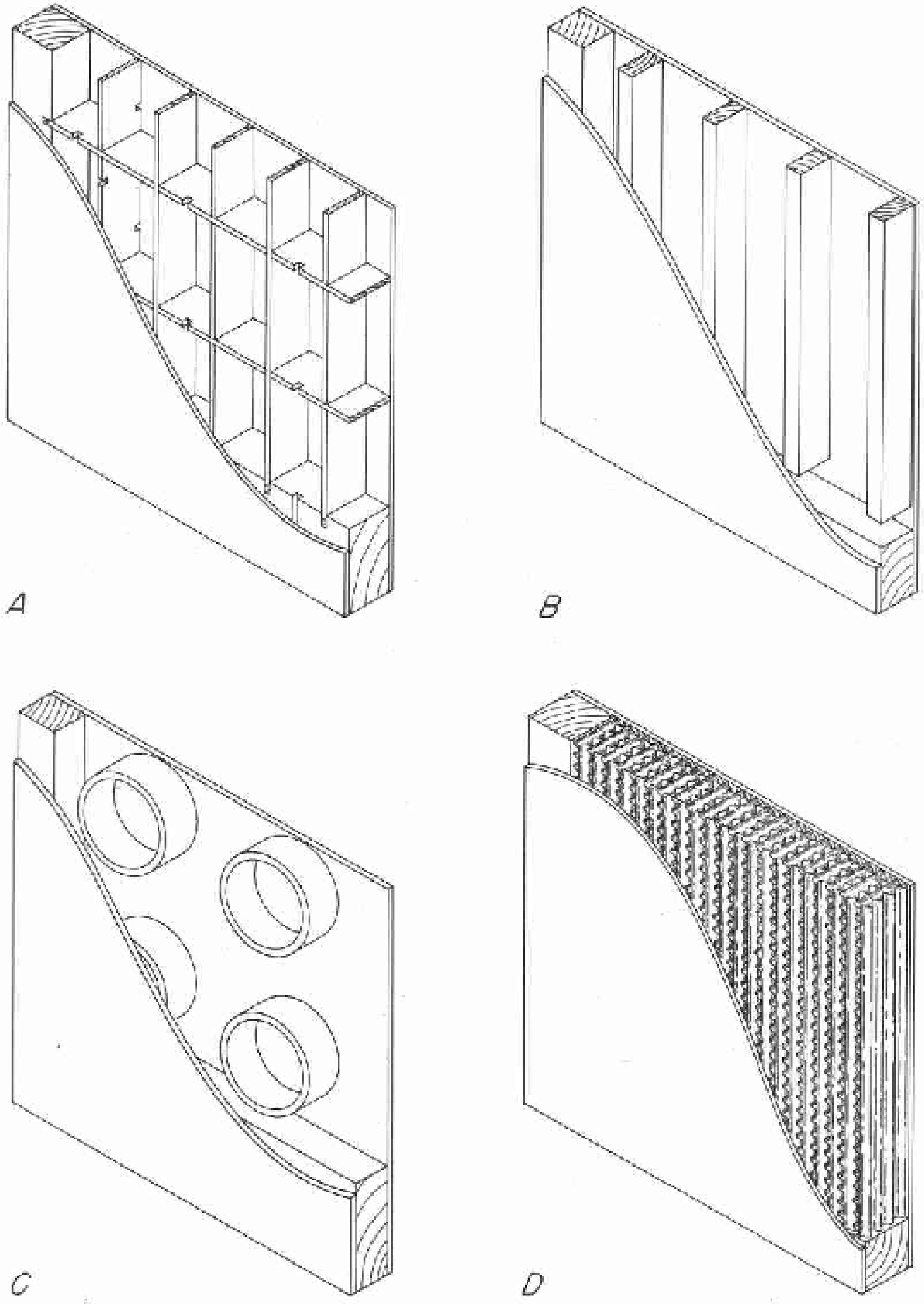

Figure 4. --Common types of hollow-core door construction.

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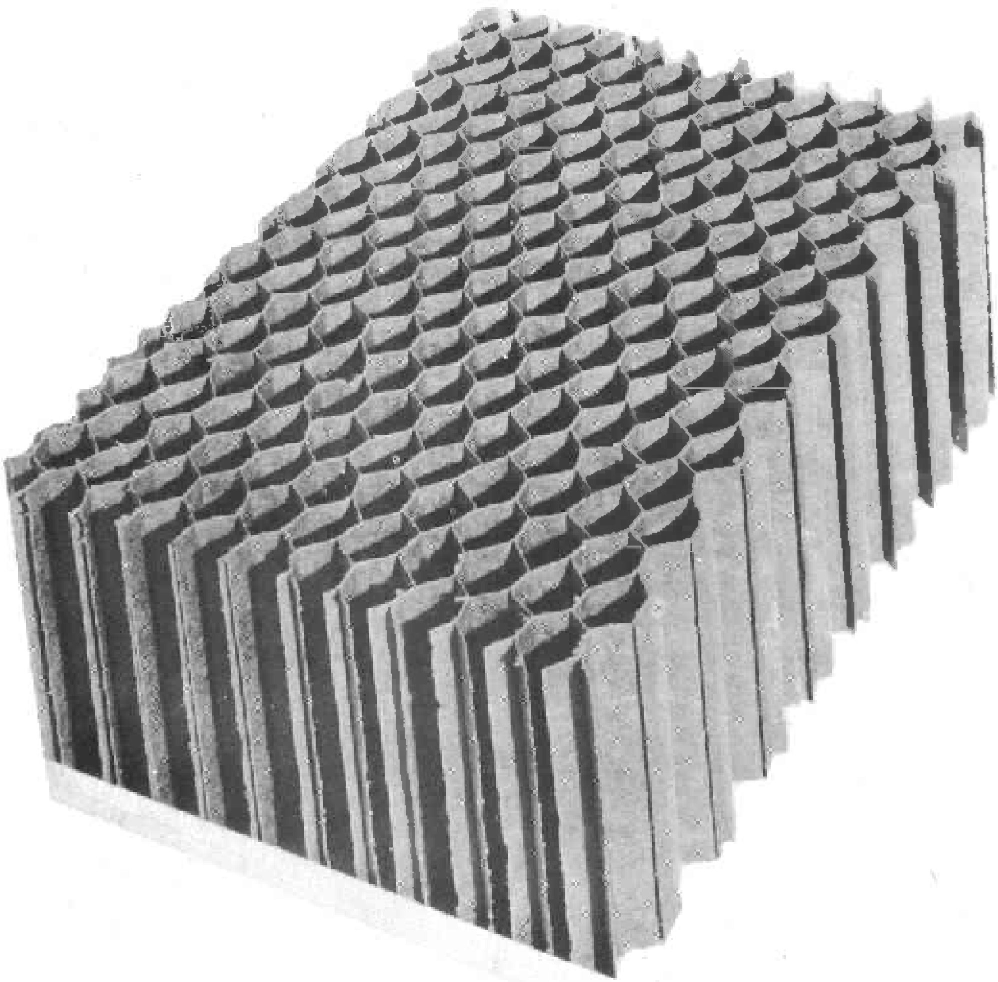

Figure 5. --Expanded hexagonal paper-honeycomb sandwich core.

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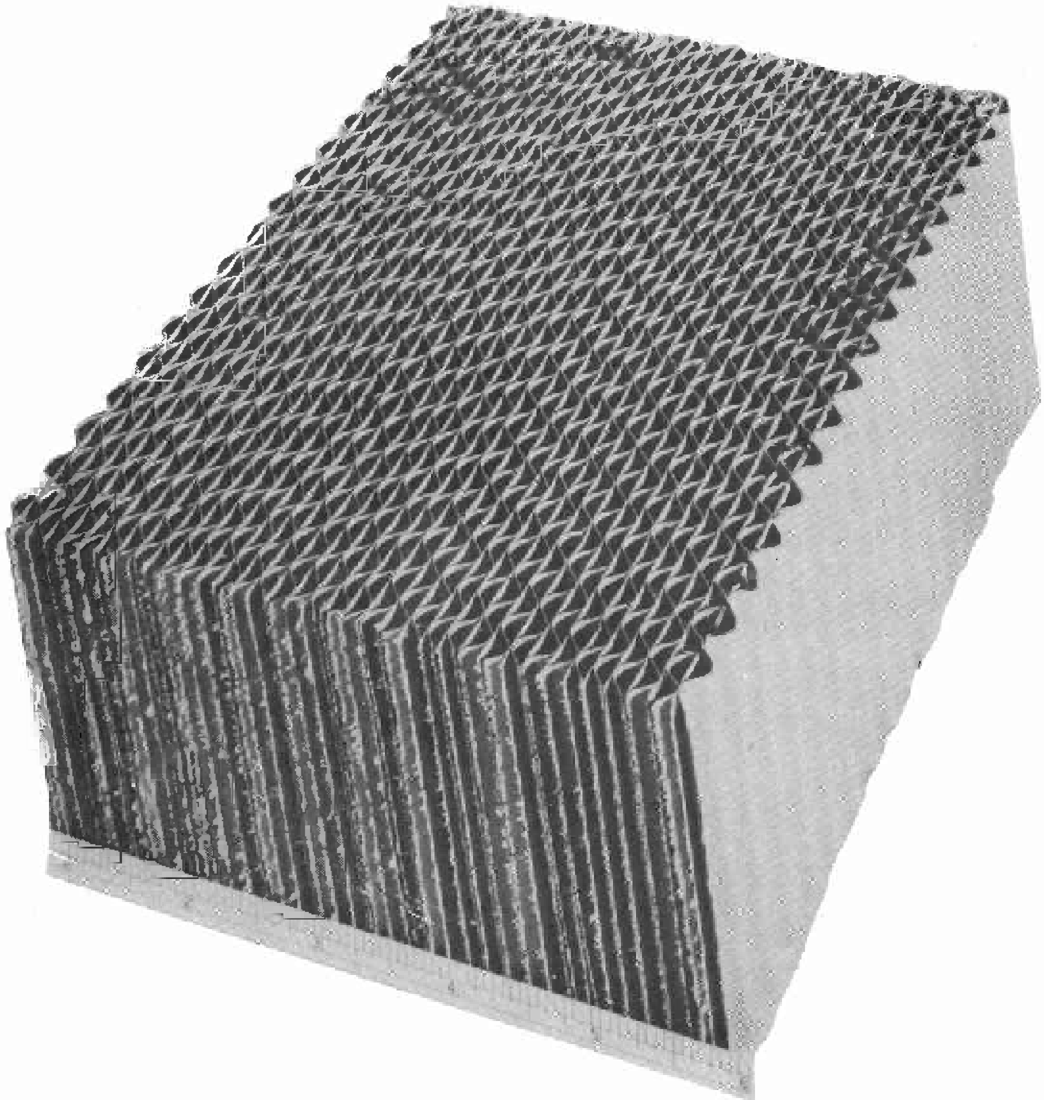

Figure 6. --PNL type of corrugated-paper honeycomb sandwich core with flat interleaves.

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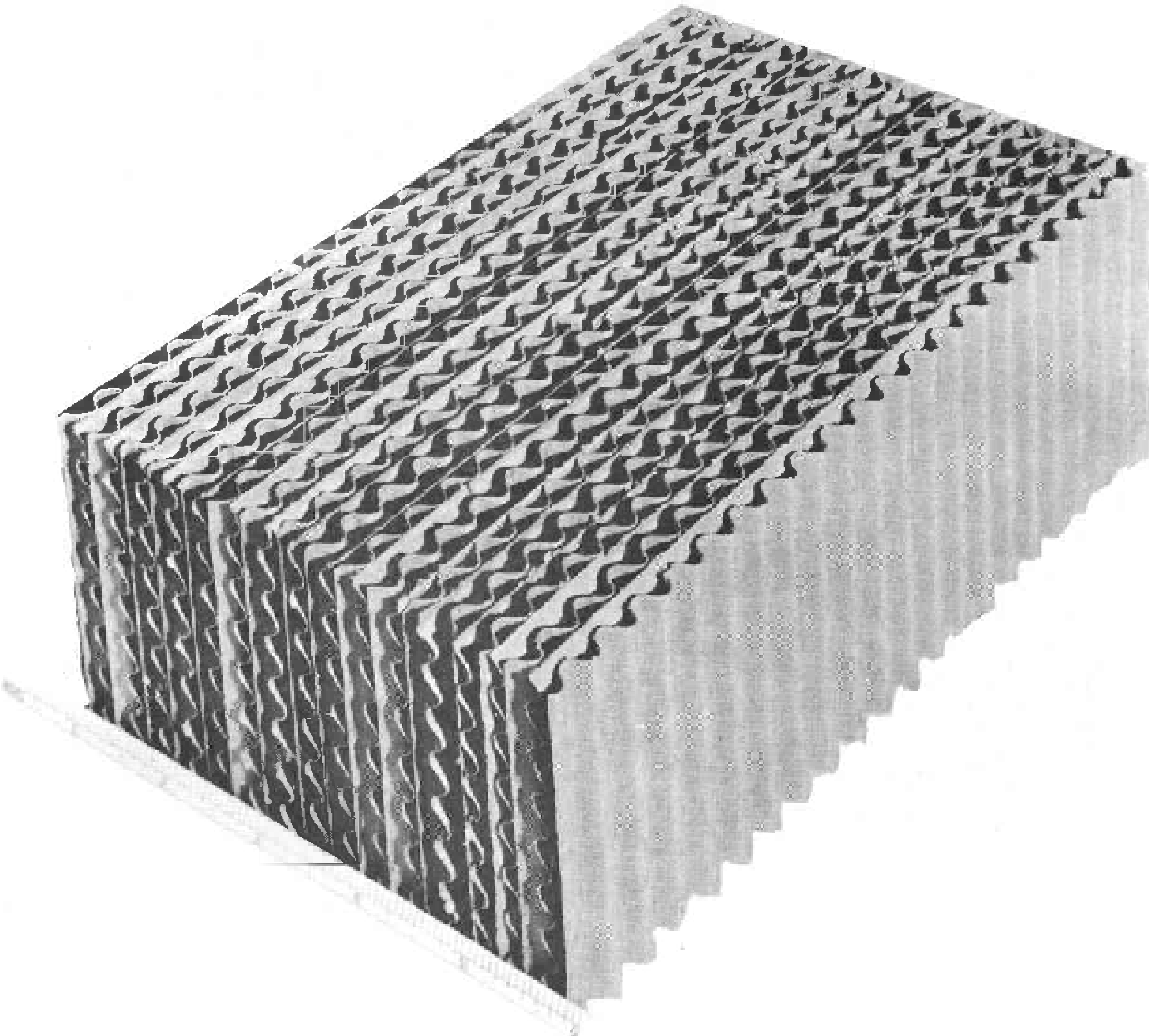

Figure 7. --XN type of corrugated-paper honeycomb sandwich core.

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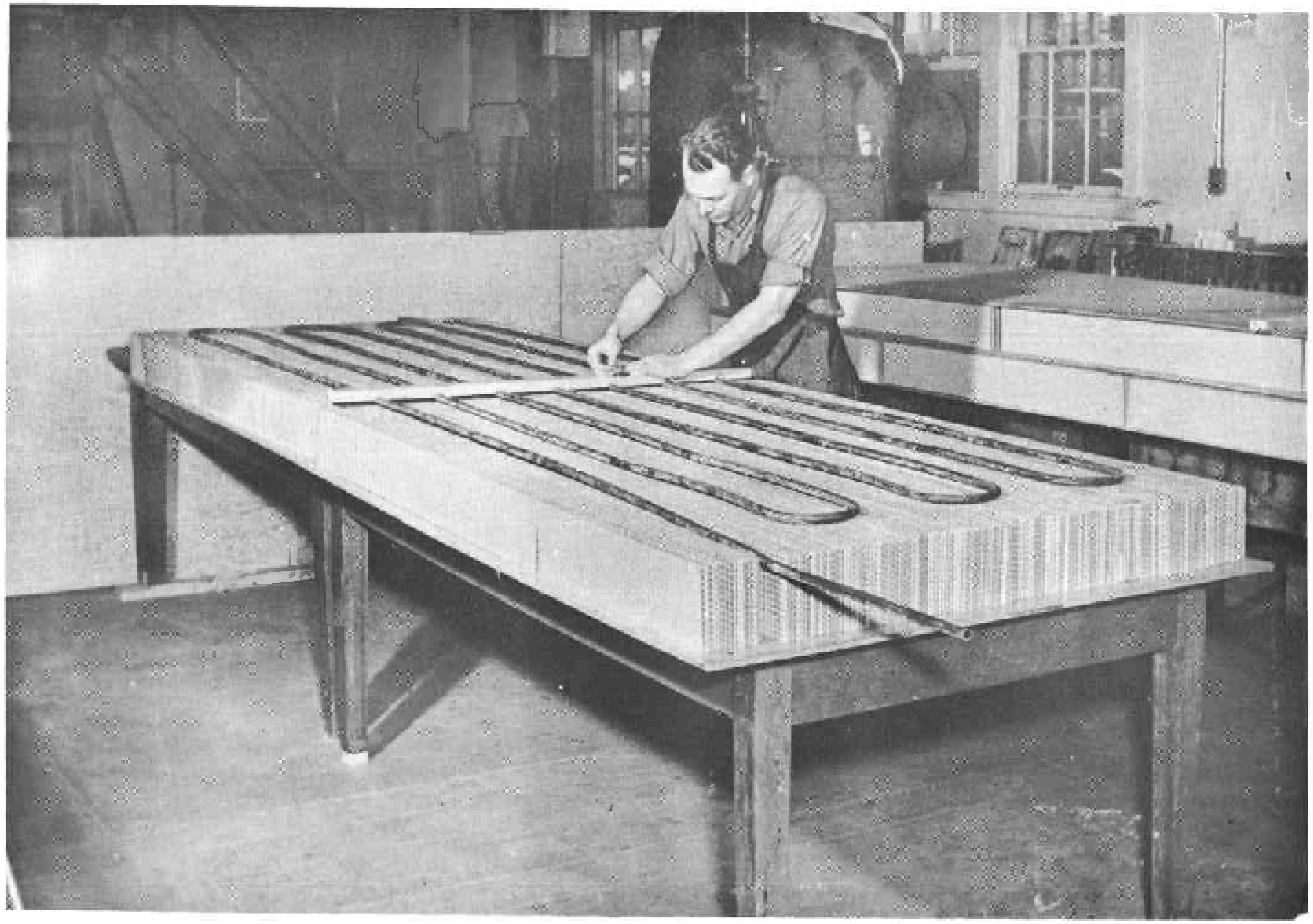

Figure 9. --Hot-water conduits pressed into paper-honeycomb core without routing grooves to receive them.

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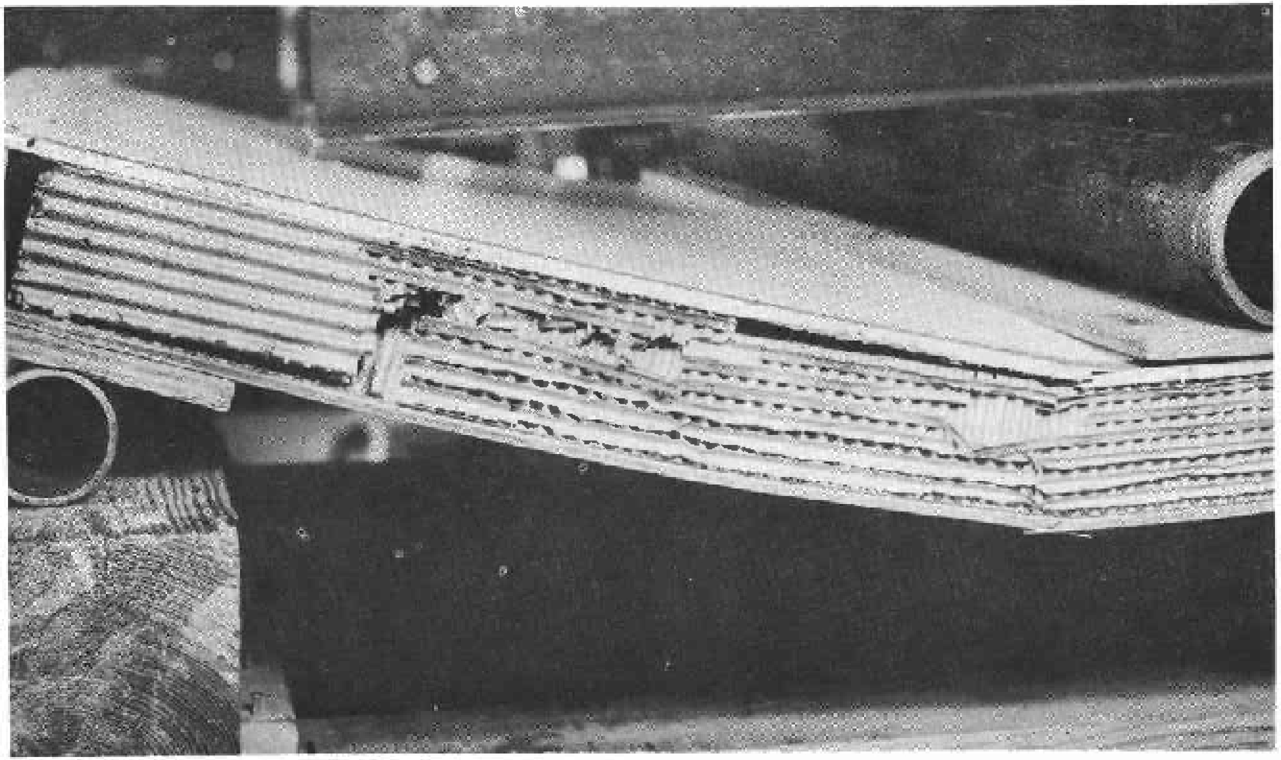

Figure 10.--Plywood-faced sandwich wall panel after failure in bending test at 391 pounds per square foot, or nearly 20 times design load.

ZM 79375 F

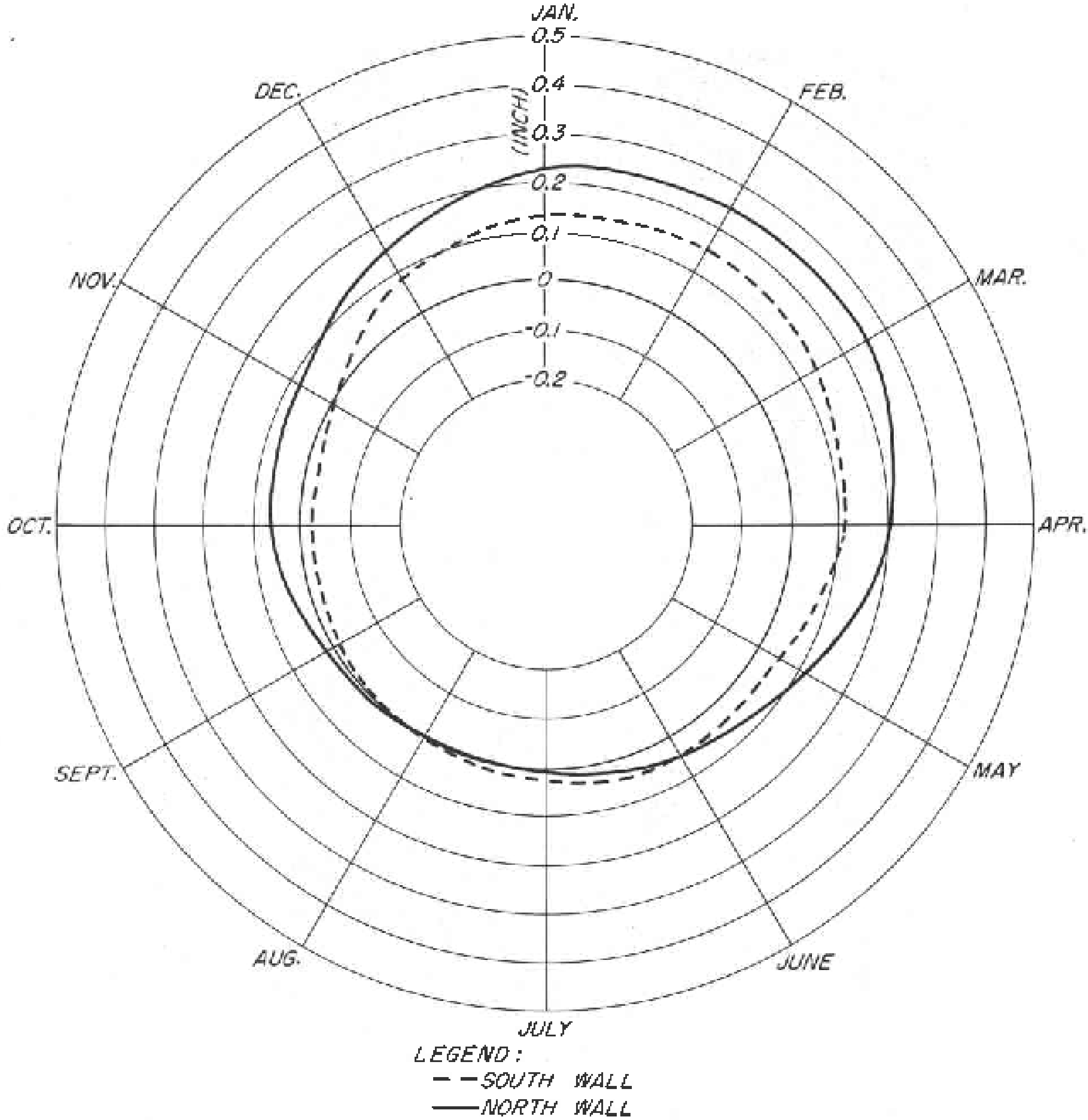

Figure 11. --Average bow of plywood- and veneer-faced sandwich wall panels 3 inches thick while in exposure unit, by months.

ZM 110 761

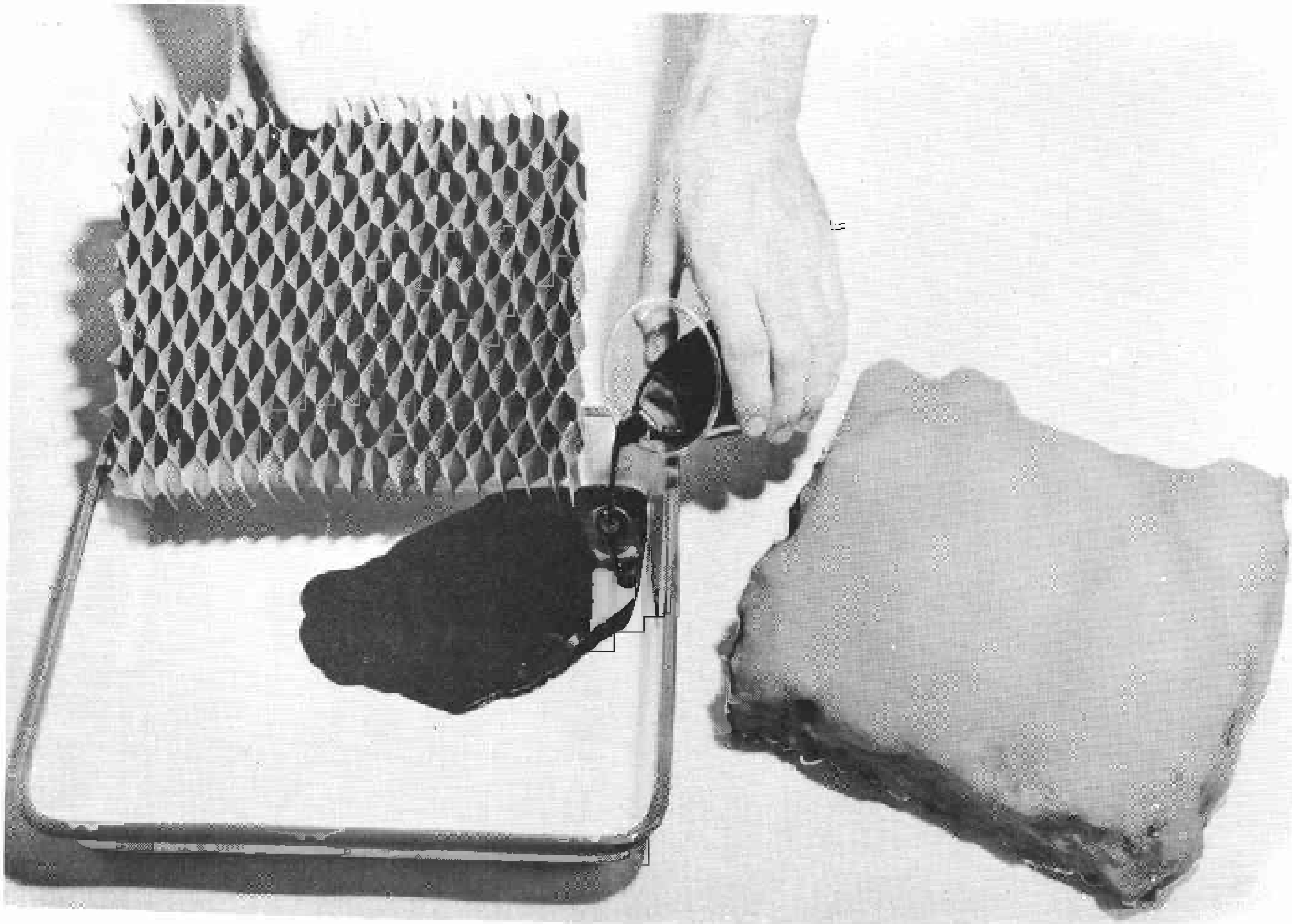

Figure 12. --Left, resin in container before foaming in the core; right, block of core with foamed-in-place resin.

ZM 93824 F

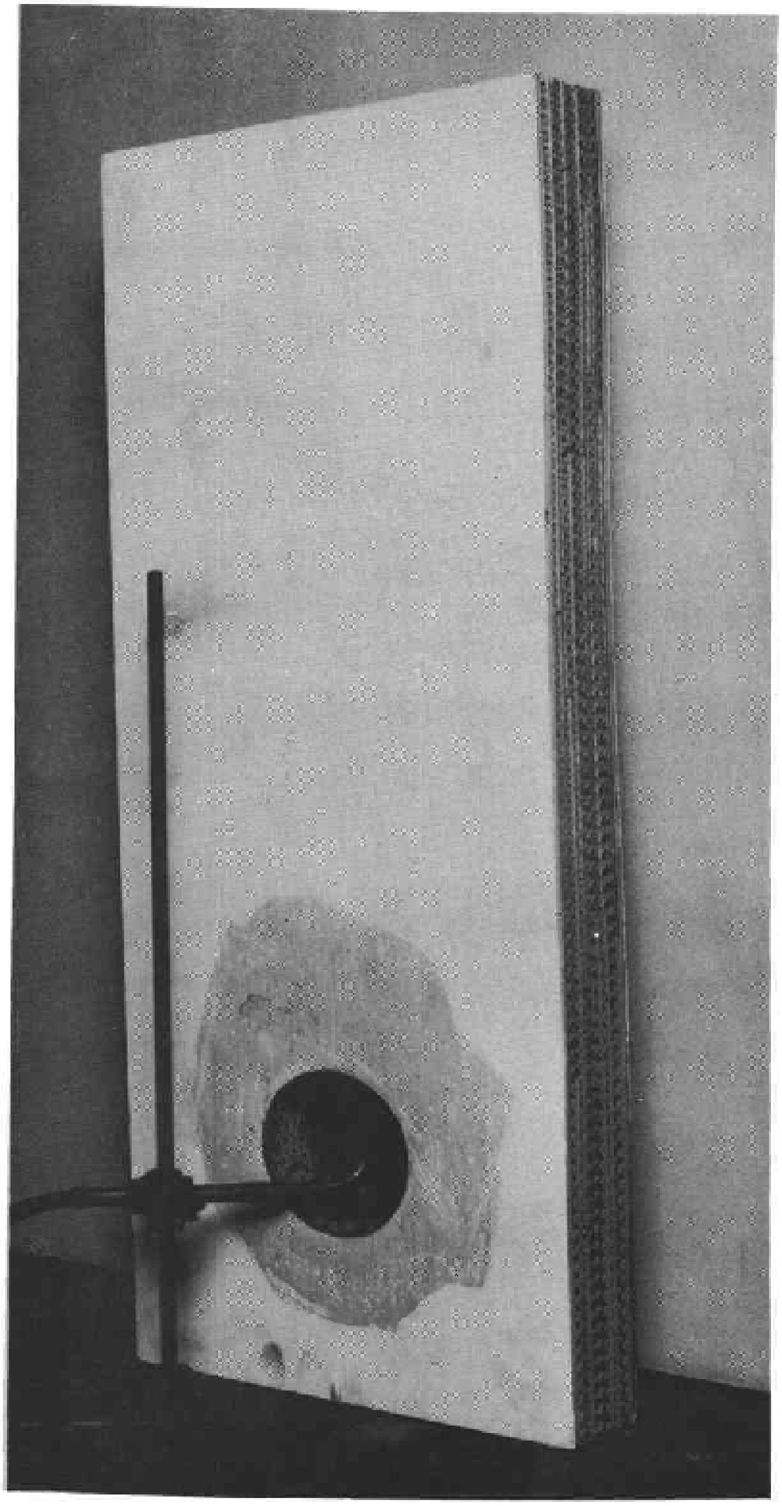

Figure 13. --Arrangement of gas burner used to test flame spread in the honeycomb core of a sandwich panel.

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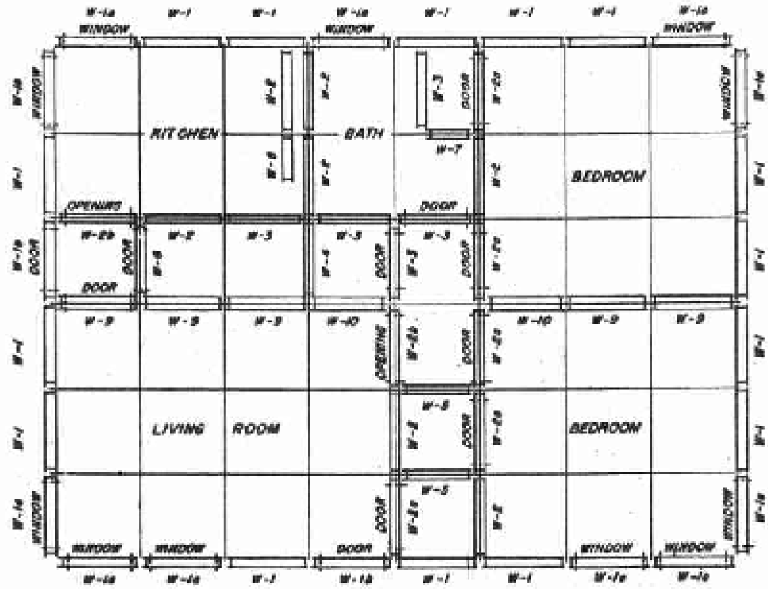

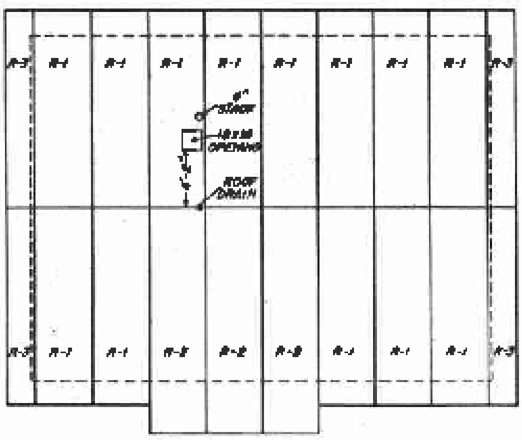

PANEL SCHEDULE

LOCATION	MARK	NUMBER REQUIRED	PANEL SIZE	DEPTH	REMARKS
WALL	W-1	15	48 x 96	3"	BLANK PANEL
DO	W-1a	11	48 x 96	3"	WINDOW PANEL
DO	W-1b	2	48 x 96	3"	DOOR PANEL
DO	W-2	7	48 x 96	3"	BLANK PANEL
DO	W-2a	5	48 x 96	3"	DOOR PANEL
DO	W-2A	2	48 x 96	3"	FRAMED PANEL
DO	W-3	5	46½ x 96	3"	2 DOOR PANELS
DO	W-4	1	45½ x 96	3"	BLANK PANEL
DO	W-5	2	45 x 96	3"	BLANK PANEL
DO	W-6	1	44 x 96	3"	DOOR PANEL
DO	W-7	1	30 x 96	3"	BLANK PANEL
DO	W-8	1	23½ x 96	3"	BLANK PANEL
DO	W-9	3	48 x 96	4½"	1 DOOR PANEL
DO	W-10	2	46½ x 96	4½"	BLANK PANEL
ROOF	R-1	13	48 x 168	4½	
DO	R-2	3	48 x 152	4½	
DO	R-3	4	24 x 168	4½	

Figure 14. --Panel schedule and assembly plan for walls and flat roof in a suggested design for a sandwich-panel house, based on a 4-foot molule.

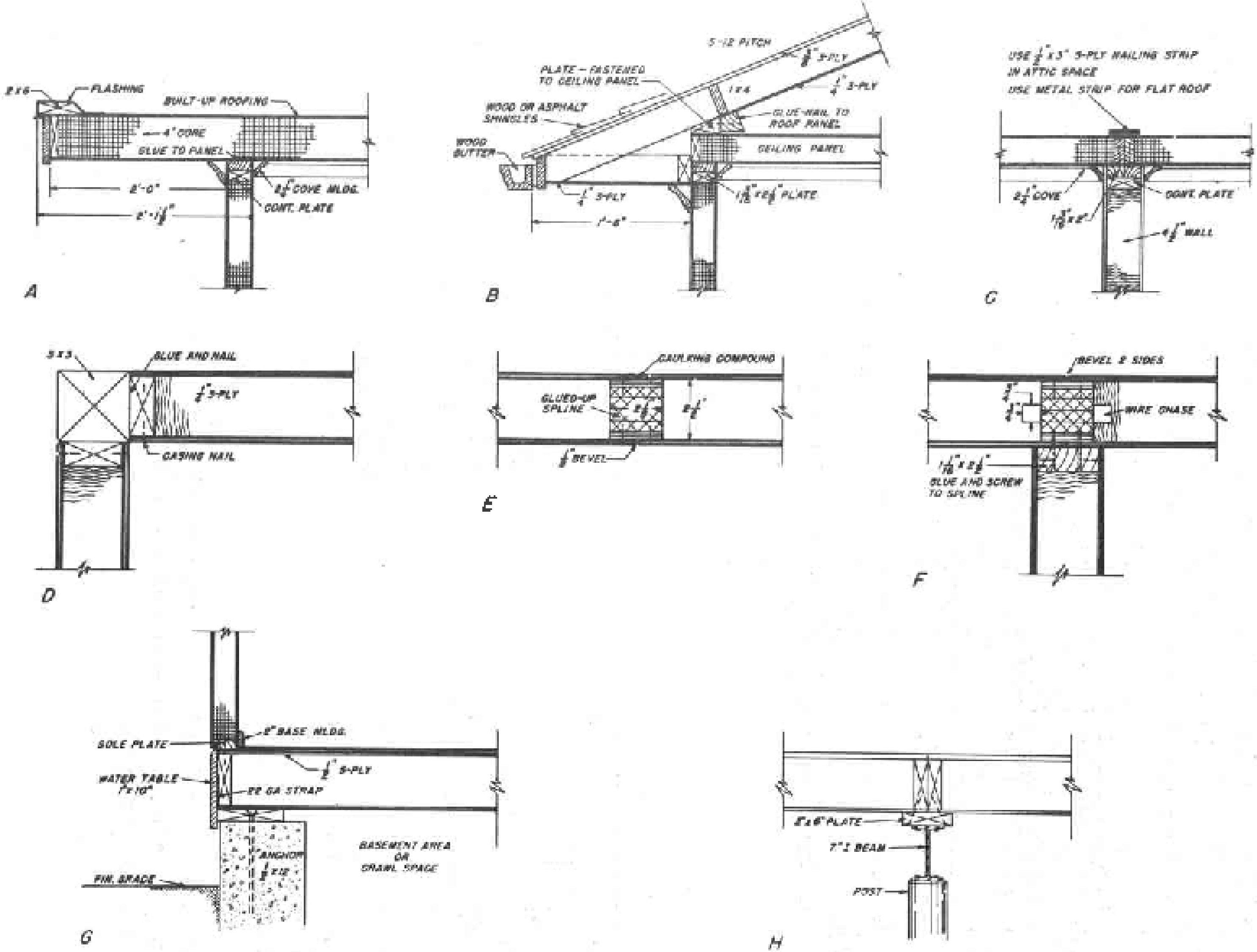

Figure 15. --Essential joint details in a suggested design for a sandwich-panel house. A, flat roof; B, pitched, panelized roof; C, joint over center bearing wall for ceiling or flat roof; D, wall corner-post assembly; E, spline joint for wall panels; F, partition-wall joint; G foundation-to-floor assembly; H, floor joint detail over main girder.

ZM 75738 F