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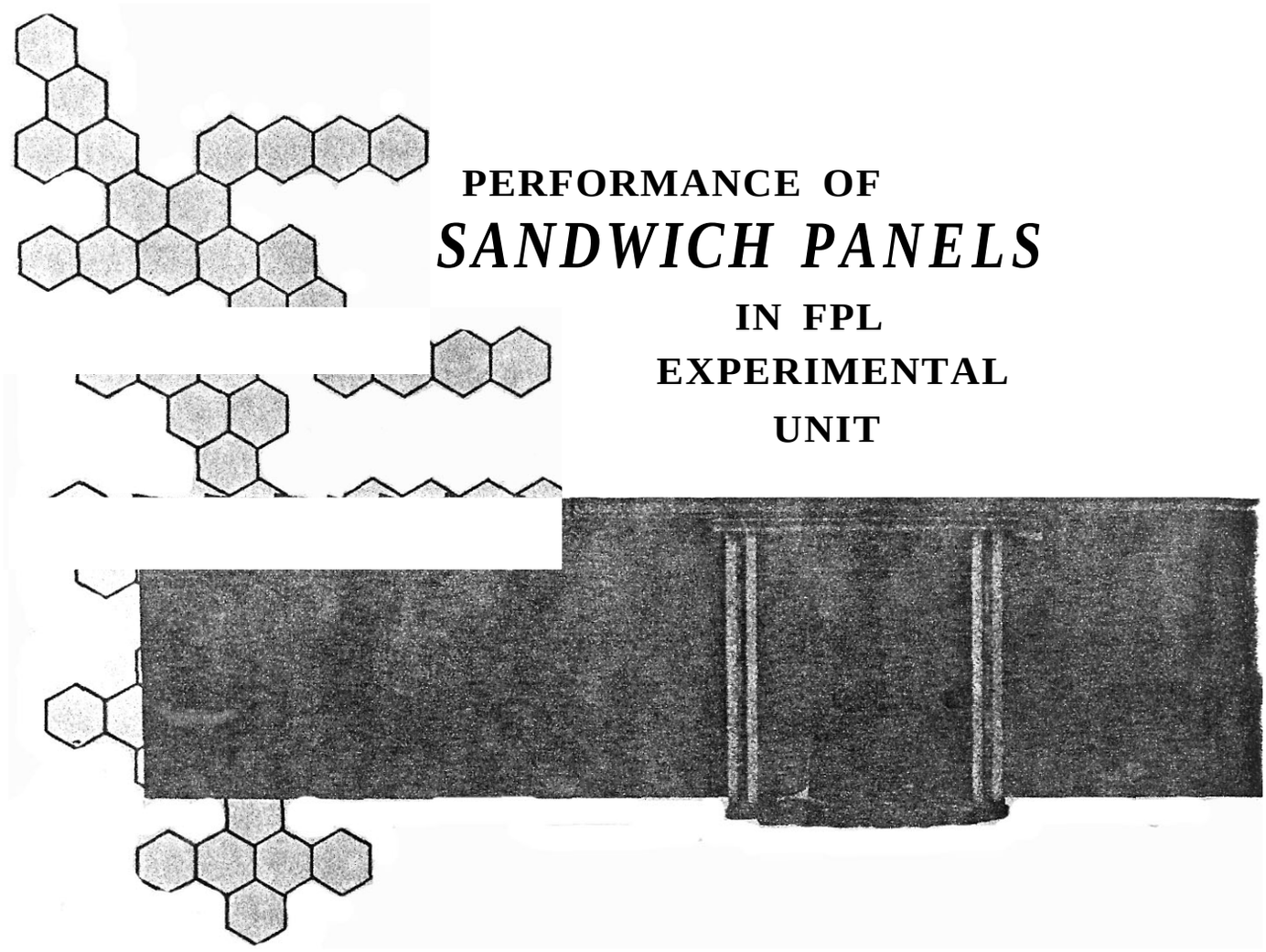

PERFORMANCE OF *SANDWICH PANELS* IN FPL EXPERIMENTAL UNIT

U. S. DEPARTMENT OF AGRICULTURE. FOREST SERVICE
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SUMMARY

Numerous Laboratory and exposure tests have shown that sandwich wall panels of nominal thicknesses and constructions can be satisfactorily used for housing construction. In addition to initial strength tests, exposure of test panels for 15 years in the Forest Products Laboratory's experimental unit have indicated that loss in stiffness and strength is insignificant for certain combinations of materials.

The wall panels made of resin-impregnated paper cores and plywood facings have demonstrated excellent performance, based on retention of stiffness and strength, However, other combinations of facings and paper cores have resulted in only fair to moderate performance.

PERFORMANCE OF *SANDWICH PANELS* IN FPL EXPERIMENTAL UNIT[1]

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INTRODUCTION

Although structural sandwich construction has attained its well-deserved recognition only in recent years, its concept and a vision of its possibilities are not new. An efficient sandwich composed of metal facings and a plywood core was produced commercially some four decades ago and no doubt there were applications at even earlier dates. World War II witnessed one of the most spectacular applications of modern structural sandich construction in the design of the mosquito bomber by DeHaviland, employing birch plywood facings with a lightweight balsa wood core.

The possibilities through structural design of utilizing materials more efficiently and of achieving lightweight construction constitute the impelling challenge of structural sandwich construction. The relatively recent significant advances in synthetic resins and adhesives that fostered glued-laminated construction, the development of fabricating techniques, and the post war production and availability of a great variety of facing and core materials, have ushered in an unlimited new era for structural sandwich constructions.

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[1] Supersedes U.S. Forest Products Lab. Rpt. 2121, Sandwich Panels for Building Construction. Oct. 1958. Also Forest Products Lab. Rpt. 2165, Long-TermCase Study of Sandwich Panel Construction in FPL Experimental Unit. Oct. 1959.

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

Background

Some of the early developments in structural panel design, with special application to prefabricated houses, employed the stressed-skin principle of construction. This is an efficient form of construction in which the covering materials carry a share of the imposed load. The stressed-skin principle has been extensively employed in one form or another in prefabricated buildings, and involves the bonding of the facings to longitudinal members, simulating box-beam design . Stressed-skin construction should not be confused with sandwich construction, which involves the concept of a distributed and continuous core. One definition of structural sandwich construction is: "A layered construction comprising a combination of relatively high-strength facing materials intimately bonded to and acting integrally with a low density core material."

The shortage of housing in the late forties and the potential of increasing production through prefabrication led to early consideration of the possibilities of structural sandwich design. Among the first prefabricated houses that were developed employing sandwich panels were the homes produced by Lincoln Industries, Inc., Marion, Va. The panels were constructed of aluminum facings bonded to a paper honeycomb core of the expanded or Christmas-bell type.

Research Problems

The application of a new and untried construction to housing naturally raised a great many questions directly related to design, material selection, fabrication methods, strength, and durability. It was also desirable to determine, by some accelerated method, the relative serviceability of the various combinations of facings and cores of the proposed sandwich panels.

The need for basic information on these and related questions led to the development of a continuing research program extending over a number of years. Research reports relating to many of the specific problems are now available, and serve as a basis for greatly improved technical developments in structural sandwich panel design. Refer to bibliography at the end of this Research Paper,

It was recognized that even with the extensive research seeking an answer to the many questions and with the encouraging results of accelerated aging tests, the question remained as to how far accelerated aging tests could be depended upon to give an accurate indication of longtime serviceability. The most effective and convincing answer to the question of serviceability and durability would obviously be through a record of actual performance over a long period of time. Such exposures would also provide data to aid in the development of accelerated aging tests.

Experimental Unit Employing Sandwich Construction

To obtain the necessary longtime exposure and service test data on sandwich constructions, it was decided to erect an experimental test unit to simulate service conditions. Accordingly, such a unit was built on the grounds of the U.S. Forest Products Laboratory at

Madison, Wis., in 1947, to provide a facility for longtime exposure tests under conditions simulating those of actual dwellings.

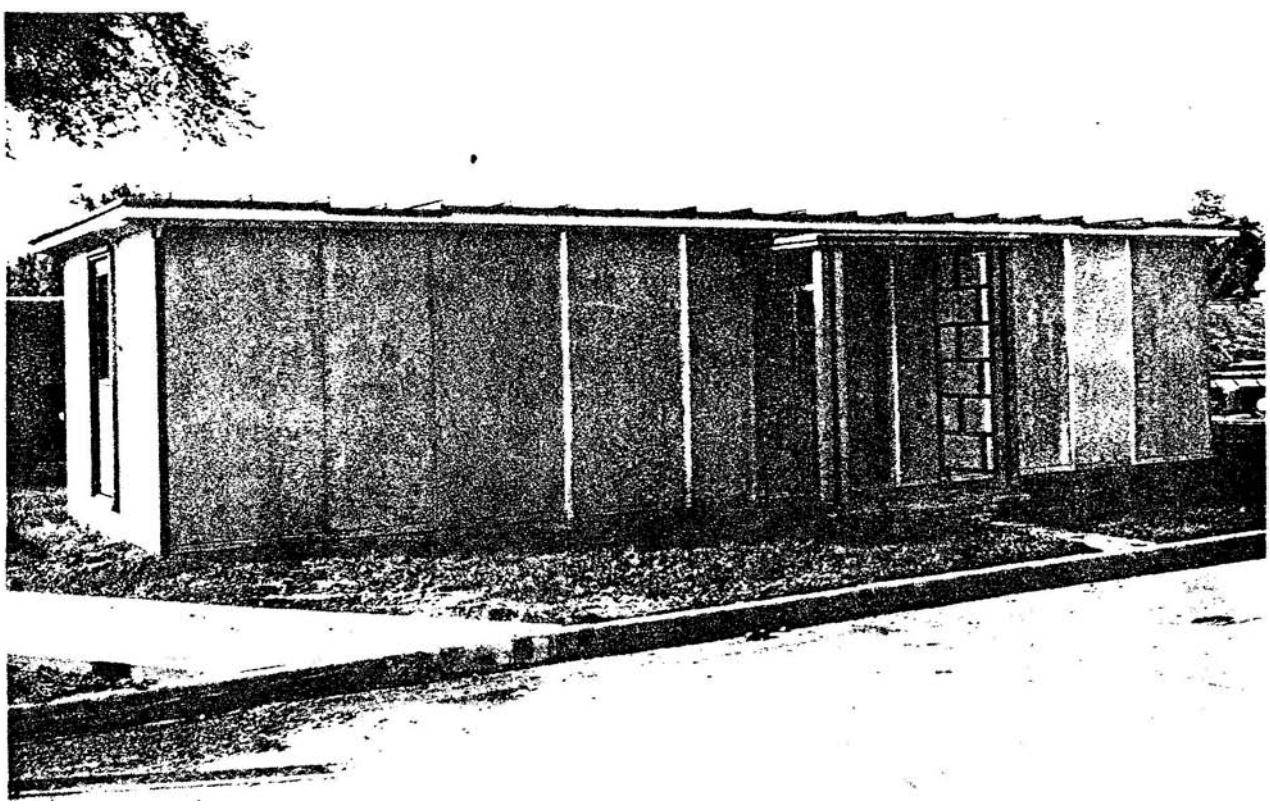
Some of the design details necessarily differed from those that would be employed in an actual house. For example, provision was made for the easy removal and replacement of individual panels. Also, the desirability of installing the sandwich panels so that each could react independently was apparent. Accordingly, the joints between adjacent roof panels and adjoining wall panels were designed for removal and to permit unrestrained bending or bowing of each panel individually in response to thermal effects or moisture changes.

Because of the research nature of this project, detailed technical information was obtained on the strength and stiffness of each of the variety of panels utilized in the construction of the experimental unit or facility, and detailed performance records have been kept since erection. The FPL experimental unit comprises one of the most extensively documented constructions employing structural sandwich construction in existence, not only from the standpoint of technical details of the strength and stiffness of the structural units, but also with respect to continual measurements of pertinent factors and characteristics such as moisture content of the wood components, temperature and temperature effects, and bow of the panels. Measurements of bow in each of the wall and roof panels have been made regularly over a period of years.

General Features

The complete experimental unit is shown in figure 1. Overall dimensions are 38 feet 6 inches long by 12 feet 6 inches wide by 8 feet high. The front of the unit faces north, and both the front and the rear walls were constructed of

Figure 1.--ForestProducts Laboratory sandwich experimental unit. ZM 116 396



10 sandwich panels, generally installed in matched pairs. The roof consisted of 10 sandwich panels. Four of the wall panels and two of the roof panels had aluminum facings, and all others, except one, had plywood or other wood-base facings. Both the east and west end walls consisted of three panels. Those on the east were of sandwich construction and those on the west were of stressed-skin construction. One of the panels units in each end wall and in the south wall contained a window.

The interior was divided into two 12- by 15-foot rooms and one 8- by 12-foot utility room, with an exterior door, located in the north wall, opening directly into the utility room. Another special feature of the construction was the use of sandwich panels over a crawl space for the floor of the east room, with copper heating pipes installed in the panels during fabrication to determine the effect of radiant heating with hot water on the long-range performance, The west room had a concrete subfloor with radiant heating to permit study of wood finish floors under such heating conditions.

DETAILS OF PANEL DESIGN

Cores

The cores used in the intial group of sandwich panels were paper honeycomb of two different kinds. These may be designated the expanded or Christmas-bell type, and the corrugated paper type. The expanded core represents a long-established fabrication principle in which sheets of paper assembled flatwise are bonded along continuous narrow hands at regular intervals across the sheet, the bonds being staggered in adjacent sheets (fig. 2). Such material can be readily fabricated with as many sheets or in such thickness as required, and with any desired size of honeycomb cell. Segments of the bonded sheets are cut off in accordance with the required thickness of the sandwich. The segments are then expanded to develop the honeycomb pattern, and bonded to the facings of the sandwich panel with the axis of the honeycomb perpendicular to the facing. These cores of the expanded type were used in the original group of aluminum-faced panels. Expanded paper honeycomb cores were also used in replacement panels erected in 1961 and 1962.

The corrugated paper type core was made at the Forest Products Laboratory. The corrugations or flutes were formed by running the flat sheet through a corrugating machine such as used in the fabrication of container fiberboard. The corrugated sheets were then assembled in various patterns. Three of the patterns used in sandwich panels made at the Laboratory are illustrated in figures 3, 4, and 5.

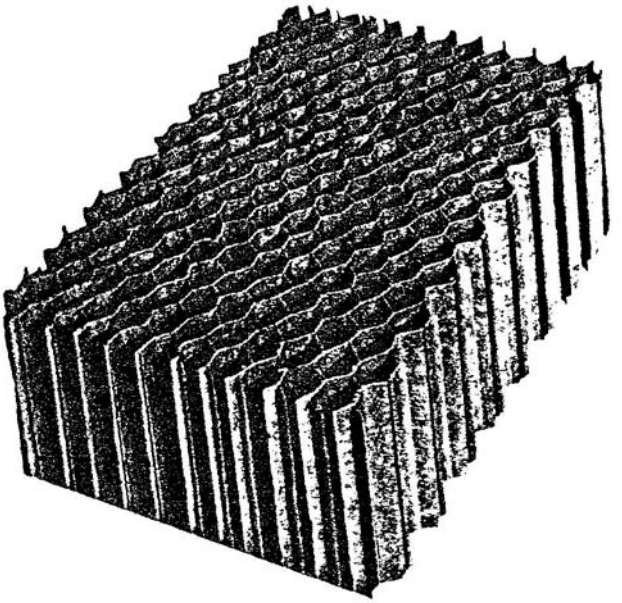


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Figure 2.--Expanded hexagonal paper-honeycomb sandwich core.

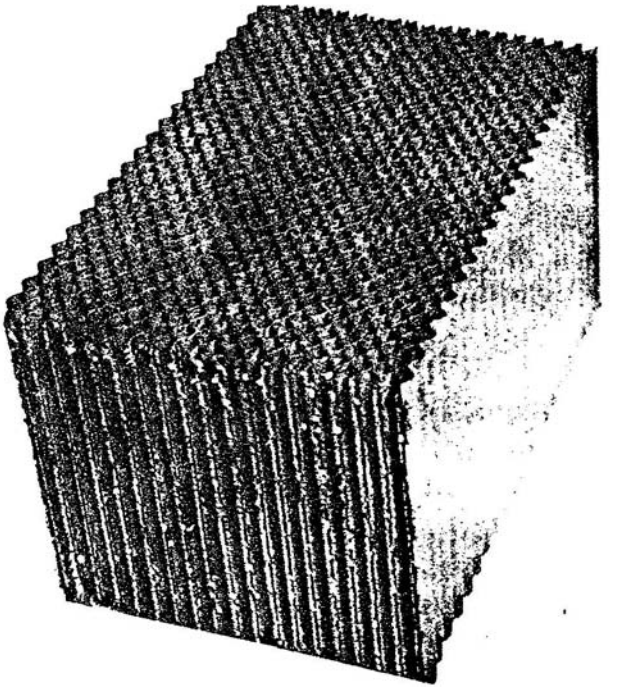

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Figure 4.--PN type of corrugated-paper honeycomb core.

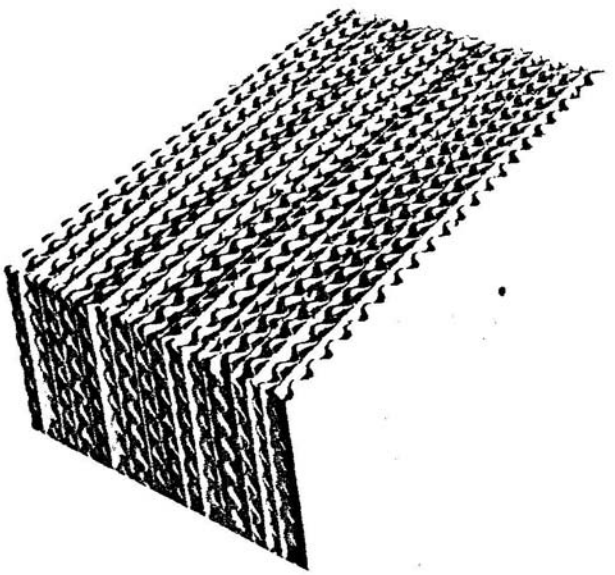

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Figure 3.--XN type of corrugated-paper honeycomb core.

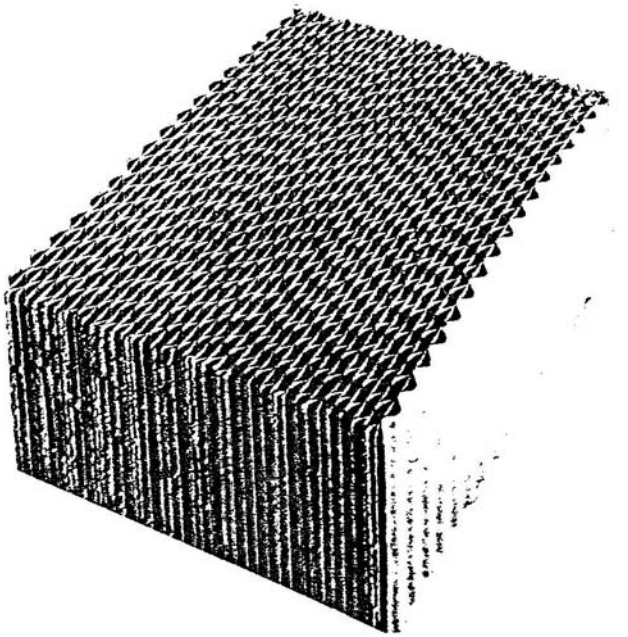

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Figure 5.--PNL type of corrugated-paper honeycomb core with flat interleaves between the corrugated sheets.

Paper used in the corrugated-paper core was a typical kraft paper weighing about 45 pounds per ream (24 by 36 inches--500),impregnated with about 15 percent of a water-soluble phenolic resin. Bonding of the sheets composing the core was with an acid-catalyzed phenolic resin. Bonding of the core to the facings was with an acid-catalyzed intermediate-temperature-setting phenolic resin.

The original expanded core used in the aluminum-faced panels was commercially manufactured of kraft paper treated with a thermosetting phenolic resin. It was bonded to the aluminum facings with a phenol-vinyl adhesive. Expanded core used in replacement panels contained 8 or 11 percent resin.

The core designated XN (fig. 3) consists of resin-treated corrugated kraft paper sheets glued together so that the corrugations of adjacent sheets are at right angles, the assembly being sawed into panel thicknesses and laid on edge between the facings. In such an assembly the axes of the flutes in alternate layers are perpendicular and parallel, respectively, to the plane of the facings. Cores designated XF are similar except that, as placed in the panel, the flutes are all parallel to the plane of the facings, but with the flutes of alternate layers parallel and perpendicular to the length of the panel, respectively. This kind of placement is obviously weak in flatwise compression, but has better thermal insulation properties. Another unfavorable factor is that a poor glue bond between corrugations would probably result in low shear strength.

Cores designated PN (fig. 4) are assembled and glued at the nodes with the direction of all the flutes parallel. Segments, the thickness of the panel, are then sawn from the block and assembled in the panel with the axis of the honeycomb cells perpendicular to the facings.

Cores designated PNL (fig. 5) are assembled in the same manner as the PN core, except that single-face corrugated board (corrugated board faced on one side with a paper sheet) is used. However, this type of core was not used for the original panels.

Walls

Wall panels originally placed in the experimental unit included both 4- by 8-foot sandwich panels, 3 inches thick, with plywood or veneer facings, which were made in the Laboratory, and 3- by 8-foot panels, 2 inches thick, with aluminum facings which were commercially fabricated. The wall panels were designed for a wind load of 20 pounds per square foot, and some of the Laboratory-made panels had resin-treated paper overlays. All of the panels in the north, south, and east walls were of sandwich construction. For the most part, the same combination of core and facing types was used in matched pairs in both the north and south walls. For comparative purposes, the west wall was built of insulated 4- by 8-foot stressed-skin panels, consisting of plywood facings glued to a wood framework.

Five types of facings were used in the original Laboratory-made panels: (1) 1/4-inch, 3-ply Douglas-fir of exterior type; (2) 1/4-inch, 3-ply Douglas-fir,

exterior type, with 25 percent phenolic resin-treated paper overlay on one face; (3) 2-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; (4) single-ply 1/8-inch Douglas-fir veneer with resin-treated paper overlays on both sides; and (5) 3/8-inch, 5-ply Douglas-fir, exterior type (for floor panels).

Ten panels representing all types described were installed in both the north and the south walls of the test unit. The east wall consisted of three sandwich panels with type XN cores and 1/4-inch, 3-ply Douglas-fir facings. A window was provided in the center panel. These panels were fastened together by means of an insulated spline consisting of laminated fiberboard faced on two sides with plywood. As already mentioned, the west wall consisted of stressed-skin panels. One interior partition consisted of uninsulated stressed-cover panels, and the other was made of three sandwich panels containing type XN cores and 1/8-inch veneer facings overlaid on both sides with resin-treated paper.

Panels in the north and south walls were fastened together with continuous 3/4 - inch top and 1- 5/8-inch-thick bottom plates seated in grooves formed by routing out the cores at the top and bottom of the panels. Cleats glued to the roof panels seated into the wall panel grooves. Wall panels were fastened to the roof cleats and top and bottom plates with roundhead screws to insure easy panel removal. A 1/2-inch space was provided between each panel. Insulation was added and the joint sealed with a waterproof tape in a manner to allow for unrestricted bowing.

Roof

Ten sandwich panels were used for the roof of the experimental unit. These were 14 feet long and spanned the width of the structure with 9-inch overhangs. The panels were designed for a load of 25 pounds per square foot. The eight Laboratory-made roof panels were 4 feet wide (less 1/2 inch), and 4-1/2 inches thick, with facings of 1/4-inch, 3-ply Douglas-fir. All three of the corrugated paper-type cores used in the wall panels were represented. Three of the eight panels thus made had ventilating flues 2 by 3 inches in cross section and were spaced 6 inches apart, extending lengthwise through the panel. The facings of one of the ventilated panels had paper overlays, and one was given two coats of aluminum paint with an additional coat of inside white paint on the interior face to provide for increased resistance to water vapor movement.

The other two roof panels were factory made. They are 3 feet wide (less 1/2 inch) and 3 inches thick, with aluminum facings on expanded paper honeycomb cores.

The 1/2-inch space between each roof panel was insulated and the interiorface of the joints taped in the same manner as the wall panels, permitting unrestricted bowing. Those panels directly over the center wall partitions were seated in them with cleats. A metal roof with standing seams at the panel intersections and a sliding metal cap over a taped joint insured a weatherproof covering, and permitted easy removal of any roof panel.

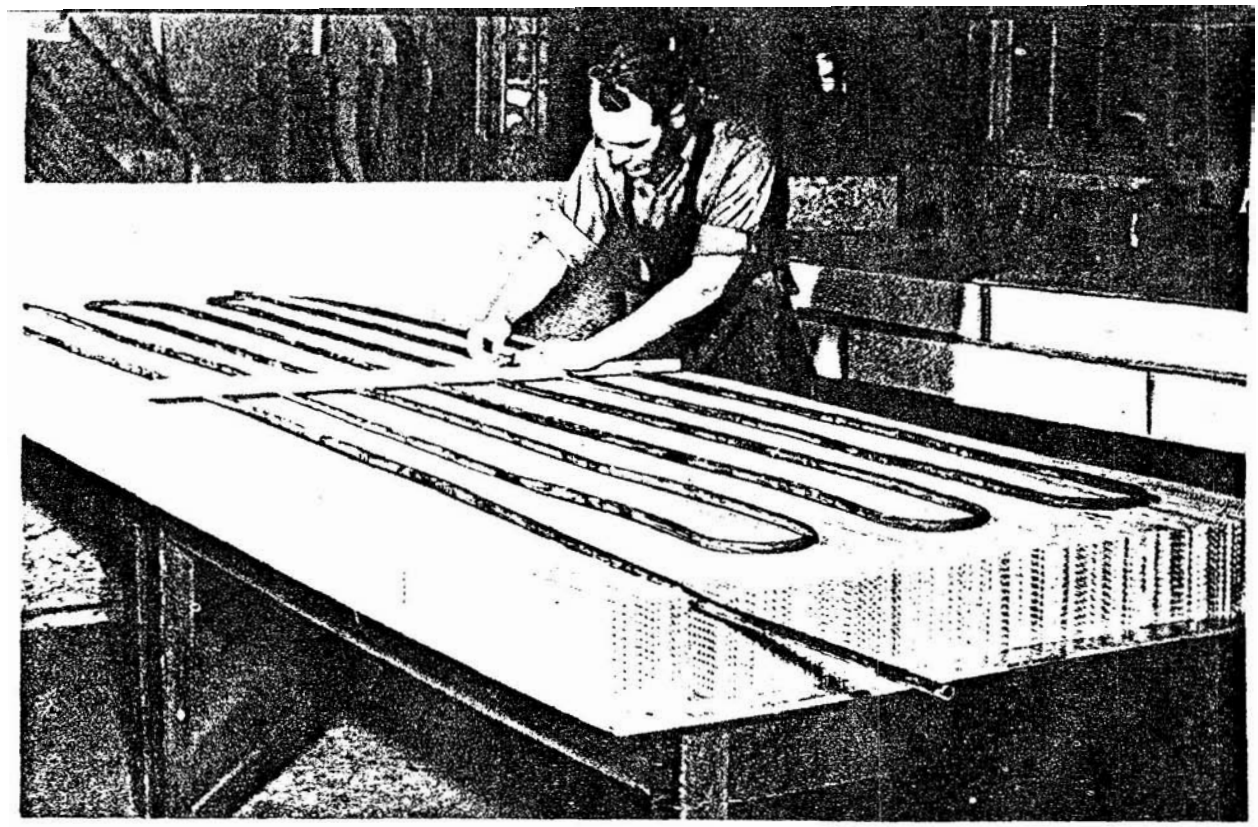

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Figure 6.--Heating pipes placed in sandwich floor panels. They were pressed into the core without previous routing of grooves.

Floors

The east room flooring, below which is the crawl space, consisted of sandwich panels 12 feet long by 3 feet 8-1/2 inches wide by 6 inches deep, with type XN cores and 3/8-inch, 5-ply Douglas-fir facings. The floor panels were designed for a load of 40 pounds per square foot. Copper hot water heating pipes were installed in these panels during manufacture to determine the effect of radiant heating upon them (fig. 6). Panels were connected together with an insulated spline similar to that used in the east wall.

To study the effect of radiant heating, the floor of the west room included a reinforced concrete slab with perimeter insulation, gravel subbase, and a roll-roofing vapor barrier. Heat was supplied from 1-inch pipes placed over the concrete. Hardwood strip flooring, 25/32 by 2-1/4 inches, was laid over 2-inch-thick anchored sleepers, spaced about 18 inches on center. Sections of the finish flooring were installed at moisture contents of 3, 6, 9, and 12 percent, to study the optimum moisture content of floors subjected to radiant heating.

Doors and Windows

Three flush doors were made at the Laboratory with cores of type XN. The exterior door had a birch frame and 2-ply crossbanded birch facings made of 1/16-inch veneer. The interior doors had Douglas-fir frames; one was covered with the paper-overlaid 1/8-inch Douglas-fir veneer,. and the other with overlaid 2-ply Douglas-fir. A glue of the same general type used in the panels

was also used in the doors. Wall panels with door or window openings were made up with rough frames glued in place when the panels were pressed. Standard double-hung sash were used, with special frames adapted to the 3-inch wall thickness.

DETAILS OF FABRICATION AND ASSEMBLY

Of the original panels, all but the six aluminum-faced panels used in the experimental unit we re fabricated at the Forest Products Laboratory. The aluminum-faced panels were obtained from a commercial source, and complete information is not available on the method of assembly and the bonding. The aluminum facings were 0.02 inch in thickness and smooth faced. In fabricating the remaining sandwich panels at the Laboratory, a considerable amount of hand labor was required because of the variety of facings and cores employed.

Fabrication of Cores

A typical kraft pulp made in large quantities for corrugated fiberboard boxes and other purposes was selected as the base material for the honeycomb cores, primarily because it is extensively produced, and also because its durability compares favorably with that of most other types of paper. Strength tests indicated that paper having a ream weight of 45 pounds (24 by 36 inches--500) would be adequate both from the standpoint of strength and handling ease.

Exploratory tests indicated that a resin content of about 15 percent by weight would provide the necessary strength under wet conditions and make the paper resistant to attack by decay fungi.[3] At this resin content, cores made from this paper retained 60 percent of their dry compressive strength when soaked in water, and 90 percent as much tensile strength as that of dry, untreated paper. Kraft paper was commercially treated with water-soluble phenolic resin, diluted to about 40-percent concentration (by weight) in a mixture of half water and half alcohol, to prevent breaking of the paper web as it passed through the drying tower. Two heating zones were used, one at 275° F. and the other at 290° F.

Treated paper was corrugated in an A-flute pattern on an experimental machine at the Laboratory. Glue was applied in a glue spreader to the nodes on one side of 4-foot-squaresheets of corrugated paper, with the flutes in the direction of movement of the sheet. An acid-catalyzed phenolic-resin glue was used. For example, type XN core (fig. 3), was laid up in stacks so that the flutes of adjacent sheets were at right angles.

[3] Seidl, R. J., Kuenzi, E. W., Fahey, D. J., and Moses, C. S. Paper Honeycomb Cores for Structural Building Panels: Effect of Resins, Adhesives, Fungicide, and Weight of Paper on Strength and Resistance to Decay. U.S. Forest Products Lab. Rpt. 1796. Sept. 1961.

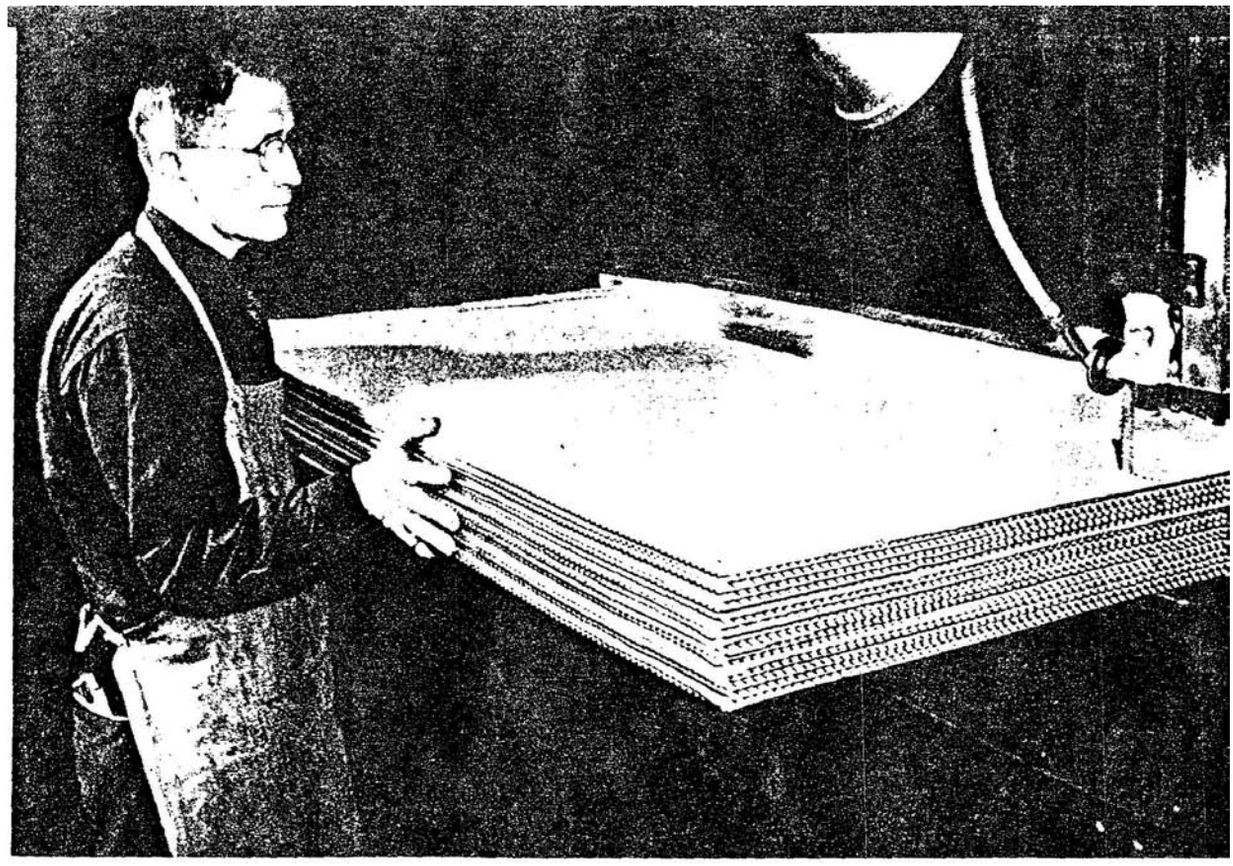

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Figure 7.--Cutting of paper-honeycomb sandwich core on a bandsaw.

For ease in sawing the core, a sheet without glue was laid at intervals of about 5 inches to act as a separator. Four-foot cubes were laid up, compressed slightly, and cured in a kiln at 210° F. for 24 hours.

The finished core blocks were bandsawed to the required size within a tolerance of 0.015-inch, considered necessary for satisfactory gluing to the panel facings. Cores for wall panels were sawed to thicknesses of 2-1/2 to 2-11/16 inches, according to the type of facing later to be glued to them, for an overall panel thickness of 3 inches. Those for roof panels were sawed 4 inches thick, and those for floor panels 5-1/4 inches thick (fig. 7). After being sawed, the core strips were cleaned of sawdust with an air jet to provide a clean surface for gluing.

Fabrication of Facings

Douglas-fir plywood panels used for the facings and the 1/8-inch veneer were obtained commercially. The 2-ply crossbanded facings were made from 1/10-inch Douglas-fir veneer cut at the Laboratory and glued up unsanded. The impregnated overlay paper was applied to the plywood and veneer in a commercial hot press.

Facings longer than 8 feet, for roof and floor panels, were made by scarfing two sheets together at a slope of 1 in 12 with a melamine-resin glue.

The overlay paper used on some of the facings was a commercial product reported to contain about 20 to 25 percent of phenolic resin in addition to a dried phenolic-resin glue line on one side. This paper was applied to the ply-

wood and veneer in a commercial hot press at a pressure of 175 to 200 pounds per square inch for 6 minutes at 285° F. The overlay paper was applied so that the machine (grain) direction of the paper was parallel to that of the adjacent ply of both the 2- and 3-ply plywood, but at right angles to the grain of the single veneer facings.

Assembly of Panels

Exploratory work.--Exploratory tests in which small test panels about 1 inch thick were made to try out different gluing and fabricating methods preceded the fabrication of the full-sized panels, Gluing of facings to cores required a short pressing cycle and along assembly time, so an intermediate temperature-setting phenolic glue was selected. In tension tests, this glue gave an average tensile strength of about 70 pounds per square inch with an average core failure of 80 percent, when used to bond 1/4-inch 3-ply plywood facings to type XN cores.

Compression tests of type XN paper-honeycomb cores showed a crushing strength of about 50 pounds per square inch at a temperature of 200° F. The small test panels were therefore glued at pressures ranging from 15 to 45 pounds per square inch, and inspected for adequacy of contact between core and facing and for possible crushing of the cores. At the lower pressures poor contact was evident, while the higher pressures caused occasional crushing. Compression measurements showed that collapse of the core occurred when compression exceeded 0.030 to 0.035 inch.

Assembly details.--The most satisfactory gluing pressure, as indicated by these tests, was 20 to 25 pounds per share inch, with a compression of about 0.015 to 0.020 inch. Later experience with fabrication of full-sizepanels, however, resulted in lowering the pressure to 15 pounds per square inch for type XN cores when some crushing persisted at the higher pressures, although 20 pounds was found low enough to avoid crushing in gluing facings to type PN cores. Panels with type XF cores were pressed with stops in the press, so that the actual pressure exerted upon them was unknown. The stops permitted 2-to 3-percent compression of the panel assembly.

Glue was applied to all cores and facings with hand rollers in the amount of 22 grams a square foot (one-half on the core and one-half on the facing). After glue was applied, the cores and facings were allowed to stand for 3 to 20 hours before being assembled, to evaporate the solvent. They were then assembled and put into a hot press for cure of the glue at 230° F.

Because of the size of equipment available at the Laboratory, all panels were step pressed in a single-opening 50- by 50-inch hot press at a platen temperature of 230° F. The usual procedure was to insert the first 4 feet of panel and cure it for 40 minutes. The press was then opened and the panel advanced 2 feet for a period of 25 minutes. This process of advancing 2 feet and curing for 25 minutes was continued until the final step, which was cured for 40 minutes. Thus every point on the panel was cured for 40 minutes or more.

Sizing and routing of panels.--Wall

panels were trimmed, after assembly, to a standard size of 3 feet 11-1/2 inches by 7 feet 11-1/2 inches. Grooves in the tops of the wall panels were made by routing out the cores to a depth of 1-3/4 inches with a shaper for the continuous headplate and roof cleats, and those in the bottom of the panels to a depth of 1-3/4 inches for the soleplates. Sides of the panels used in the east and center walls were routed to a depth of 1-1/8 inches to receive the insulated splines that connect the panels of these walls.

Panels of the north and south walls that would be adjacent to crosswise partition panels were designed with cleats glued along an inside edge to fit into the grooves of the adjoining partition panels.

Roof panels made at the Laboratory were trimmed to a final size of 3 feet 11-1/2 inches by 14 feet and routed at the ends to receive filler or nailing cleats glued in place to provide a nail base for facia boards. Lengthwise cleats were glued to the edges of those roof panels that joined interior partitions. Cross cleats were glued to the underside of the panels near the ends for later attachment to the tops of the wall panels.

The aluminum roof panels were sized with a metal-cutting saw and fitted with cleats and end fillers which were glued in place with a commercial wood-to-metal glue at 300° F. and a pressure of 15 pounds per square inch.

Floor panels made at the Laboratory were trimmed to a final size of 3 feet 8-1/2 inches by 11 feet 11-1/2 inches. Panel ends and outside edges of the two panels at either end of the floor were trimmed flush. Edges where panels joined were routed to a depth of 1-1/8 inches to receive the insulated floor splines used to fasten them together. Slots were cut in the bottom facings of the panel ends to permit bending of the radiant heating pipes for connection to the water supply and return lines.

Window and door frames.--Because of the 3-inch thickness of the wall panels, window frames were specially designed for the double-hung windows. Window frames were made from nominal 2- by 6-inch stock and were installed so that they projected on the exterior side. A shallow saw cut was made in the outside plywood panel cover above the head jamb to receive metal flashing, and was filled with caulking compound to insure a positive seal. The inside casing acts as a window stop.

The outside door frame was also made from 2- by 6-inch stock and similar to the window frames in form. Side and head jambs were of pine and the sill of oak. The frame extends approximately 2-1/2 inches beyond the outside wall surface. Inside door frames resembled conventional frames except in width. The casing was of the type used on the window frames.

All window and door frames were screwed to the rough frames installed in the panels.

Insulated splines.--The insulated splines used in the east and center walls and floor panels were made of 1/2-inch insulating board glued up to the desired core thickness with 3/8-inch Douglas-fir plywood facings. Their resilience was sufficient to compensate for expansion and contraction of the core.

Miscellaneous parts.--The 3- by 3-inch corner posts were made of Douglas-

fir and cleats were glued to one side to receive the routed edges of the end-wall panels. End-wall cornices were preassembled for site erection as a unit. Water table, facia boards, and other trim were made in random lengths and installed during erection of the unit.

ERECTION OF THE UNIT

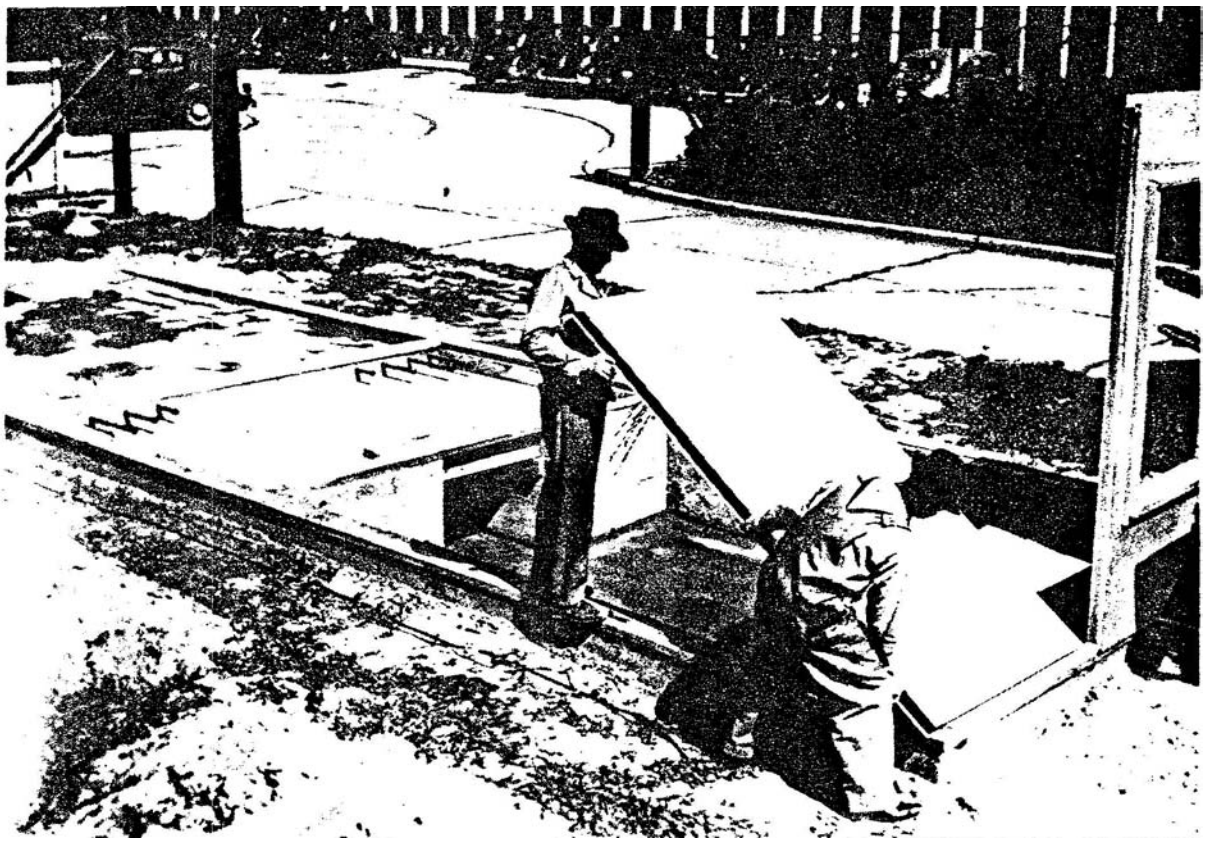
The superstructure of the experimental sandwich panel unit was erected on the prepared foundation in 2-1/2 days, June 3 to 5, 1947 (fig. 8). Thereafter, roofing, heating plant, flooring, and other installations were made.

Exterior Painting

All bare wood, including exterior frames, exterior surfaces of the sandwich panels, facia boards, and trim, was given a prime coat of aluminum paint. Window and door frames were primed before they were fitted into the wall panels. The aluminum-faced panels were given a zinc oxide prime coat on exterior faces.

After erection, all exterior surfaces were given 2 coats of a standard outside paint consisting of titanium, lead, and zinc. After installation of the replacement panels in 1962, several types of primers were used depending on the type of facing, but the top coats consisted of an acrylic latex paint.

Figure 8.--Erection of superstructure of sandwich experimental unit. ZM 73607 F



RESEARCH AND TESTING PROGRAM

The design of the sandwich panels and the construction of the FPL experimental unit involved a great deal of research and development work. As a research unit, not only were the panels subjected to initial stiffness tests, but also prototype panels were tested to failure to establish both strength and stiffness data. In addition, frequent measurements were made to determine the effect of changes in relative humidity as related to moisture content and temperature on the straightness of the panels. This was possible because the individual panels were not joined but were left unrestrained to permit deflection. In addition, accelerated aging tests were conducted on the core material and on sandwich panel samples, and the effect of moisture was studied. Later, several panels were removed from the experimental unit for evaluation after 16 months of service, and after 8, 13, and 15 years.

Structural Tests

Tables 1 and 2 give results of bending tests on prototype sandwich panels and stiffness tests of the panels used in the experimental unit. Figure 9 shows the location of original wall and roof panels in the unit. Tests were made by supporting the panel on rollers near the ends and slowly applying load at the quarter points (fig. 10). Test spans were 90 inches on the wall panels and 138 inches on the roof and floor panels. The tabulated values show that the equivalent uniform loads at failure of the prototype panels exceeded by many times the design loads of 20 pounds per square foot for walls, 25 pounds per square foot for the roof, and 40 pounds per square foot for the floor. All except the aluminum-faced panels used in the experimental unit had deflections at design toad that were less than 1/270 of the span.

Figure 9.--Positions of original numbered wall and roof panels in sandwich experimental unit.

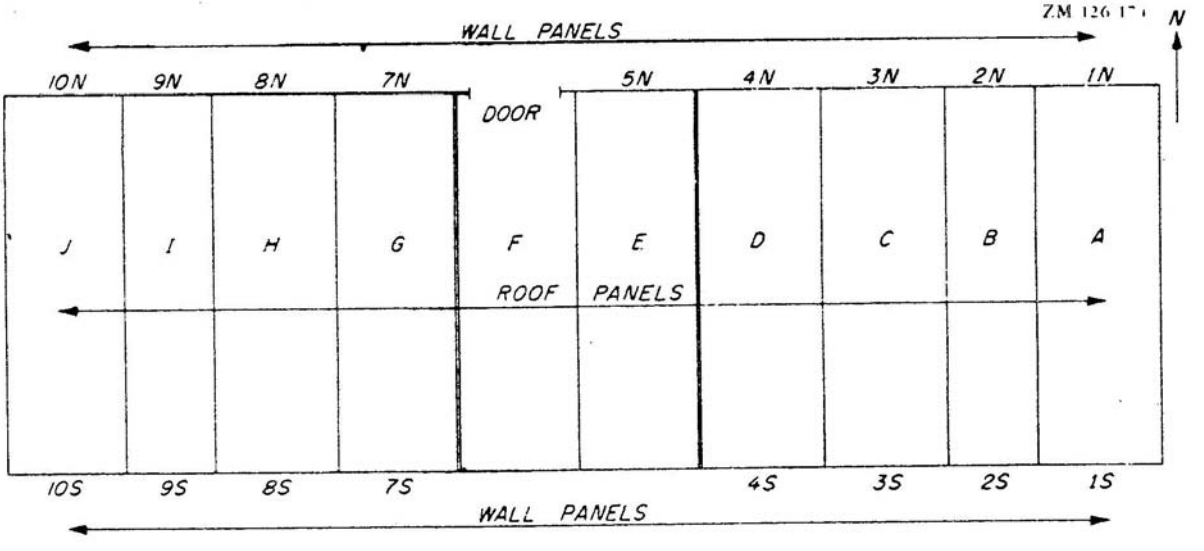


Table 1.--Bending tests of sandwich wall panels

Panel No.	Paper-honeycomb core type	Facing	Type adhesive and press	Exposure: Year in	Exposure: Year out	Exposure: Total exposure	Stiffness[1]: Before exposure: Deflection	Stiffness[1]: Before exposure: Deflection-span ratio	Stiffness[1]: After exposure: Deflection	Stiffness[1]: After exposure: Change	Strength: Before exposure	Strength: After exposure: 96-inch span	Strength: After exposure: Change
						Years	Inch		Inch	Percent	Lb. per sq. ft.	Lb. per sq. ft.	Percent
			ORIGINAL PANELS										
1N1	Corrugated XN	1/4-inch Douglas-fir plywood overlay[2]	Phenol-resorcinol; hot press[3]	1947	[4]1962	15	0.121	1/790	0.115	+ 5	[5]263	365	+38
1S1	.....do.....	.....do.....	.....do.....	1947	[4]1962	15	.125	1/770	.111	+11	263	367	+38
2N1	Expanded	0.02-inch aluminum	Phenol-vinyl; press not known	1947	[4]1962	15	.365	1/260	.363	+ 1	200	118	-41
2S1	.....do.....	.....do.....	.....do.....	1947	[4]1962	15	.370	1/260	.365	+ 1	200	160	-20
3N1	Corrugated XN	1/4-inch Douglas-fir plywood	Phenol-resorcinal; hot press	1947	1948	1	.115	1/835	.102	+11	263	391	+48
3S1	.....do.....	.....do.....	.....do.....	1947	1948	1	.115	1/835	.098	+15	263	344	+31
4N1	.....do.....	.....do.....	.....do.....	1947	1962	15	.112	1/855	.113	- 1	263	331	+26
4S1	.....do.....	.....do.....	.....do.....	1947	1962	15	.127	1/755	.113	- 4	263	297	+13
5N1	Corrugated XF	.....do.....	.....do.....	1947	.....	.....	.182	1/525	.....	.....	.....	.....	.....
5S1	.....do.....	.....do.....	.....do.....	1947	.....	.....	.162	1/590	.....	.....	.....	.....	.....
7N1	Corrugated XN	0.2-inch two-ply Douglas-fir plywood with overlay.[2]	.....do.....	1947	.....	.....	.158	1/610	.....	.....	.....	.....	.....
7S1	.....do.....	.....do.....	.....do.....	1947	.....	.....	.157	1/605	.....	.....	.....	.....	.....
8N1	.....do.....	1/8-inch Douglas-fir veneer with overlay.[2]	.....do.....	1947	1948	1	.141	1/680	.127	+10	.....	272	.....
8S1	.....do.....	.....do.....	.....do.....	1947	1948	1	.158	1/610	.141	+11	.....	330	.....
9N1	Expanded	0.02-inch aluminum	Phenol-vinyl; press not known	1947	1955	8	.365	1/260	.365	0	200	129	-36
9S1	.....do.....	.....do.....	.....do.....	1947	1955	8	.358	1/270	.361	- 1	200	148	-26
10N1	Corrugated PN	1/4-inch Douglas-fir plywood	Phenol-resorcinol; hot press	1947	[4]1962	15	.120	1/800	.115	+ 4	251	410	+63
10S1	.....do.....	.....do.....	.....do.....	1947	[4]1962	15	.125	1/770	.118	+ 6	251	321	+28
			REPLACEMENT PANELS										
2N2	Expanded	1/4-inch particle board	Phenol-resorcinol; hot press	[6]1962	.....	.....	.320	1/300	.....	.....	121	.....	.....
2S2	.....do.....	.....do.....	.....do.....	[6]1962	.....	.....	.306	1/315	.....	.....	121	.....	.....
3N2	Corrugated XN	1/4-inch cement asbestos	.....do.....	1948	1961	13	.070	1/1370	.041	+41	194	135	-30
3S2	.....do.....	1/4-inch hardboard	.....do.....	1948	1961	13	.214	1/450	.181	+15	315	247	-22
3N3	Expanded	0.1-inch paperboard (Pan-L)[7]	.....do.....	1961	[4]1962	1	.302	1/320	.371	-22	118	76	-26
3S3	.....do.....	.....do.....	.....do.....	1961	[4]1962	1	.306	1/315	.320	- 4	118	101	-15
3N4	.....do.....	1/2-inch medium density fiberboard	Acid catalyzed phenolic glue; cold press	1962	.....	.....	.268	1/360	.....	.....	123	.....	.....
3S4	.....do.....	.....do.....	.....do.....	1962	.....	.....	.259	1/370	.....	.....	123	.....	.....
4N2	.....do.....	1/8-inch tempered hardboard	Contact adhesive, nip-roll bonding	1962	.....	.....	.286	1/335	.....	.....	109	.....	.....
4S2	.....do.....	.....do.....	.....do.....	1962	.....	.....	.282	1/340	.....	.....	109	.....	.....
8N2	Corrugated XN	1/8-inch hardboard	Phenol-resorcinol; hot press	1948	.....	.....	.245	1/390	.....	.....	201	.....	.....
8S2	.....do.....	.....do.....	.....do.....	1948	.....	.....	.243	1/395	.....	.....	201	.....	.....
9N2	Corrugated PNL	1/8-inch hardboard, porcelainized steel	.....do.....	1955	.....	.....	[8].053	1/1810	.....	.....	222	.....	.....
9S2	.....do.....	.....do.....	.....do.....	1955	.....	.....	[8].053	1/1810	.....	.....	222	.....	.....
10N2	Expanded	1/4-inch birch plywood (inner face) 1/8-inch aluminum hardboard (outer face)	Acid catalyzed phenolic glue; cold press	1962	.....	.....	.226	1/425	.....	.....	105	.....	.....
10S2	.....do.....	.....do.....	.....do.....	[6]1962	.....	.....	.227	1/425	.....	.....	105	.....	.....

[1] Based on design load of 20 pounds per square foot, 96-inch span.

[2] Overlay consists of resin-impregnated kraft paper.

[3] Intermediate-temperature-setting phenolic glue, fabricated in hot press.

[4] One-half width of panel tested, one-half remaining in place.

[5] Based on test to failure of duplicate panels.

[6] Only one-half panel installed.

[7] Polyethylene film used under surface layer of paperboard facing.

[8] Based on calculated value (properties of core and facings).

Figure 10.--Method of testing sandwich wall panel with bending load applied at quarter points of span.

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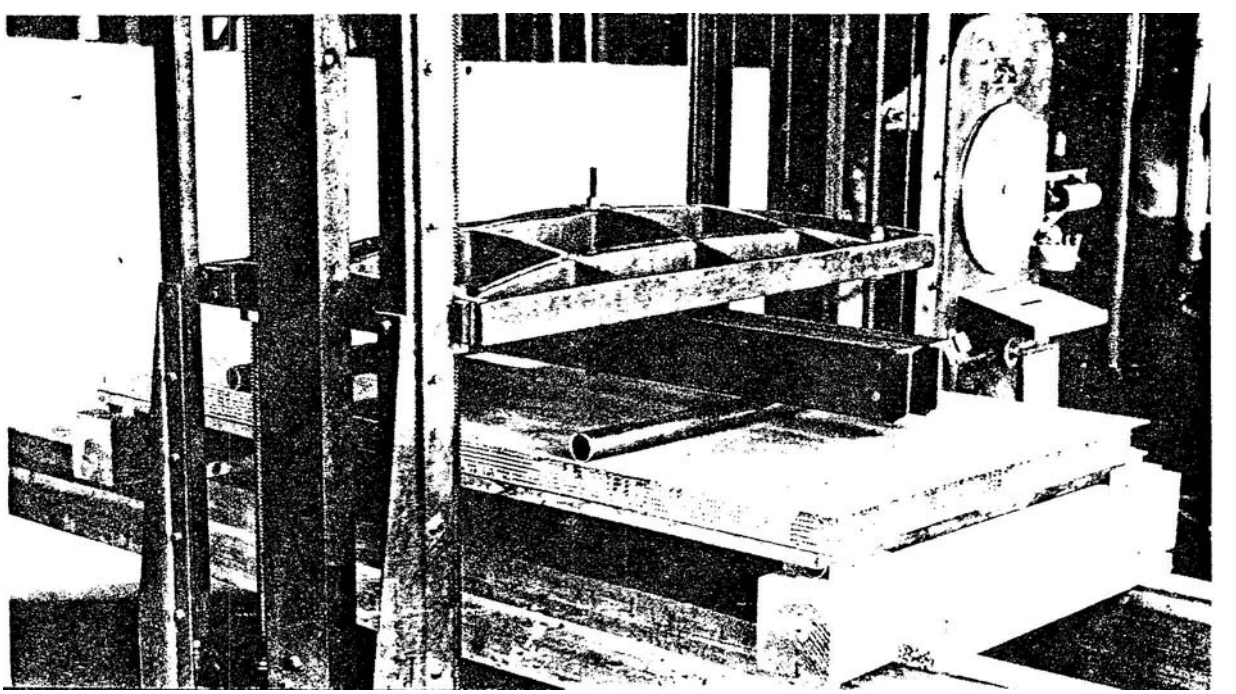

Table 2.--Details of sandwich roof and floor panels in Forest Products Laboratory experimental unit

Panel position	Paper-honeycomb core type	Facing[1]	Construction	Thickness	Stiffness: Deflection[2]	Stiffness: Deflection-span ratio	Strength: Maximum uniform load equivalent for 144-inch span[3]
				Inch	Inch		Pounds per square foot
			ROOF PANELS				
A	Corrugated, XF	Plywood, 1/4-inch, 3-ply	Unventilated	4-1/2	0.440	1/328	.....
B	Expanded	Aluminum, 0.02-inch	.....do.....	3	[4]1.085	1/133	51
C	Corrugated, XN	Plywood, 1/4-inch, 3-ply	Ventilated	4-1/2	.369	1/390	.....
D	.....do.....	.....do.....	Unventilated	4-1/2	.361	1/399	.....
E	.....do.....	.....do.....	Ventilated	4-1/2	.376	1/383	.....
F	.....do.....	.....do.....	Unventilated	4-1/2	.338	1/426	.....
G	.....do.....	Plywood, 1/4-inch, 3-ply, resin-treated paper on outside of each facing	Ventilated	4-1/2	.305	1/472	.....
H	.....do.....	.....do.....	Unventilated	4-1/2	.339	1/425	.....
I	Expanded	Aluminum, 0.02-inch	.....do.....	3	[4]1.123	1/128	.....
J	Corrugated, PN	Plywood, 1/4-inch, 3-ply	.....do.....	4-1/2	.374	1/385	.....
			FLOOR PANELS				
(5)	Corrugated, XN	Plywood, 3/8-inch, 5-ply	Pressed-in hot-water tubing	6	.297	1/485	376

[1]Both facings of each panel were the same. All plywood was Douglas-fir.

[2]Deflection at design loads of: 25 pounds per square foot on roof panels; 40 pounds per square foot on floor panels.

[3]Test of prototype panels of the construction indicated.

[4]Aluminum-faced panels were designed for 15 pounds load per square foot.

[5]There were 4 floor panels, all of identical construction.

Aluminum-faced wall panels showed more deflection at design load because they were originally designed for a lighter load (15 pounds per square foot). These tests clearly show the relatively high strength and stiffness values afforded by sandwich panels. Figures 11 and 12 show aluminum- and plywood-faced wall panels after failure in the bending test. Both type panels had been exposed for 15 years.

Impact bending tests were made on prototypes of a plywood-facedwall panel, an aluminum-faced wall panel, a plywood-faced floor panel, and an aluminum-faced roof panel. Panels were supported near the ends. Impacts were from a 60-pound sandbag dropped on the center of the panel from increasing heights until failure occurred. Heights of drop at failure were 8 feet for the plywood-faced wall panel, 7 feet for the aluminum-facedwall panel, and exceeded 10 feet for the floor panel and 4 feet for the roof panel. There was no damage from the 3-foot drop on wall or roof panels, or from the 6-foot drop on the floor panel. These values had been suggested as performance requirements in this test.

Concentrated loads of 50 to 200 pounds on an area 1 inch in diameter caused less deflection of the aluminum-faced panels than that under design load in static bending. Permanent denting of the 1/50-inch facings occurred at loads

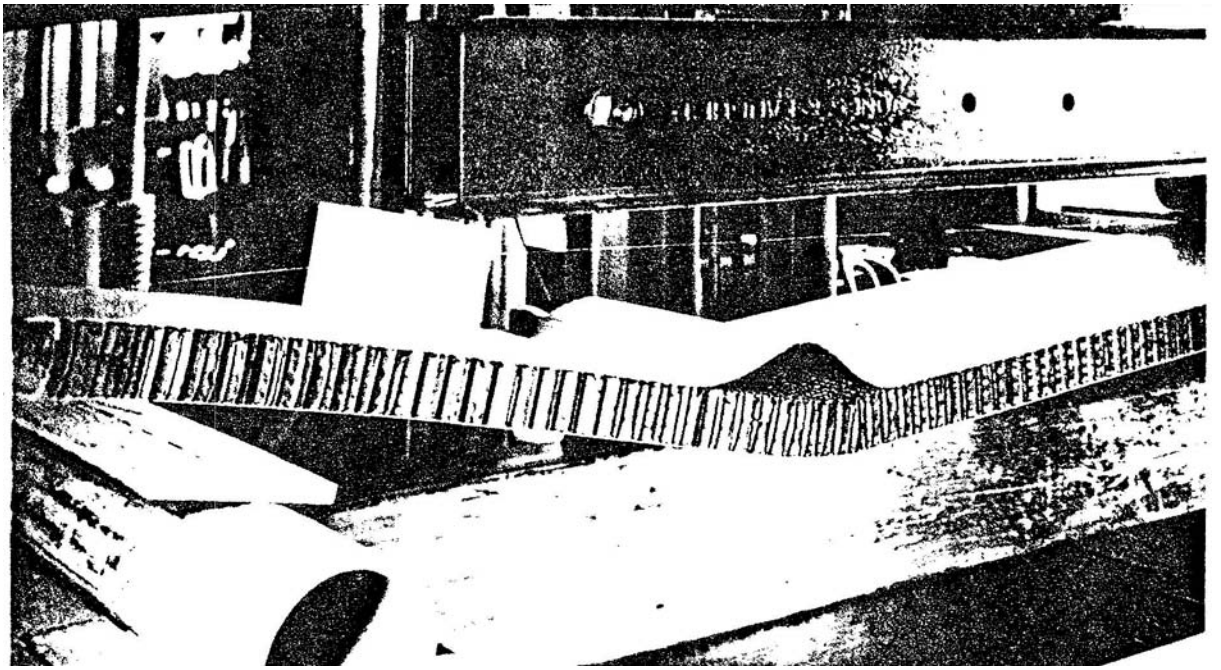

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Figure 11.--Final failure of aluminum-faced panel No. 2-S-1 in static bending test. Failure occurred at a load of 118 pounds per square foot and at a load of 160 pounds per square foot for a duplicate panel exposed on the south side of the experimental unit. Both panels had been exposed for 15 years.

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.

Compressive loads up to 500 pounds per lineal foot caused negligible deformation and no damage to plywood- and aluminum-faced panels 8 feet in length.

Figure 12.--Plywood-faced exposure panel No. 1-S-1 after final failure in bending test. This panel had been exposed in the unit for more than 15 years and the average maximum strength of the north and south panels was more than 360 pounds per square foot.

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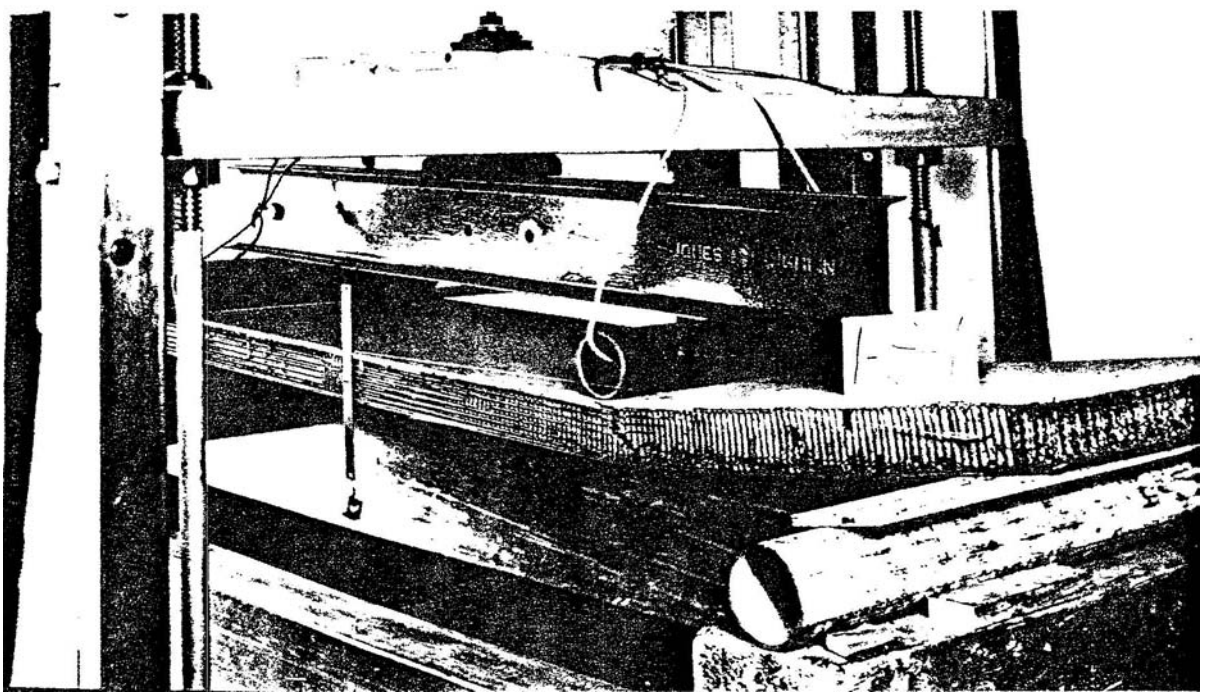

Three aluminum-faced panels failed by buckling of a facing at loads of 2,300 to 3,100 pounds per lineal foot. An 8-foot panel faced with 1/4-inch plywood had developed a load of 19,000 pounds per foot of width at failure.

Three aluminum-faced panels 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 similar to that expected in service.

Tension Tests

Flatwise tension tests were made of small sections of sandwich panels to determine the type of failure that might occur in the facing, glue line, or paper core after exposure, ASTM procedure C 297, "Tension Test of Flat Sandwich Construction in Flatwise Plane," was used for these tests. Small 2- by 2-inch-square sections of the exposed sandwich panels were glued to steel plates. After conditioning, a tension load was applied to the steel plates until failure of the specimen occurred. Both plywood- and aluminum-faced specimens had average maximum loads greater than 50 pounds per square inch.

Accelerated Durability Tests

Paper honeycomb cores.--Prior to the selection of core for the exposure panels, some 72 types of treated paper-honeycomb cores were subjected to ASTM procedure C 481, "Laboratory Aging of Sandwich Constructions." A few representative results of the subsequent tests are listed in table 3. General results indicated that strength and stiffness were reduced about 20 percent and shock resistance very little.

Sandwich panels.--Small sandwich panel specimens with cores and wood facings similar to the panels in the FPL experimental unit were subjected to ASTM aging procedure C 481 and tested in bending. Generally, the reduction of shear stress in the cores of the aged specimens was about 20 to 30 percent. The reduction in stiffness was about 20 percent, and no visual defects or warping were observed in the aged specimens.

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 4. The tests showed that appreciable softening occurred in the adhesive bonding of the core 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.

Moisture and Temperature Effects

Moisture and temperature are important factors that may affect the structural properties of sandwiches made of wood or wood-base materials. They may have an immediate effect on

Table 3.--Effect of aging on paper-honeycomb sandwich cores[1]

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 consisting 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.

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 constructions are largely controlled by the facings, these effects are important. Table 5 gives the structural properties of a number of common facing materials, both wet and dry.

Table 5 shows the moisture effects, both on dimensions and on strength and stiffness 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 6 were tested for compres-

Table 4.--Average results of tension tests on specimens of sandwich wall panels[1]

Exposure					Test results[2]		
Reference No.	Description	Total time before testing			Tensile strength	Location of failure	
						In glue	In paper
		Weeks	Days	Cycles	P.s.i.	Percent	Percent
1.	Conditioned at 80° F. and 65 percent relative humidity. Tested dry.	.....	....	.....	75	58	42
2.	48 hours in water at 80° F. Tested wet.	.....	2	.....	44	82	18
3.	1 hour at 180° F. Tested at 180° F.	.....	....	.....	28	94	6
4.	Continuous exposure to 97 percent relative humidity at 80° F.	1	....	.....	70	69	31
		2	....	.....	85	54	46
		4	....	.....	78	58	42
		8	....	.....	88	39	61
		12	....	.....	69	60	40
		16	....	.....	88	46	54
5.	1 cycle (4 weeks): 2 weeks at 80° F. and 97 percent relative humidity, and 2 weeks at 80° F. and 30 percent relative humidity. Then repeated.	4	....	1	91	49	51
		8	....	2	74	59	41
		12	....	3	71	63	37
		16	....	4	95	31	69
		24	....	6	80	34	66
6.	1 cycle (2 days): 1 hour in water at 122° F., 3 hours in wet steam at 200° F., 20 hours at 10° F., 3 hours at 212° F., 3 hours in wet steam at 200° F., and 18 hours in dry air at 212° F. Then repeated.	.....	2	1	49	79	21
		.....	4	2	50	91	9
		.....	6	3	66	77	23
		.....	8	4	38	96	4
		.....	10	5	41	86	14
		.....	12	6	32	94	6
7.	1 cycle (2 days): 24 hours at 158° F., and 24 hours at 40° F. Then repeated.	.....	10	5	92	42	58
		.....	20	10	82	33	67
		.....	30	15	82	57	43
		.....	40	20	83	30	70
8.	1 cycle (2 weeks): 2 days in water, 12 days at 80° F. and 30 percent relative humidity Then repeated.	2	....	1	88	35	65
		4	....	2	63	59	41
		6	....	3	80	52	48
		8	....	4	83	28	72
		12	....	6	50	53	47

[1] Each value is the average of 10 specimens from each panel subjected to exposures 1, 2, or 3, and of 5 specimens for each panel tested at the end of each period after being subjected to exposures 4, 5, 6, 7 or 8. The wall panels consisted of 0.020-inch aluminum faces bonded to a 2-inch-thick honeycomb core of resin-treated paper.

[2] Average of 4 panels.

Table 5--Average properties of some sandwich facing materials[1]

Material	Thickness	Dry weight	Moisture content		Absorption[2]	Linear expansion[4]		Compression and tension parallel to length of sheet						Impact puncture resistance[6]	
								Compression[5]		Tension					
			Dry	Soaked[3]		Parallel to length of sheet	Perpendicular to length of sheet	Maximum crushing strength	Modulus of elasticity	Maximum tensile strength		Modulus of elasticity		Dry	Soaked[2]
										Dry	Soaked[2]	Dry	Soaked[2]		
	Inch	Pounds per sq. ft.	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.	Inch-pounds	Inch-pounds
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.

sive 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 6.

Temperature effects on strength are generally not important in sandwiches for building construction. The strength of most wood materials increases or decreases only 0.33 to 0.50 percent from that at 70° F. for each degree of temperature change. [4] Adhesives that become plastic at high temperatures should be used with care where there is a possibility of high temperatures 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 with the phenol-vinyl resin adhesive.

The effect of severe temperature differences was shown by previous laboratory tests on six sandwich panels 20 by 72 by 3 inches in size. 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 continuing exposure, the bow was reduced because of expansion in the facings on the cold

[4] U.S. Forest Products Laboratory. Wood Handbook. U.S. Department of Agriculture Handbook No. 72. 1955.

Table 6.--Mechanical properties of several types of honeycomb cores

Designation	Type[1]	Weight of assembled core	Compressive strength[2]	Shear properties[3]	
				Shear strength	Modulus of rigidity
		Pounds per cubic foot	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.

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.

Effect of Temperature and Moisture Changes on Bowing

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 twofacings are generally exposed to different con-

ditions and thus assume different dimensions; the resultant unbalance 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. Table 5 gives linear-expansion values for a number of facings.

Heat Transfer

A variety of sandwich-paneljoint 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 paper-honeycomb cores and 1/4-inch plywood or 0.02-inch aluminum facings. Under these conditions, the plywood-facedpanel and the surface at a joint with a plywood-fiberboard spline had surface temperatures of about 66°F. on the warm side. 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 about 57° F. on the warm side, 36° F. on the warm side of a joint with continuous metal from outside to inside, and intermediate values for other joints designed so that the continuity of the metal was interrupted from cold side to warm side. With a facing temperature of 57° F., condensation would occur at an indoor relative humidity of 65 percent, and with a temperature of 36° F., at a relative humidity of 30 percent.

Condensation

If sandwich panels with expanded or corrugated paper cores 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, unless cores with more efficient insulation are used. The problem is most acute with sandwiches having metal facings and heat-conductive cores, and at joints or around openings.

Replacement Panels

The panel replacement schedule included wall panel changes from 1947 to 1962, the first 15 years of exposure. During this time panels were removed and tested after 1, 8, 13, and 15 years of exposure. In some cases entire panels (both north and south exposure panels) were removed and tested for stiffness and strength. In other cases where further data and exposure information were required, panels were sawed in half lengthwise, so that one half could be tested and the remaining half left in the walls. Figure 13 illustrates the method used in installing panels. while the earlier replacement panels had cores made of corrugated paper similar to the original panels, cores of later panels consisted of expanded paper cores obtained from commercial sources. Cell sizes varied from 9/16 to 1 inch in diameter and resin content from 8 to 11 percent. A paper-faced panel is shown in figure 14 after bending test.

Details of the replacement panels are listed in the following tabulation and in table 1.

Replacement Panels

Facings	Core	Adhesive
1/4-inch particle board (redwood flakes and fines--12 percent resin)	Expanded honeycomb 1-inch cell size 11 percent resin	Intermediate-temperature-setting phenolic glue. Hot press
1/4-inch cement asbestos (cold-pressed type) (north panel) 1/4-inch tempered hard-board (south panel)	Corrugated XN type	Intermediate-temperature-setting phenolic glue. Hot press
0.1-inch paperboard (5-mil kraft bonded to 90-mil board with 2-mil polyethylene)	Expanded honeycomb 1-inch cell size 8 percent resin	Intermediate-temperature-selling phenolic glue. Hot press
1/2-inch medium-density fiberboard (primed siding grade)	Expanded honeycomb 1-inch cell sire	Acid catalyzed phenolic glue. Cold press
1/8-inch tempered hard-board	Expanded honeycomb 1-inch cell size 8 percent resin	Improved elastomeric adhesive for contact application[1]
1/8-inch tempered hard-board	Corrugated XN type	Intermediate-temperature-setting phenolic glue. Hot press
0.020-inch porcelainized steel bonded to 1/8-inch hardboard with contact adhesive	Corrugated PNL type	Intermediate-tempemlure-setting phenolic glue. Hot press
0.024-inch aluminum with baked enamel finish bonded to 1/10-inch hardboard (outer facing) 1/4-inch birch plywood 3-ply (inner facing)	Expanded honeycomb 1-inch cell size 11 percent resin	Acid catalyzed phenolic glue. Cold press

[1]These panels were bonded with an experimental modified-elastomer adhesive in a conventional nip-roll landing process in a commercial plant under Laboratory supervision.

STRENGTH TESTS OF PANELS REMOVED AFTER SERVICE

Table 1 lists the test values of full-length sandwich panels removed from the FPL experimental unit after various exposure periods in the walls of the building heated during cold weather. The wood-faced panels showed no reduction in bending strength or stiffness after service of up to 15 years, and no evidence of glue joint deterioration, The aluminum-faced panels showed no loss of stiffness, and although they lost about 30 percent of their bending strength after 8 and 15 years of service, the strength remaining was still about 5 to 6 times the design strength. It was estimated that this loss of bending strengthshowed that the adhesive bond of the core to the

Figure 13--Installing replacement panels in experimental unit. Several 4-foot-wide exposed panels were ripped in half lengthwise, one-half being tested and the remainder replaced in the unit for further exposure.

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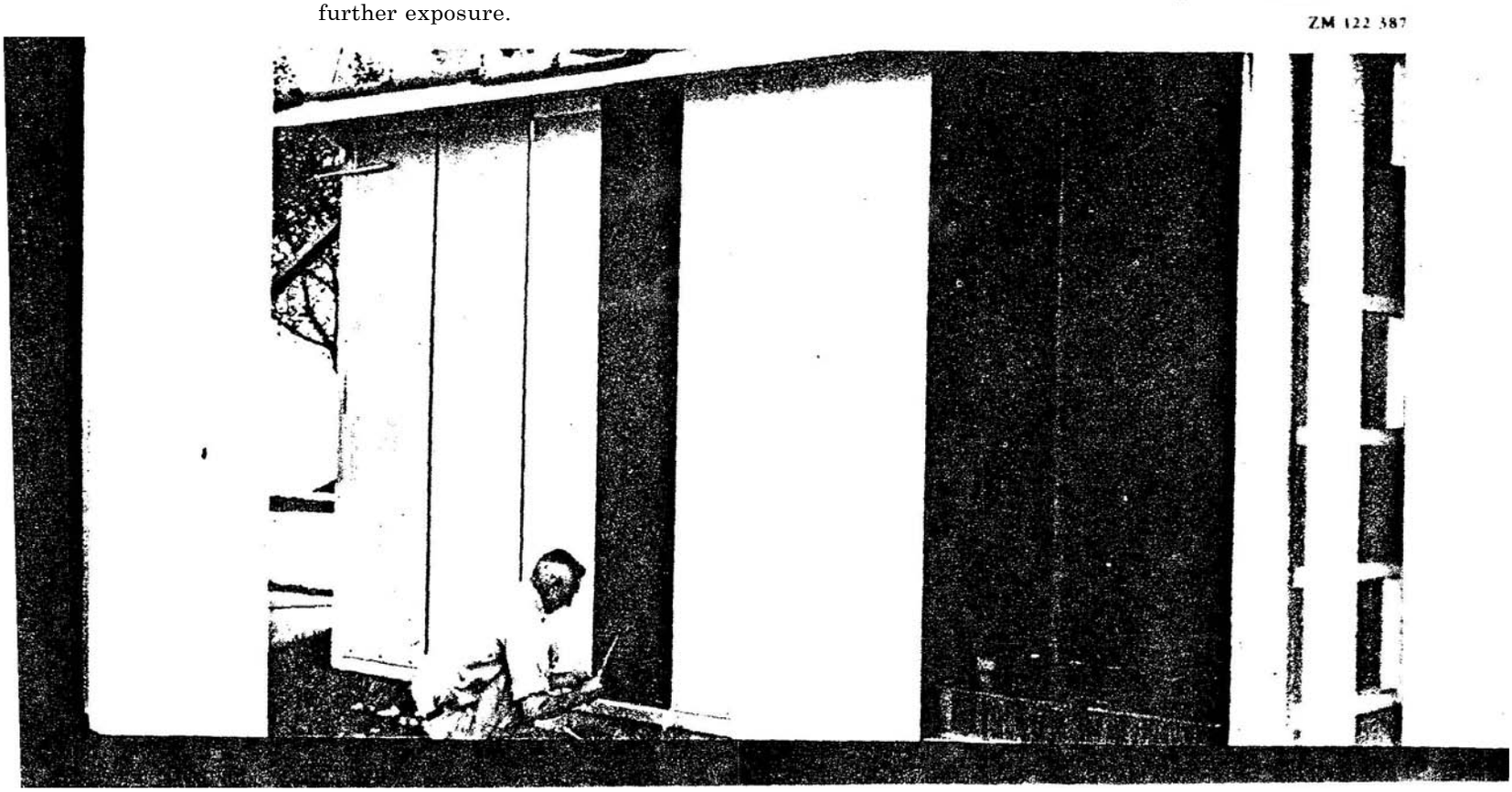

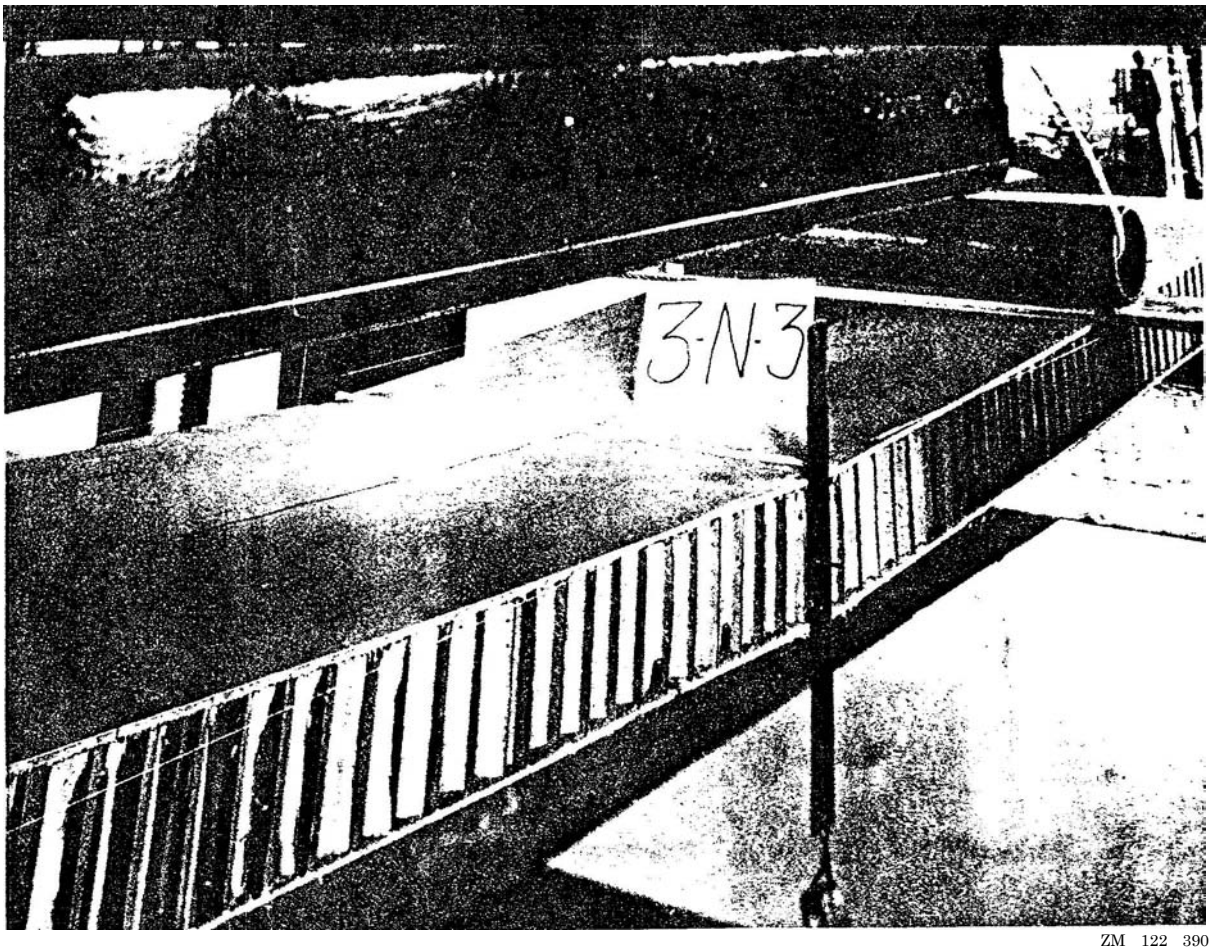

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Figure 14.--Finalfailure of panel No. 3-N-3,which consisted of honeycomb core with 0.1-inchpaper-board facings. These panels had been exposed for one year and had lost about 20 percent of their original strength, based on test of a duplicate panel.

facings may have been reduced to about 30 percent of its original value.

The cement-asbestos-facedpanel and the 1/4-inch hardboard-faced panel exposed for 13 years had no loss in stiffness, but from 20 to 30 percent loss in strength. This also indicated that the adhesive bond of the core to both types of facings had been reduced from its original value. The paperboard-faced panels exposed for 1 year had a moderate indicated loss in both stiffness and strength. This may have been due in part to differences in moisture content of exposed and unexposed panels.

Bowing of Wall and Roof Panels

Observations of panels in the FPL experimental unit give an interesting picture of the tendency to bow when unrestrained under actual service conditions. 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 15 years have been analyzed.

Bowing was found to follow a cyclic pattern, panels generally showing about the same values in the same season year after year. The plywood-faced wall panels (fig. 15) show the seasonal bow during an average year. The panels on the south wall were essentially flat for 6 months, from May to November, while the maximum outward bow during the remainder of the year was slightly more than 1/10 inch. The panels on the north, however, remained flat only from

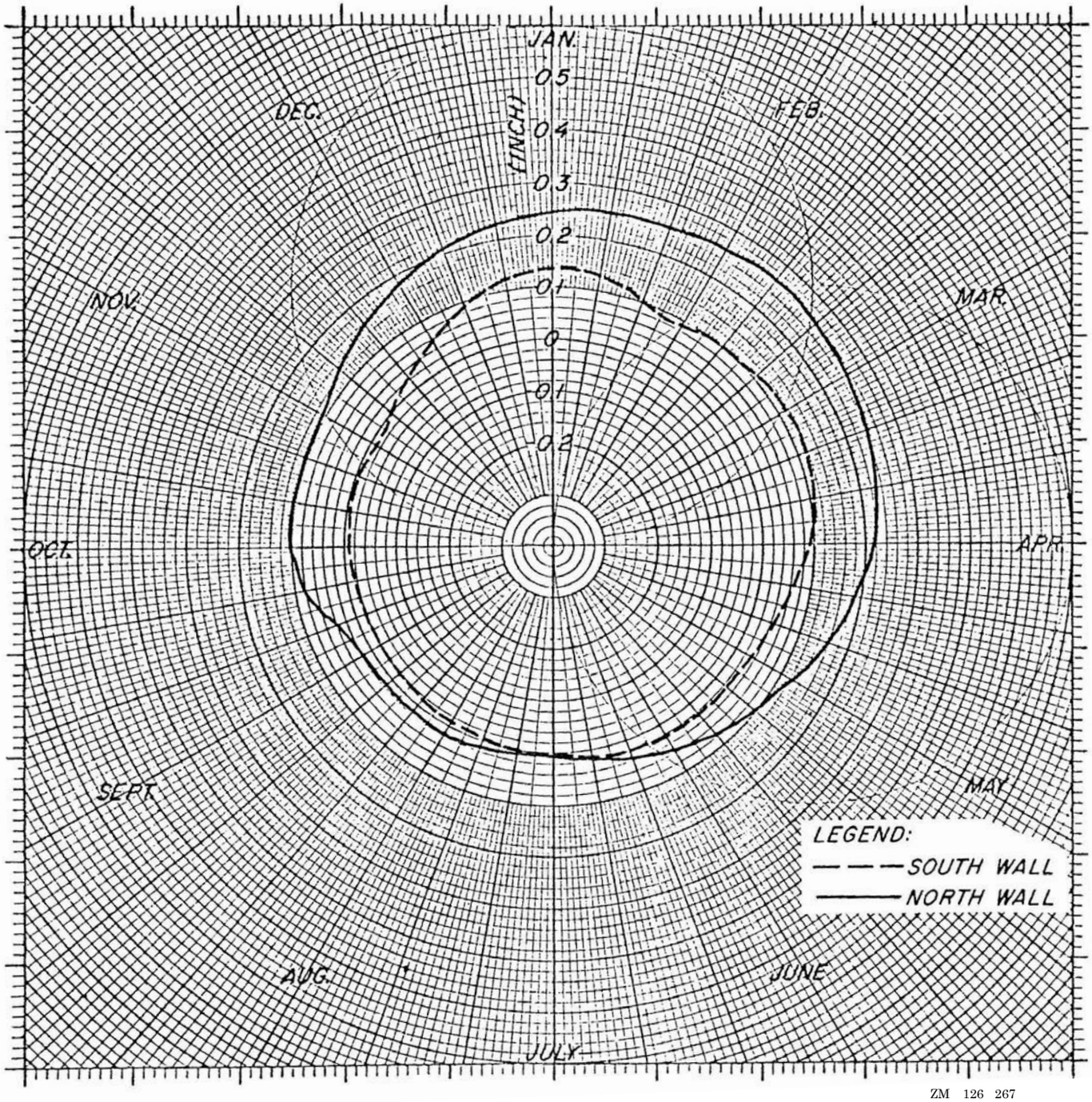

Figure 15.--Average bow of plywood-faced sandwich wall panels by months during exposure from August 12, 1947 to June 12, 1962.

about June to September, bowing outward the remainder of the year. The maximum bow of the panels was about 1/4 inch. This difference in bowing between the north and the south exposures can be attributed to lower temperatures and higher moisture contents of the exterior plywood facings on the north panels.

The average seasonal bowing of the four aluminum-faced sandwich wall

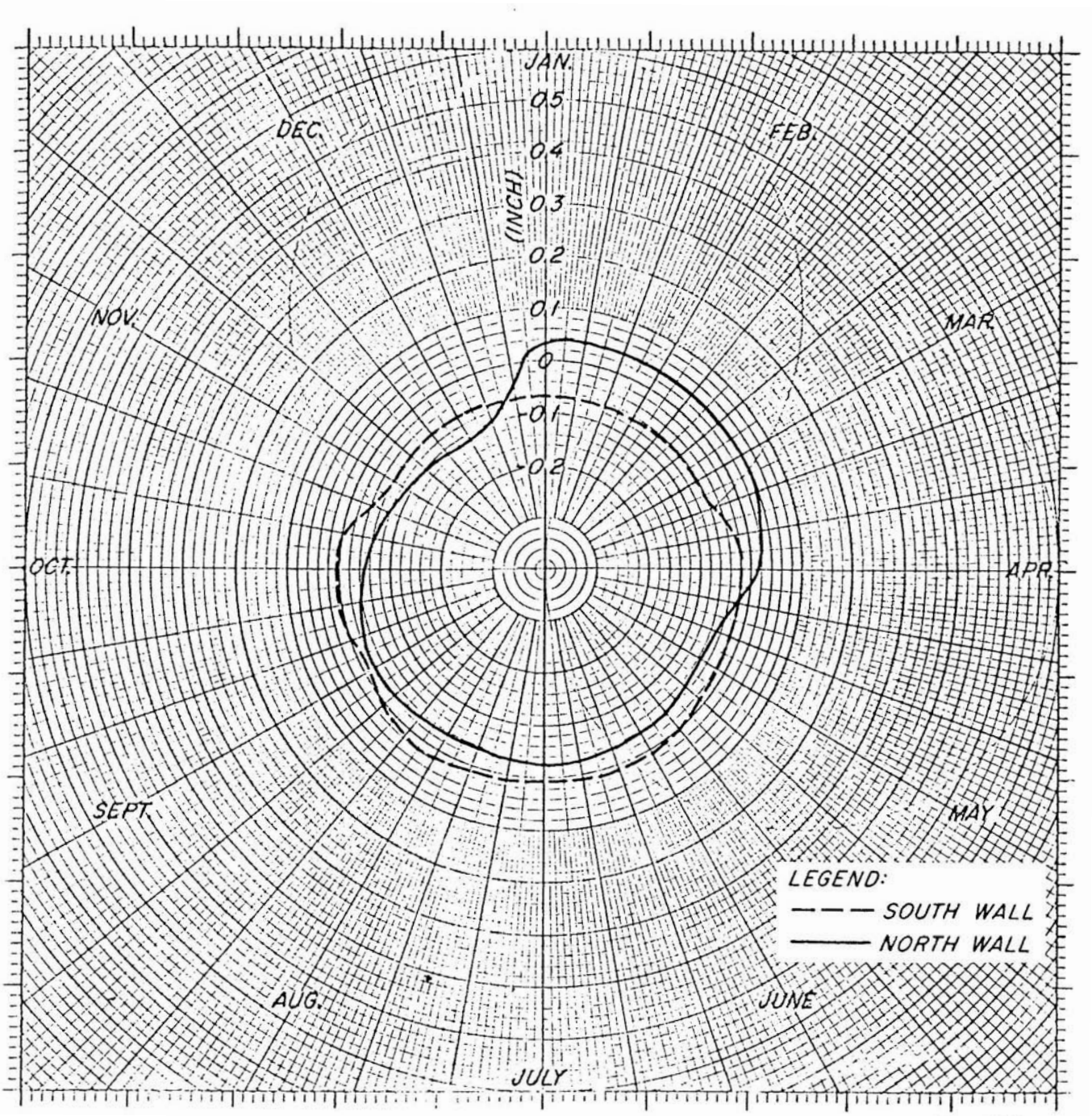

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Figure 16.--Averagebow of aluminum-faced sandwich wall panels by months during exposure from August 12, 1947 to June 12, 1962.

panels is shown in figure 16. The south panels were nearly flat from April to October, but during the winter (heating season) had an inward bow of slightly less than 1/10 inch. This was caused by a difference in temperature of the two facings. The panels on the north side had a slight inward bow during all months except from January to April, when a slight outward bow occurred.

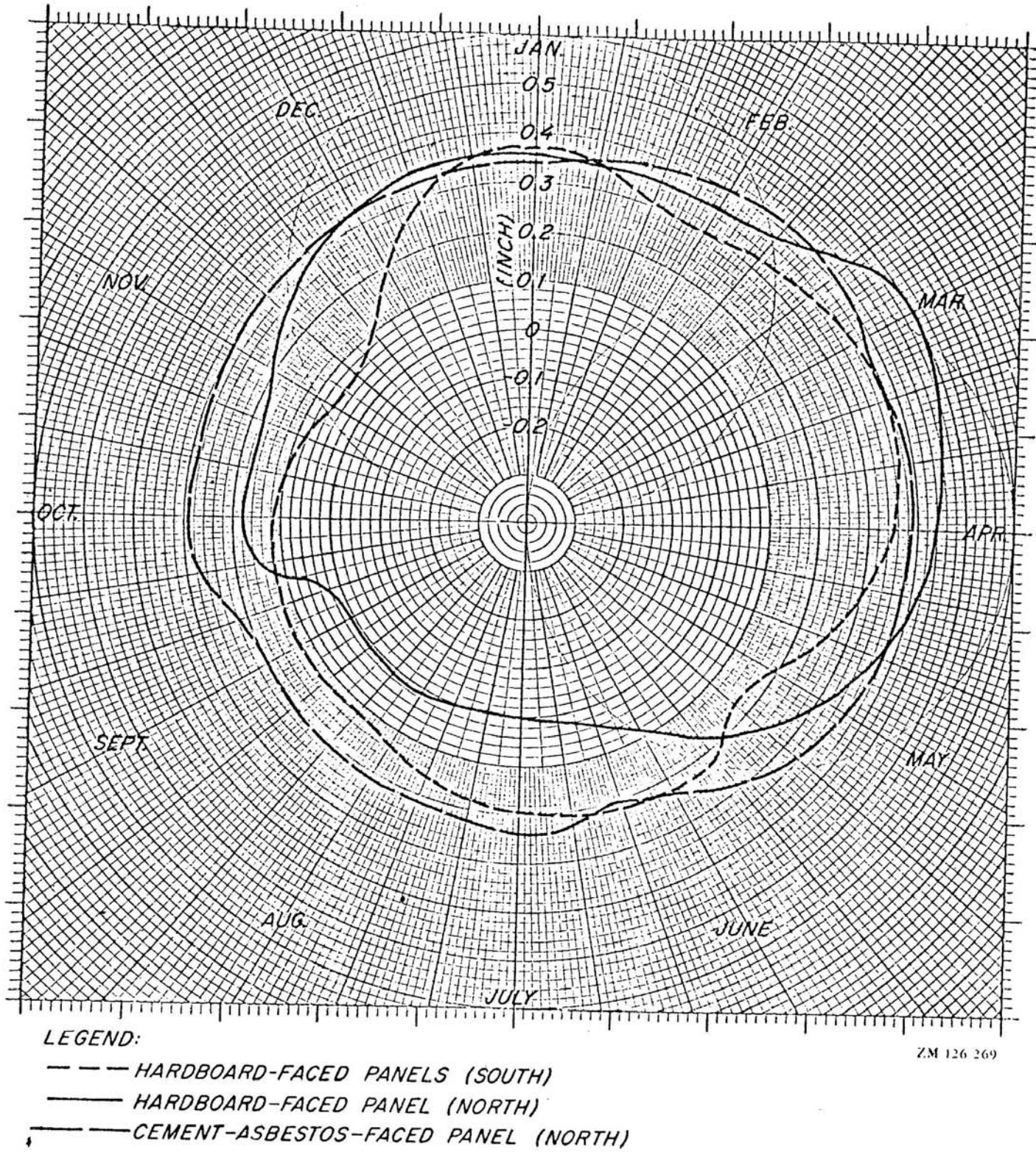

Figure 17.--Average bow of hardboard-faced and cement-abestos-faced sandwich wall panels by months during exposure from August 12, 1947 to June 12, 1962.

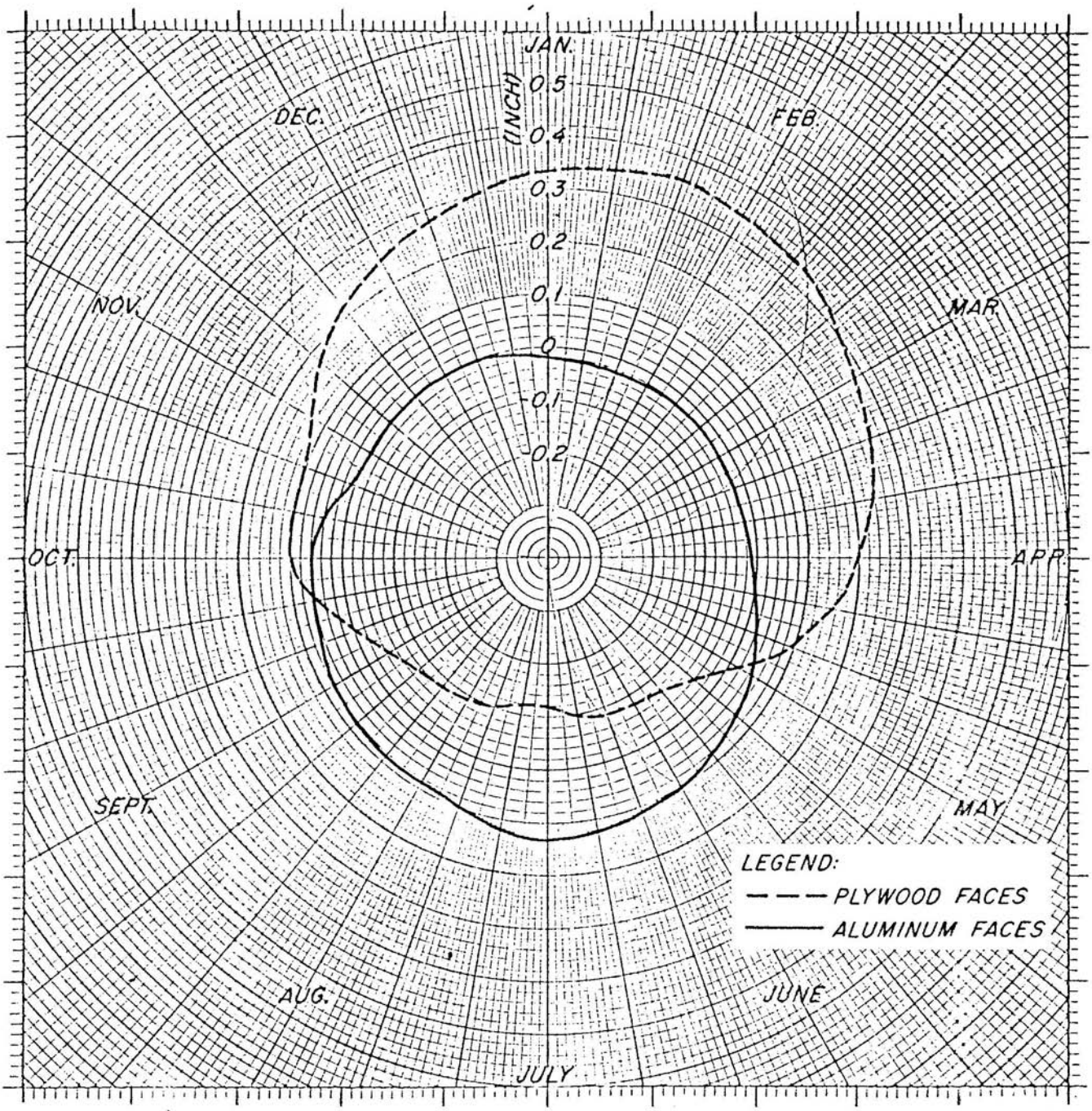

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Figure 18.--Average bow of plywood-faced and aluminum-faced sandwich roof panels by months during exposure from August 12, 1947 to June 12, 1962.

Average seasonal bowing curves of test panels faced with hardboard and cement-asbestos are shown in figure 17. The hardboard-faced panel exposed on the north side of the unit had the greatest variation between summer and winter deflections, ranging from a flat condition in July and August to an outward bowing of almost 1/2 inch in March. The hardboard-faced panels on the south

side varied from an outward bow of 0.1 inch in summer to an outward bow of almost 0.4 inch at the end of the winter. The cement-asbestos-faced panel was somewhat more stable, with a maximum variation of about 0.2 inch between winter and summer conditions.

The average bowing of the plywood-faced and the aluminum-faced roof panels is shown in figure 18. Bowing of the plywood-faced panels varied from an in-bow of about 1/10 inch during the summer months to an out-bowing of about 1/3 inch during the coldest months of the year. The aluminum-faced roof panels remained quite flat during the heating season but had an outward bow of about 1/10 inch during the summer months. Bowing of the aluminum-faced panels was lessened because of a significant heat loss, which resulted in high temperatures of the outer facings. Had these roof and wall panels been designed for a colder climate with better insulation and a lower U value, the bowing would have been much greater because of a greater temperature differential between the inner and outer facings during the heating season.

Winter bow in panels faced with wood or wood-base materials was clue 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, from the observed amount of how, 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 14 percent in the outside facings and 6 percent in the inside facings seem reasonable.

Theoretical analysis shows that the bow is proportional to the square of the length aid inversely proportional to the thickness. For example, if the bow of an 8-foot plywood-faced panel is 1/4 inch in winter, 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, such as partitions, Bowing of the wall panels and roofpanels did not produce an objectionable appearance if adjacent panels bowed in the same direction and in the same amount. Only where a roof panel intersected a wall panel was there evidence of any bowing present. In practice, this area is normally covered with a molding, which successfully conceals most of the movement. The same is true of the intersection of an interior wall with the exterior wall.

When the outside temperature approached zero, some condensation appeared on screws holding the wood wall panels to the soleplate and partition cap. Enough moisture gathered to stain the plywood slightly. Generally, during these periods, condensation gathered on the inner facings of the aluminum-covered wall panels, appearing in very small

droplets. From time to time these droplets would collect in one large drop and run down the face of the panel.

Tension Tests

To assess bond performance flatwise, tension tests, were made of specimens taken from several types of sandwich panels that had been exposed for 1 year and for 15 years. The following is a summary of the results of these tests.

1. Plywood - faced panels. - - These panels had been exposed for 15 years and consisted of 1/4-inch Douglas-fir plywood with type XN corrugated paper cores. The average load at failure was slightly over 60 pounds per square inch, and there was no significant difference between north and south panels. The majority of the failures occurred in the core itself, only a small percentage occurring in the glue line.

2. Aluminum - faced panels.--These panels were tested after 15 years of exposure and consisted of 0.02-inch-thick aluminum facings and expanded paper core. The average values at failure were quite high; 175 pounds per square inch for the north panel and 140 pounds per square inch for the south panel. The difference was probably due to the better glue bond of the north panel specimens. The paper thickness of the core of the north panel was 0.012 inch, and 0.006 inch for the core used in thesouthpanel. The greatest percentage of the failures was in the glue line.

3. Paperboard-faced panels. --These panels consisted of 0.10-inchpaperboard covers and expanded paper cores. Exposure period was 1 year. The average tension values were quite low (16 pounds per square inch), and there was little difference between the north and south panels. Most of the failures occurred in the facings and few, if any, in the glue line.

DISCUSSION OF STRUCTURAL TESTS AND PERFORMANCE

Design

From the standpoint of structural and performance requirements, at least five criteria must be met in sandwich panels for house construction. These are strength, stiffness, resistance to surface indentation, insulation, and durability in the sense of long-term service. These five characteristics are given particular consideration here. Other features are, of course, also important, such as acoustical properties, surface appearance, ease of maintenance, and resistance to decay, termites, and fire. From the data presented in tables 1 and 2, it is obvious that it is possible to design lightweight sandwich panels with paper-honeycomb cores within practical thickness limits that generously exceed the usual criteria of strength and stiffness for roofs, walls, and floors. Resistance to surface inden-

tation is readily obtained or controlled by the characteristics and properties of the facings.

Insulation

Acceptable or adequate insulation is provided in the types of cores used in the panels for many regions of the United States. However, the panels have greater heat losses than a modern-conventional house constructed in the colder climates. The overall U value of the plywood-faced sandwich panel 3 inches thick is about equivalent to a conventional wood-frame wall with the addition of 1/2 inch of blanket insulation. This value would likely meet FHA Minimum Property Standards in many areas. Nevertheless, it is desirable to improve the U value of this type of panel. This can be done by increasing the thickness of the panel or, more logically, by reducing the size of the cells, or by filling them with some type of insulating material. The use of a foam-type adhesive in gluing facings to cores is a possibility.

Bowing

Considerable data have been presented on the effect of temperature and moisture content on the bowing of sandwich panels with different facings when unrest rained to permit free movement. The results reflect what would be expected with moisture changes in plywood and wood-base materials, and temperature effects with metal facings. It should be noted that such measurements of bow as were observed in the experimental unit are, of course, related to pertinent conditions at time of fabrication that are subject to control. It should be noted also that the stresses induced by bowing of the panel in the degree observed are relatively small. The actual bowing of sandwich panels when restrained, as in a house or other structure, would likewise be relatively small,

This was confirmed by the performance of the panels in the east wall of the structure, which was composed of three 4-foot-wide sandwich panels fastened securely around their perimeters. There has been no noticeable movement or change in this wall. It is believed that under normal conditions good fastening methods in the construction of a panel house would virtually make any bowing movement unnoticeable.

Adhesives

The use of a resin-impregnated core and a waterproof adhesive in fastening facings to the core has insured high strength even under severe moisture conditions. This was established in the testing of minor specimens. Panels produced at the Forest Products Laboratory and removed after 13 and 15 years of service had every indication that this property had been retained. Exposure of the panels in the experimental unit has thus far indicated that the synthetic resins and bonding methods used are satisfactory. Furthermore, improvements in both adhesives and assembly techniques should extend the durability of such panels in service even more.

Quality Control

Good bonding of facings to the core is

necessary to produce a structurally sound sandwich panel. From all tests made thus far, the panels fabricated at the Laboratory have had satisfactory glue bonds. This was accomplished by good workmanship, and should he easily achieved in production by careful assembly and quality control methods, However, there is a real need for an accelerated test method or a nondestructive test to determine the quality of the glue bond, which will aid in predicting the service life of the sandwich panel.

Wall Panel Performance

The principal purpose of the FPL experimental unit was to obtain information on long-range performance. Such information cannot authoritatively be obtained from existing accelerated-aging tests, although such an approach would be extremely desirable. It is believed that sufficient data are being obtained to predict comparable service life of many combinations of materials. However, additional panels will be added from time to time whenever new facing and core materials are introduced. After 15 years of exposure, careful visual inspection of the unit has not shown any specific evidence of abnormal deterioration. Furthermore, strength and stiffness tests of panels exposed for periods of up to 15 years have indicated little change in most of the core and facing combinations.

Plywood facings.--The results of the exposure tests of wall panels have thus far indicated that the plywood-facedpanels have performed better than several other materials. This is based on changes in stiffness and strength after exposure, and in bowing characteristics. Average stiffness increased slightly and there was no evident loss in strength of the panels. The exact increases or decreases in strength are perhaps not too significant because the original strength-to-failure tests were carried out on duplicate panels, and variations in strength between panels is probable. However, the six plywood-faced panels which had been exposed for 15 years failed at an average load of more than 16 times the design load of 20 pounds per square foot. Bowing of the panels on the north side was somewhat greater than those on the south side, which was probably due to a higher moisture content of the outside facing. With perimeter fastening aid connections between panels, as would normally be used in a panel house, bowing of the panels would probably not be troublesome. The panels on the south were somewhat stiffer than those on the north, which can probably be attributed in part to lower moisture content of the facings on the south panels.

Aluminum facings.--The four aluminum panels tested after exposure of 8 and 15 years indicated little change in stiffness, but an average loss in strength of over 30 percent compared to tests of the original duplicate panel. Variation in strength between panels can probably be associated with varying qualities of the panels. For example, the expanded core of one panel was made of a heavier weight paper than the remaining three panels. In others, there was evidence of poorly bonded areas in the core to aluminum-facing glue line. However, even under these conditions, loads at failure were more than five times the

design load.

Bowing of the aluminum panels was not objectionable, as the average maximum deflection was less than 0.1 inch. This may have been due in part to the relatively high heat loss of the aluminum panel. This would result in a lower temperature difference between the inner and outer aluminum faces than would occur in a well insulated panel. Temperature differences of the two faces are responsible for bowing of metal-faced panels. In a well insulated panel, bowing would be much greater.

Miscellaneous facings.--Bending tests made of the cement-asbestos and the hardboard-faced panels after 13 years' exposure indicated no loss in stiffness, but a 20 to 30 percent loss of strength. This may have been due in part to the change in properties of the cover materials due to aging. The cement-asbestos-faced panel not only had lower initial strength than the hardboard panel, but also a greater percentage loss after exposure. Both panels carried lower maximum loads than the plywood-faced panels.

Paperboard-faced panels exposed only 1 year had a moderate loss in stiffness and strength. However, there was a marked difference between the north and south panels. This variation was likely due to the higher moisture content of the facings on the north panels, causing both greater deflections and lower maximum loads. A half-width panel was allowed to remain in the north and south walls to determine whether any further loss in stiffness and strength would occur.

Floor Panels

It will be noted that the floor panels incorporated copper tubing for radiant heating (fig. 6). In fabrication, the tubing was laid on the top of the core and forced into it when the facings were glued to the core. This was intended to afford a means of checking the long-range performance of the panel, and whether the temperature conditions associated with low-temperature hot-water heating had any effect on the properties of the honeycomb core and the integrity of the glue bonds to the facings. None of the floor panels have so far been removed for test. It can be reported, however, that no deterioration such as delamination of the facing, has as yet been observed. A careful inspection has not indicated the presence of any unbonded areas associated with separation of the facing. The radiant floor-panel heating system has been operating satisfactorily.

Roof Panels

In recognition of the condensation problem sometimes encountered in roof structures, three of the sandwich roof panels were constructed with continuous vents to afford air movement across the roof and through the panel. Observations over the years have indicated no appreciable difference in performance of the vented and unvented panels with respect to bowing or moisture accumulation under prevailing interior-humidity conditions.

SUMMARY OF OBSERVATIONS

The experimental and developmental work on sandwich panel construction, particularly with honeycomb cores, has furnished information for the basic engineering design and fabrication techniques. The numerous tests have shown that sandwich panels of the nominal thicknesses and constructions, that can be satisfactorily used for housing construction, have much more than the minimum strength and stiffness necessary to meet the general requirements usually applied to such construction. Corrugated-paper cores provide minimum insulation requirements for many areas of the United States. Nevertheless, commercially produced expanded core is potentially lower in cost and has been used in all of the wall panels recently erected. However, this type is lacking in insulating properties, and there appears to be a need for development of a foaming adhesive or similar means of reducing the U value of the panel.

With the advent of synthetic resins, the tests have demonstrated the techniques of adhesive bonding that will afford adequate strength and insure freedom from moisture problems at the bond. Furthermore, the incorporation of synthetic resins in the honeycomb material affords a degree of moisture resistance that insures adequate stability and strength, even when completely immersed. Development of improved contact adhesives shows signs of opening the way to rapid fabrication of core to facing materials. One such adhesive has been used in several wall panels recently placed in the experimental unit. It is likely that others will be added as further improvements are made.

It is evident from wall panels removed after 13 to 15 years of service, that the plywood-faced panels have demonstrated excellent performance, based on retention of stiffness and strength and a minimum of movement due to temperature and moisture changes. The use of mechanical fasteners in the assembly of a panel house sometimes governs the thickness of the facings. However, the use of adhesives would permit thinner facings to be used, and strength and stability would then become the governing factors. Thinner prefinished plywood with a nonmarring plastic surface for interior facings and paper-overlaid plywood for exterior facings would probably provide good acceptance and satisfactory performance. Combination materials, such as metal with wood veneer-laminated facings, might also be considered.

The experiments with floor radiant heating have shown the feasibility of this type of heating with sandwich panel construct ion.

The sandwich panels in the experimental unit exhibited varying amounts of bowing during the coldest periods of the season. This was caused mainly by the absence of fasteners to adjoining panels to allow for unrestricted movement. When panels are fastened together, as in normal construction, little panel deflec-

tion would occur if the facings were relatively stable. Panels with facings that are seriously affected by moisture and temperature changes would be undesirable because of likely cross bowing or cupping.

With the selection of proper combinations of facings, core, and adhesives, satisfactory sandwich panels can be assured by careful fabrication techniques and quality control. This was indicated by the results of strength and durability tests conducted on panels that have been exposed for periods as long as 15 years. There was little or no change in the stiffness and strength of those panels containing a good choice of materials, even after 15 years' service. The development of a simple nondestructive test for evaluating glue joints would be invaluable in eliminating inadequate panels and in developing the full potential of adhesive bonding. Such development, in addition to the research already performed on sandwich panels, will assure greater use of this type of housing component,

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