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STRUCTURAL SANDWICH PERFORMANCE AFTER 31 YEARS OF SERVICE.(U)
1979   J PALMS , G E SHERWOOD
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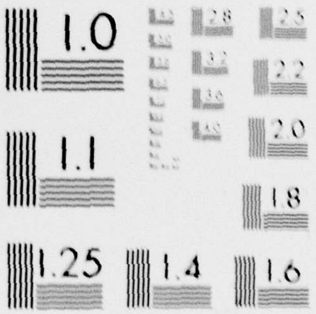

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

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United States
Department of
Agriculture

⑨ Forest Service

Forest
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Laboratory

Research
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This research paper
supersedes
U.S. Forest Service
Research Paper
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Laboratory in 1970.

Abstract

Study of the design and fabrication of structural sandwich panels was initiated at the Forest Products Laboratory in the mid 1940's. It was recognized that, even with extensive basic research, additional information would be needed on the long-term serviceability and durability of sandwich panels as a building component. Accordingly, an experimental unit was built on the laboratory grounds in 1947 to provide for long-term exposure tests of panels.

Selected sandwich panels placed in the exposure unit were evaluated for bending strength and stiffness after various lengths of service between the years 1947-1978. Panels were constructed with a variety of facing materials including plywood, aluminum, particleboard, hardboard, paperboard, and cement asbestos, and with cores of paper honeycomb, polyurethane, and extruded polystyrene. Measurements were kept of the bowing of panels due to seasonal climatic changes.

This information should be useful to building manufacturers, building code authorities, and others concerned with design and manufacture of housing.

Contents

Structural Sandwich Performance After 31 Years of Service

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Introduction

The sandwich panel is a layered structural system composed of a low density core material bonded to, and acting integrally with, relatively thin, high strength facing materials. When used as a wall, roof or floor element in housing, the sandwich panel provides exceptional strength for the amount of material used. In a load-bearing wall, the two facings act as slender columns continuously supported by the core material to resist compression and buckling. In bending due to a live load or wind load applied to a panel, the facings take most of the tensile and compressive forces and the core provides resistance to shear. The core and facings acting integrally provide exceptional stiffness to the member.

In response to the scarcity of building materials immediately following World War II, and to the development of a great variety of core and facing materials during the War, the Forest Products Laboratory instituted a research program to design and evaluate the performance of sandwich panels. Application of a new and untried construction to housing raised many questions concerning design, choice of materials, fabrication techniques, satisfaction of code requirements, and long-term structural performance. While the results of accelerated aging tests were encouraging, there was, and is no definite correlation with actual durability over a long period of time, so that in 1947 the laboratory erected an experimental unit to monitor the actual in-service performance of sandwich panels.

Over the past 31 years, panels have been periodically removed from the unit and tested for bending strength and stiffness. From time to time, some of the original panels have been replaced with new ones which incorporated new core and facing materials and adhesives. Over the same period, records have been kept of the bowing of panels from season to season. Panels have been examined for deterioration due to weather and biological decay. After 31 years of testing, the panel exposure program has been terminated. This final report documents the cumulative test results and presents a summary analysis of the tests and other recorded data.

History and Design of the Experimental Unit

The experimental unit was designed to evaluate, under actual weathering conditions, the long-term performance of a variety of types of sandwich panels intended for house construction. The design of the unit allowed for periodic removal, testing, and reinstallation or replacement of individual wall, roof, and floor panels. The unit served the purpose of a research facility and was not intended as a demonstration house. The floor layout included a central control room and two adjoining rooms.

The Original Unit—1947

Construction of the original experimental unit was carried out in June 1947 (fig. 1). The overall dimensions were 38 feet 6 inches by 12 feet 6 inches.

Foundation and Floor. —An 8-inch wide concrete foundation was poured with anchor bolts provided at 4-foot intervals. Two 6-inch-thick cross walls provided support for the room partitions.

In the east room, a crawl space was provided beneath the floor panels. The room was heated with a forced hot-water system using ⅝-inch copper tubing pressed into the core material of the floor panels at 6-inch intervals. Additional supply and return outlets were installed along the outside walls for baseboard heating, to be used alone or in tandem with the floor system.

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

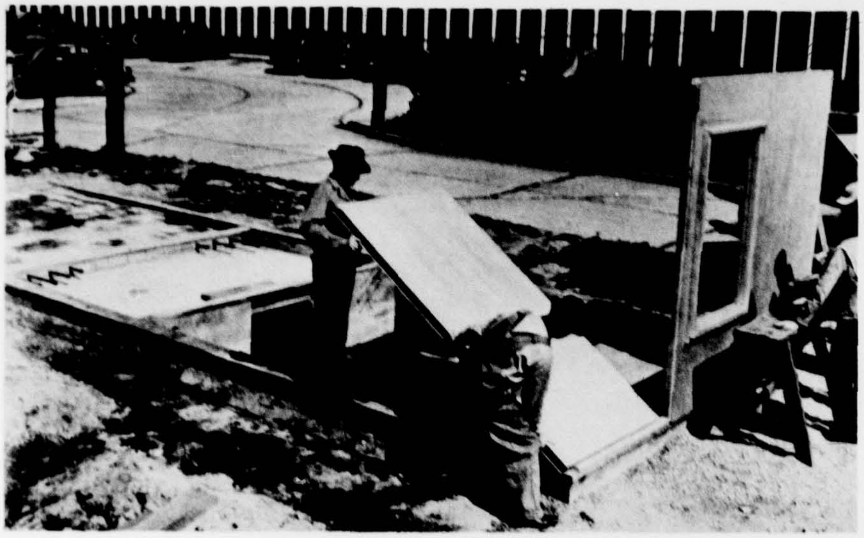

Figure 1.—Construction of the original experimental unit in 1947 in front of the main building of the Forest Products Laboratory. Note both the crawl space for the east room in which the floor panels were installed, and the concrete subfloor for the remainder of the unit. (M 73607 F)

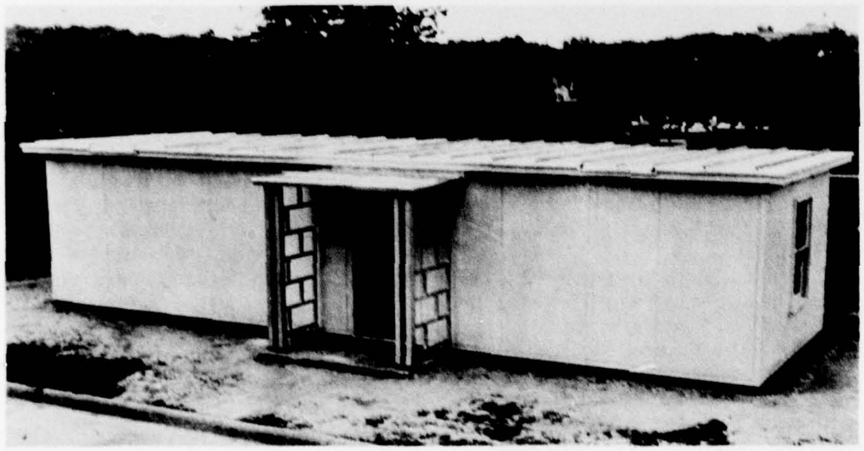

Figure 2.—Original Forest Products Laboratory experimental unit. (M 73988 F) or = (FM 116 396)

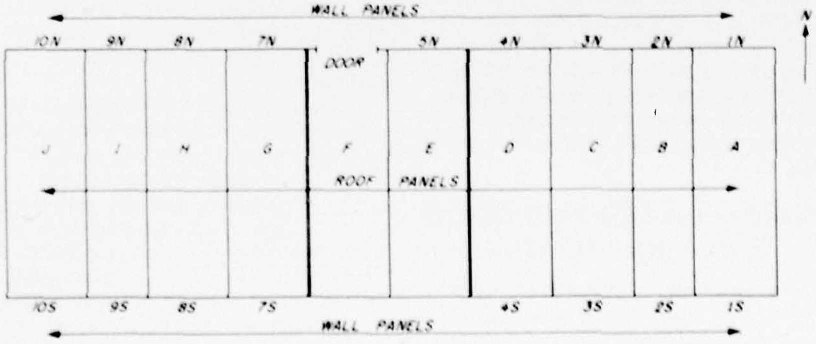

Figure 3.—Positions of original numbered wall and roof panels in sandwich experimental unit. (M 126 174)

Four floor panels were installed in the east room. They were designed for a load of 40 pounds per square foot. Each panel measured 12 feet long by 3 feet 8½ inches wide by 6 inches thick.

In the west room, radiant heat was provided from pipes imbedded 1 inch in the concrete subfloor.

Walls.—The completed experimental unit, shown in figure 2, was oriented so that long sides fronted north and south for minimum and maximum exposure respectively to the sun. Ten panels were placed in each of the two elevations, as shown in figure 3, generally in matched pairs so the effect of differing degrees of exposure to the sun could be studied. The panels rested directly on the sill, fitting over a sole plate secured to the sill. Panels were 8 feet high and either 3 feet 11½ inches or 2 feet 11-inches wide. A ½-inch space was provided between panels allowing independent movement of each panel that could be measured in response to seasonal weather changes. The space was filled with a felt gasket and sealed with tape. A ¾-inch by 2½-inch continuous plate, placed in a groove along the top of the panels, tied the panels together. Cleats glued to the roof panels were seated in the same groove above the continuous plate and the panel facings were fastened to the cleats with screws.

Roof.—A flat roof was selected because it presented a more severe insulation and condensation problem than with a pitched roof. There were 10 roof panels, each 14 feet long and spanning the width of the structure with 9-inch overhangs. The panels manufactured at the laboratory were designed for a load of 25 pounds per square foot and measured 3 feet 11½ inches wide by 4½ inches thick. The commercially manufactured panel with aluminum facings was designed for a 15-pound-per-square-foot load and measured 2 feet 11½ inches wide by about 3 inches thick. In anticipation of possible condensation problems, three of the original panels were ventilated with 2-inch by 3-inch ventilating flues spaced 6 inches apart and extending lengthwise through the panels.

The ½-inch space between panels was again filled with a felt gasket to allow independent movement and then sealed with tape. The panels were covered with a metal roof. The standing seams at joints were also taped and then covered with a sliding metal cap.

Relocation of Unit—1968

It was necessary to disassemble the

experimental unit and reconstruct it at a new site in 1968 (fig. 4). The dimension of the long side was modified to 32 feet 6 inches, which accommodated nine panels instead of the previous ten (fig. 5). Three sandwich floor panels, instead of four, were placed in the west room. The radiant heating system was replaced by electric space heaters in the relocated unit, although the copper tubing in the floor panels remained intact.

Panel Descriptions

After the installation of the original panels in 1947, some of them were replaced from time to time with new panels incorporating newly developed materials. The core and facing materials used in all panels, along with the type of adhesive, are described in table 1.

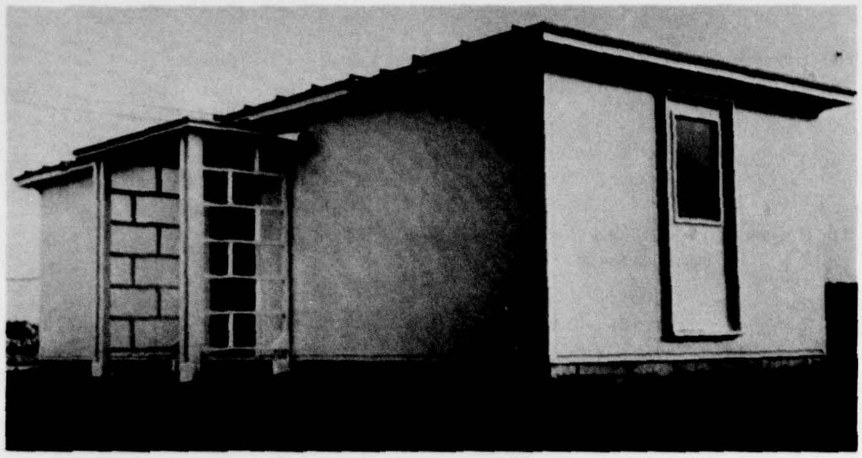

Figure 4.—Sandwich experimental unit as re-erected in 1968. (M 135 634-3)

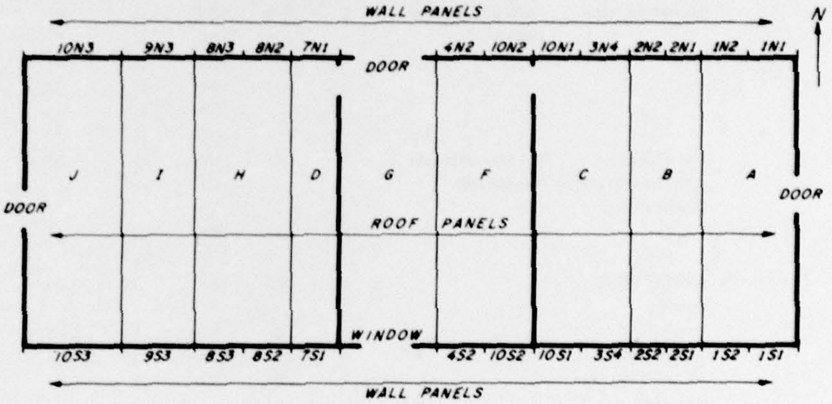

Figure 5.—Positions of numbered wall and roof panels in the sandwich experimental unit (1968). (M 138 281)

Original Panels—1947

Panels installed in 1947 had one type or another of paper honeycomb core. A variety of facing materials was used, mostly wood-based but also some aluminum.

Core Material. —Four types of paper honeycomb core were used in the original panels.

An expanded type core (Fig. 6) was produced from sheets of paper bonded flatwise at intermittent lengths and then pulled—or expanded—to develop a hexagonal pattern. Only the commercially manufactured panels had expanded cores.

The three other core types were made from a corrugated kraft paper weighing about 45 pounds per ream (500 sheets 24 by 36 in.), impregnated with about 15 percent of a water-soluble phenolic resin. The corrugated sheets were bonded together with an acid-catalyzed phenolic resin.

The core designated XN (fig. 7) was made up of corrugated sheets glued together with corrugations of adjacent sheets at right angles. The assemby was cut in the required thickness and arranged so that alternate corrugated sheets were positioned with flutes parallel and perpendicular to the facing.

The core designated XF was identical to that designated XN except that it was placed in the panel with all flutes parallel to the facings. This orientation results in better insulation, but it is weak in flatwise compression. The limited glue surface between corrugations is a likely cause of low shear strength.

The core designated PN (fig. 8) was assembled with all flutes parallel. Panels were assembled with flutes perpendicular to the facings.

Facings. —The facings used on the original panels manufactured by the laboratory were plywood or veneer: ¼-inch, three-ply Douglas-fir, exterior type; ¼-inch, three-ply Douglas-fir, exterior type, with 25 percent phenolic 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; ⅛-inch Douglas-fir veneer with a resin treated paper overlay on both sides; and ⅜-inch, five-ply Douglas-fir, exterior type (for floor panels).

The facings on the commercially manufactured panels were 0.02-inch aluminum.

Replacement Panels—1948

For the purpose of observing the performance of a wider variety of facing materials, two panels (3N1, 3S1) were removed and two replacement panels installed, one with ¼-inch cement asbestos board facings (3N2) and the other with ¼-inch high-density hardboard facings (3S2). A second pair of panels (8N1, 8S1) was replaced by two with ⅛-inch high-density hardboard facings (8N2, 8S2).

Replacement Panels—1955

One of the two pairs of commercially manufactured panels with aluminum facings (9N1, 9S1) was replaced with two panels (9N2, 9S2) of unbalanced construction, having ⅛-inch high-density hardboard on one face and porcelainized steel on the other. The core material was a type PNL paper honeycomb, a variation on the type PN core with layers of single-faced corrugated board (corrugated paper faced on one side with a flat sheet of paper, assembled as shown in fig. 9).

Table 1.–Panel descriptions

Panel no.	Core type	Facing[1]	Type adhesive and press construction details	Thickness	Exposure			Stiffness[2]				Strength		
					Year in	Years tested	Total exposure	Initial		Final	Change	Initial[3]	Final	Change
								Deflection	Deflection span ratio	Deflection				
				In.			Yr	In.		In.	Pct	Lb/ft^2[4]	Lb/ft^2[4]	Pct
						WALL PANELS								
1N1	Corrugated XN	1/4-inch Douglas-fir plywood with overlay[6]	Acid-catalyzed phenolic glue; cold press	3	1947	1962[5]	15	0.121	1/790	0.115	+ 5	263	365	+ 39
						1968	21	"	"	.095	+ 21			
						1978	31	"	"	.105	+ 13	"	363	+ 38
1S1	"	"	"	3	1947	1962[5]	15	.125	1/770	.111	+ 11	263	367	+ 40
						1968	21	"	"	.120	+ 4			
						1978	31	"	"	.112	+ 11	"	300	+ 14
1N2	Expanded	0.1-inch paperboard (Pan-L)[7]	"	4	1961	1962[5]	1	.302	1/320	.371	-23	118	76	-36
						1968	7	"	"	.300	+ 1			
						1978	17	"	"	.347	-15	"	99	-16
1S2	"	"	"	4	1961	1962[5]	1	.306	1/315	.320	+ 11	118	101	-14
						1968	7	"	"	.287	+ 6			
						1978	17	"	"	.331	- 8	"	75	-36
2N1	"	*0.02-inch aluminum*	*Phenol vinyl, press not known*	2	1947	1962[5]	15	.365	1/260	.363	+ 1	200	118	-41
						1968	21	"	"	.365	0			
						1978	31	"	"	.377	- 3	"	70	-65
2S1	"	"	"	2	1947	1962[5]	15	.370	1/260	.365	+ 1	200	160	-20
						1968	21	"	"	.365	+ 1			
						1978	31	"	"	.381	- 3	"	50	-75
2N2	"	1/4-inch, 2-layer particleboard with facings of redwood flakes[8]	Acid-catalyzed phenolic glue; cold press	3	1962	1968	6	.320	1/300	.330	- 3			
						1978	16	"	"	.384	-20	121	121	0
2S2	"	"	"	3	1962	1968	6	.306	1/315	.339	-11			
						1978	16	"	"	.382	-25	121	118	- 2
3N1	Corrugated XN	1/4-inch Douglas-fir plywood	"	3	1947	1948	1	.115	1/835	.102	+ 11	263	391	+ 49
3S1	"	"	"	3	1947	1948	1	.115	1/835	.098	+ 15	263	344	+ 31
3N2	"	1/4-inch cement asbestos	"	3	1948	1961	13	.070	1/1370	.041	+ 41	194	135	-30
3S2	"	1/4-inch high-density hardboard	"	3	1948	1961	13	.214	1/450	.181	+ 15	315	247	-22
3N4	Expanded	1/2-inch medium-density fiberboard	"	3	1962	1968[5]	6	.268	1/360	.247	+ 8	123	155	+ 26
						1978	16	"	"	.271	- 1	"	119	- 3
3S4	"	"	"	3	1962	1968[5]	6	.259	1/370	.252	+ 3	123	150	+ 22
						1978	16	"	"	.259	0	"	132	+ 7
4N1	Corrugated XN	1/4-inch Douglas-fir plywood	"	3	1947	1962	15	.112	1/855	.113	- 1	263	331	+ 26
4S1	"	"	"	3	1947	1962	15	.127	1/755	.113	+ 11	263	297	+ 13
4N2	Expanded	1/8-inch tempered hardboard	Contact adhesive, nip-roll bonding	3	1962	1968[5]	6	.286	1/335	.306	- 7	109	84	-23
						1978	16	"	"	.324	-13	"	80	-27
4S2	"	"	"	3	1962	1968[5]	6	.282	1/340	.282	0	109	103	- 6
						1978	16	"	"	.331	-17	"	90	-17
5N1	Corrugated XF	1/4-inch Douglas-fir plywood	Acid-catalyzed phenolic glue; cold press	3	1947	1968	21	.182	1/525	.185	- 2	–	670	–
5S1	"	"	"	3	1947	1968	21	.162	1/590	.184	-13	–	430	–
7N1	Corrugated XN	0.2-inch 2-ply Douglas-fir plywood with overlay	"	3	1947	1968[5]	21	.158	1/610	.155	+ 2	–	246	–
						1978	31	"	"	.174	-10	–	248	–
7S1	"	"	"	3	1947	1968[5]	21	.157	1/605	.148	+ 6	–	283	–
						1978	31	"	"	.153	+ 3	–	234	–
8N1	Corrugated XF	1/8-inch Douglas-fir veneer with overlay	"	3	1947	1948	1	.141	1/680	.127	+ 10	–	272	–
8S1	"	"	"	3	1947	1948	1	.158	1/610	.141	+ 11	–	330	–
8N2	Corrugated XN	1/8-inch high-density hardboard	Phenol resorcinol; hot press	3	1948	1968[5]	20	.245	1/390	.264	- 8	201	200	0
						1978	30	"	"	.265	- 8	201	102	-49
8S2	"	"	"	3	1948	1968[5]	20	.243	1/395	.280	-15	201	220	+ 9
						1978	30	"	"	.253	- 4	"	237	+ 18
8N3	Expanded	1/4-inch, 2-layer particleboard with facings of Douglas-fir flakes[8]	Phenol resorcinol; cold press	3	1968	1978	10	.317	1/300	.313	+ 1	176	165	- 6

Table 1.—Panel descriptions (continued)

Panel no.	Core type	Facing[1]	Type adhesive and press construction details	Thickness	Exposure			Stiffness[2]				Strength		
					Year in	Years tested	Total exposure	Initial Deflection	Initial Deflection span ratio	Final Deflection	Change	Initial[3]	Final	Change
				In.			Yr	In.		In.	Pct	Lb/ft²[4]	Lb/ft²[4]	Pct
						WALL PANELS								
8S3	"	"	"	3	1968	1978	10	.287	1/335	.282	+ 2	176	203	+15
9N1	"	0.02-inch aluminum	Phenol vinyl; press not known	2	1947	1955	8	.365	1/260	.365	0	200	129	-36
9S1	"	"	"	2	1947	1955	8	.358	1/270	.361	- 1	200	148	-26
9N2	Corrugated PNL	1/8-inch, high-density hardboard, porcelainized steel	Phenol resorcinol; hot press	3	1955			.053	1/1810			222		
9S2	"	"	"	3	1955			.053	1/1810			222		
9N3	Expanded with 1-inch urethane foam	1/4-inch plywood with medium-density overlay	"	3	1968	1978	10	.115	1/835	.120	- 4	247	217	-12
9S3	"	"	"	3	1968	1978	10	.104	1/925	.115	-11	247	209	-15
10N1	Corrugated PN	1/4-inch Douglas-fir plywood	Acid-catalyzed phenolic glue; cold press	3	1947	1962[5]	15	.120	1/800	.115	+ 4	251	410	+63
						1968	21	"	"	.092	+23			
						1978	31	"	"	.097	+20	251	371	+49
10S1	"	"	"	3	1947	1962[5]	15	.125	1/770	.118	+ 6	251	321	+28
						1968	21	"	"	.113	+10			
						1978	31	"	"	.113	+10	251	325	+29
10N2	Expanded	1/4-inch birch plywood (inner face), 1/8-inch aluminum over hardboard (outer face)	"	2.75	1962	1968	6	.226	1/425	.227	0			
						1978	16	"	"	.244	- 8	105	125	+19
10S2	"	"	"	2.75	1962	1968	6	.227	1/425	.225	+ 1			
						1978	16	"	"	.229	- 1	105	116	+10
10N3	1.9 pound styrofoam	1/4-inch Douglas-fir plywood with medium-density overlay	Phenol resorcinol; cold press	3	1968	1978	10	.172	1/560	.158	+ 8	323	226	-30
10S3	"	"	"	3	1968	1978	10	.155	1/620	.140	+10	323	309	- 4
						ROOF PANELS								
A	Corrugated XF	1/4-inch 3-ply plywood	Unventilated	4½	1947	1968	21	0.440	1/330	0.419	+ 5			
						1978	31	"	"	.398	+10	–	55	–
B	Expanded	0.02-inch aluminum	"	3	1947	1968	21	1.085[9]	1/135	1.017	+ 6			
						1978	31	"	"	.994	+ 8	51	27	-47
C	Corrugated XN	1/4-inch, 3-ply plywood	Ventilated	4½	1947	1968	21	.369	1/390	.331	+10			
						1978	31	"	"	.324	+12	–	139	–
D	"	"	Unventilated	4½	1947	1968[5]	21	.361	1/400	.347	+ 4	–	172	–
						1978	31	"	"	.368	- 2	–	155	–
E	"	"	Ventilated	4½	1947	1968	21	.376	1/385	.358	+ 5	–	91	–
F	"	"	Unventilated	4½	1947	1968	21	.338	1/425	.328	+ 3			
						1978	31	"	"	.329	+ 3	–	153	–
G	"	1/4-inch, 3-ply plywood with resin-treated paper on outside of each facing	Ventilated	4½	1947	1968	21	.305	1/470	.298	- 2			
						1978	31	"	"	.306	0	–	142	–
H	"	"	Unventilated	4½	1947	1968	21	.339	1/425	.311	+ 8			
						1978	31	"	"	.324	+ 4	–	164	–
I	Expanded	0.02-inch aluminum	"	3	1947	1968	21	1.123[9]	1/130	1.038	+ 8			
						1978	31	"	"	1.000	+11	51	29	-43
J	Corrugated PN	1/4-inch, 3-ply plywood	"	4½	1947	1968	21	.374	1/385	.356	+ 5			
						1978	31	"	"	.358	+ 4	–	169	–

Table 1.—Panel descriptions (continued)

Panel no.	Core type	Facing[1]	Type adhesive and press construction details	Thickness	Exposure			Stiffness[2]				Strength		
					Year in	Years tested	Total exposure	Initial		Final	Change	Initial[3]	Final	Change
								Deflection	Deflection span ratio	Deflection				
				In.			Yr	In.		In.	Pct	Lb/ft^2[4]	Lb/ft^2[4]	Pct
						FLOOR PANELS								
1	Corrugated XN	3/8-inch, 5-ply plywood	Pressed-in hot water tubing	6	1947	1968	21	.297[10]	1/485	.230	+23			
						1978	31	"	"	.258	+13	376	163	-57
2	"	"	"	6	1947	1968	21	.297[10]	1/485	.243	+18			
						1978	31	"	"	.248	+17	376	319	-15
3	"	"	"	6	1947	1968	21	.297[10]	1/485	.230	+23			
						1978	31	"	"	.225	+24	376	152	-60
4	"	"	"	6	1947	1968	21	.297[10]	1/485	.248	+17	376	301	-20

[1] Both facings of same material unless noted. All plywood was Douglas-fir.

[2] Deflection at design load of 20 lb/ft^2 for wall panels, 25 lb/ft^2 for roof panels, and 40 lb/ft^2 for floor panels. Span length is 96 inches for wall panels and 144 inches for roof and floor panels.

[3] Test of duplicate panel of identical construction.

[4] Equivalent uniform load over 96-inch span for wall panel and 144-inch span for roof and floor panels.

[5] One-half of original panel tested; one-half remaining in place.

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

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

[8] Particleboard fabricated with fines (1/4 of total weight) on exposed surface. Phenol resin binder—6 percent in flakes, 10 percent in fines.

[9] Aluminum-faced roof panels were designed for 15 lb/ft^2 load.

[10] Average for the four panels.

Replacement Panels—1961

The panels with ¼-inch cement asbestos facings (3N2) and ¼-inch high-density hardboard facings (3S2), which had been installed a year after the original panels, were in turn replaced with a pair of commercially manufactured panels having 0.1-inch paperboard facings (1N2, 1S2).

Replacement Panels—1962

When the experimental unit was disassembled in 1962, most of the existing wall panels were cut in half, with half of each panel being reinstalled. The additional space for new panels was used for a pair of panels with facings of ¼-inch 2-layer particleboard surfaced with redwood flakes (2N2, 2S2), a pair with ½-inch medium-density fiberboard facings (3N4, 3S4) and a pair of unbalanced panels with ¼-inch birch plywood on the interior face and ⅛-inch-thick aluminum-faced hardboard on the exterior face (10N2, 10S2). An additional set of panels (4N1, 4S1) was completely replaced with panels using ⅛-inch tempered hardboard facings (4N2, 4S2).

Replacement Panels—1968

Some of the newer panels were cut in half, and half of each panel reinstalled. One pair of the original panels (5N1, 5S1) was completely removed. New panels included a pair with ¼-inch 2 layer particleboard facings surfaced with Douglas-fir flakes (8N3, 8S3).

A new generation of core materials was employed in other panels. One pair of panels used the expanded type of paper honeycomb core with polyurethane foamed into the cells to a depth of 1 inch (9N3, 9S3, fig. 10), and another pair used a solid core of extruded polystyrene (10N3, 10S3, fig. 11). Both sets of panels were faced with ¼-inch Douglas-fir plywood overlaid with medium-density paper.

Long-term Structural Performance

Test methodology and test results are presented here for tests conducted on panels to determine bending strength and stiffness prior to and following exposure periods of various lengths of time up to 31 years.

The results are summarized for other structural tests which were required as background research in the initial design and development stages prior to 1947.

Test Methodology

All panels were tested for stiffness prior to installation, and duplicate panels were destructively tested for bending strength to provide a basis for comparison with additional tests after exposure.

Whenever old panels were replaced prior to the end of the exposure period in 1978, they were immediately tested to failure. In 1962 and 1968, when many of the panels were cut in half and one-half of each replaced, the replaced half was tested to failure. Also in 1968, when the experimental unit was disassembled and moved to a new site, all panels were tested for stiffness.

Tests were conducted in accordance with ASTM Standard E72-74a(1).[2] A typical test setup is shown in figure 12.

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[2] Underlined numbers in parentheses refer to Literature Cited near end of report.

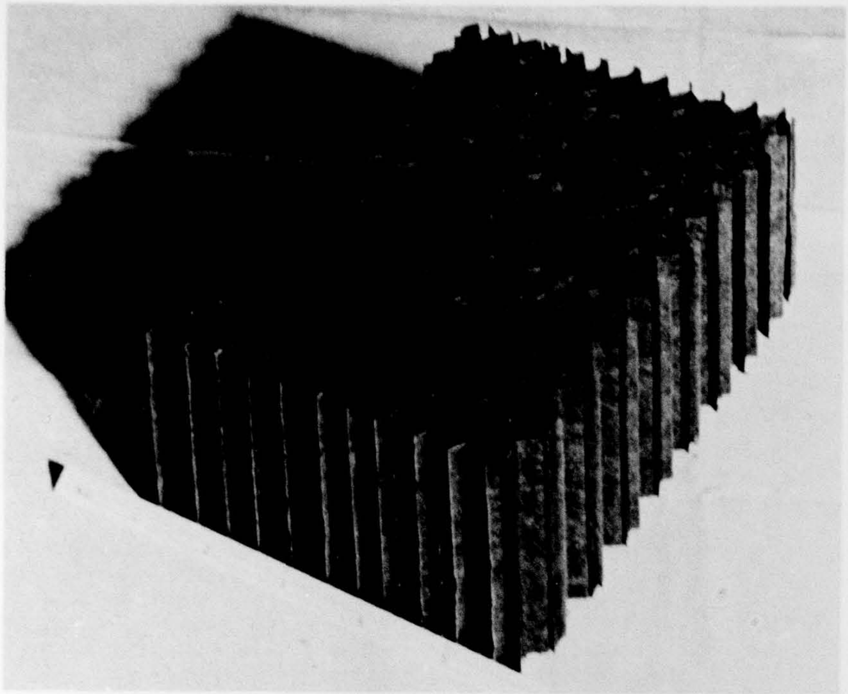

Figure 6.—Expanded hexagonal paper-honeycomb sandwich core. (M 87220 F)

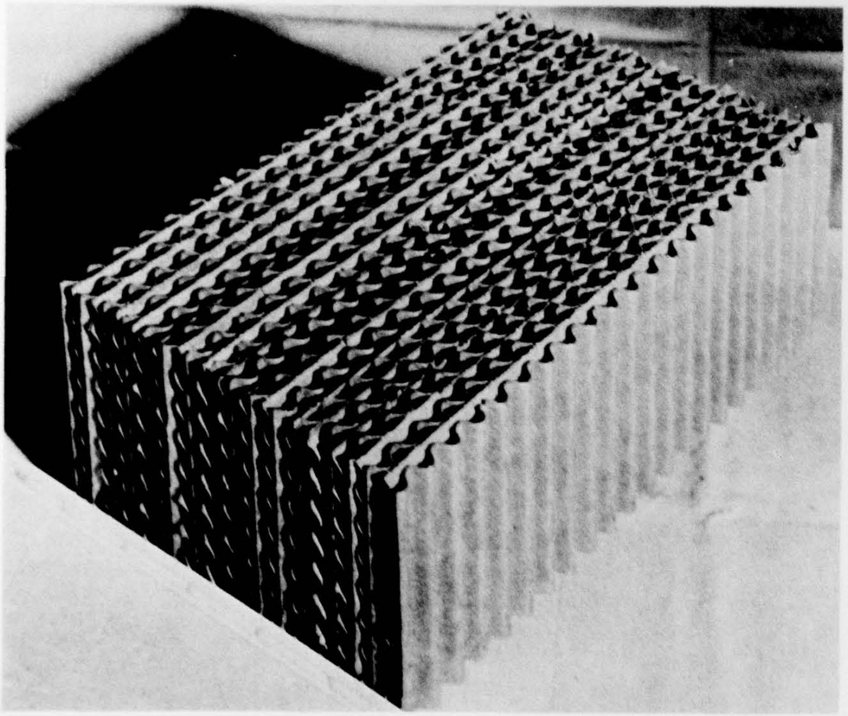

Figure 7.—XN type of corrugated-paper honeycomb core. (M 87222 F)

Quarter point loading was used to provide the same maximum shear and moment as an equivalent uniform load. Plywood yokes with attached dial micrometers were used along both sides of the panel to record deflection at midspan until the design load was reached. Design loads were 20 pounds per square foot for wall panels, 25 pounds per square foot for roof panels, and 40 pounds per square foot for floor panels. In 1978, the manual micrometers were replaced with electronic transducers, and load and deflection data were recorded automatically on an x-y plotter. Rate of loading was estimated according to a procedure in (5) to give a time of test between 6 and 20 minutes. Also in 1978, an additional pair of yokes with transducers was employed, as shown in figure 13, to measure deflection in the short span between the two quarter-point loads which is free of any effect from shear forces.

Test Results

The results are presented in table 1, including the values of deflection at design load and the values of failure strength before and after a period of exposure. The percent change in these values has also been included.

Wall Panels.—Prior to exposure, the deflection of wall panels did not exceed the original design limit of 1/270 of span length, except in the case of the commercially produced aluminum-faced panels (2N1, 2S2, 9N1, 9S2) which slightly exceeded the limit.

After exposure, based on the arbitrary assumption that a change in deflection of 10 percent or less is not significant, the deflection of a majority of panels, including the aluminum-faced panels, remained unchanged. In panels with the expanded type of paper core, the deflection most often remained unchanged except for a few increases, particularly in panels faced with paperboard (1N2, 1S2), particleboard (2N2, 2S2, but not 8N3, 8S3), and hardboard (4N2, 4S2). Panels faced with these three materials were not very stiff to begin with, so that exposure brought them near or, in the case of paperboard, beyond the allowable deflection limit of 1/270. For panels with corrugated paper cores (types XN, XF, PN), the deflection remained about the same or tended to decrease, that is, the panel became stiffer with age, as in the case of panels faced with Douglas-fir plywood or veneer (1N1, 1S1, 3N1, 3S1, 4N1, 4S1, 7S1, 8N1, 8S1, 10N1, 10S1, but not 7N1). No trends were apparent according to the type of glue that was used.

Prior to exposure, the ultimate strength of wall panels always far exceeded the required design strength of 20 pounds per square foot, from a minimum factor of 5.25 for the panels with the unbalanced construction (10N2, 10S2) to a maximum factor of over 16 for the panels with extruded polystyrene cores (10N3, 10S3).

After exposure, based on the arbitrary assumption that a change in strength of less than 20 percent is not significant, the ultimate strength of the majority of wall panels remained unchanged. For panels with an expanded paper core, ultimate strength most often remained unchanged or tended to decrease, particularly in the case of panels faced with paperboard (1N2, 1S2), aluminum (2N1, 2S1, 9N1, 9S1), and hardboard (4N2, 4S2). Even in these worst cases the factor of ultimate to design strength still remained 3.75 for paperboard, 2.5 for aluminum, and 5 for hardboard.

For panels with any of the corrugated types of paper core, ultimate strength remained about the same or else increased, as was the case in all of the panels faced with Douglas-fir plywood. Exceptions were the panels faced with materials other than Douglas-fir: cement asbestos (3N2) and hardboard (3S2, 8N2, but not 8S2).

Roof Panels. —Prior to exposure, the deflection of roof panels did not exceed the design limit of 1/270 of span length, except again in the case of the commercially produced aluminum-faced panels (B, I).

After exposure, based once again on the arbitrary assumption that a change in deflection of 10 percent or less is not significant, the deflection in all panels remain unchanged except one of the 4 panels with a type XN paper core, and one of the aluminum-faced panels.

Prior to exposure, a duplicate panel was tested to failure only for aluminum-faced panels, and its ultimate strength was more than three times the required design strength of 15 pounds per square foot for aluminum roof panels. All other panels were for a design strength of 25 pounds per square foot.

In flat roof panels there was concern that moisture condensation in the core would cause decreased performance after a period of exposure. Therefore, roof panels were constructed both with and without ventilating ducts. A

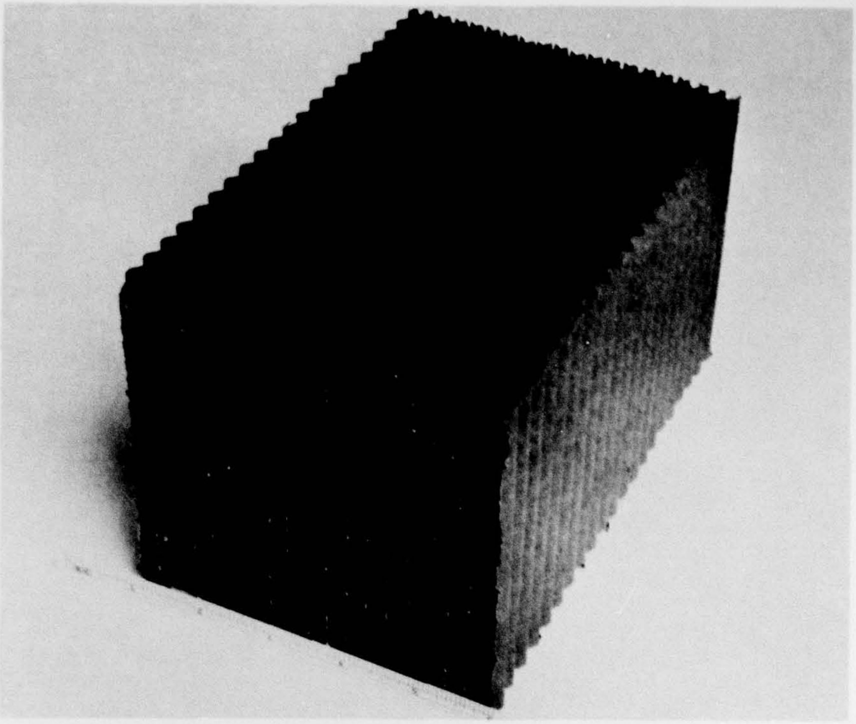

Figure 8.—PN type of corrugated-paper honeycomb core. (M 88875 F)

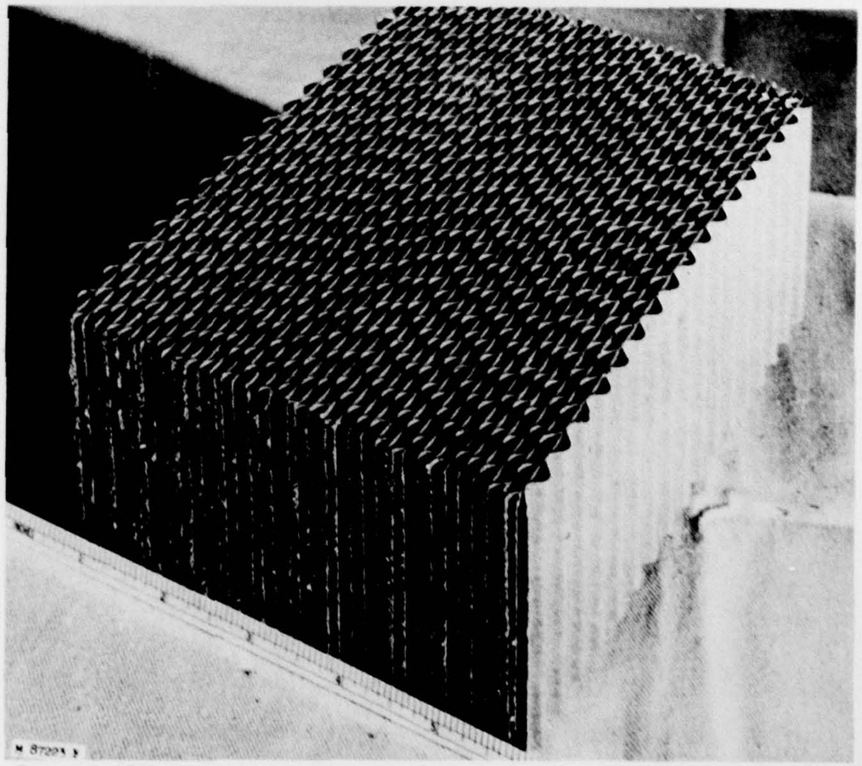

Figure 9.—PNL type of corrugated-paper honeycomb core with flat interleaves between the corrugated sheets. (M 87223 F)

U.S. Forest Products Laboratory.

Structural sandwich performance after 31 years of service, by Jerome Palms and Gerald E. Sherwood. Madison, Wis., For. Prod. Lab., 1979.
19 p. (USDA For. Serv. Res. Pap. FPL 342).

The sandwich panel is a layered structural system composed of a low density core material bonded to, and acting integrally with, relatively thin, high strength facing materials.

This report covers the history of the research and test program and documents the test results over the 31 year period, also a summary analysis of the tests and other recorded data is presented.

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comparison of strength values in table 1 shows that, if anything, there was somewhat of a decrease in strength in the ventilated panels relative to the unventilated panels rather than the reverse.

Floor Panels. —Prior to exposure, the floor panels deflected less than the required design limit. After exposure, the panels were stiffer by 13 to 24 percent.

Prior to exposure, ultimate strength of the one panel tested was far above the required design strength of 40 pounds per square foot, by a factor of over 9. After exposure, based on the arbitrary assumption that a change in strength of 20 percent or less is not significant, two of the four panels nevertheless decreased in strength by 57 and 60 percent.

Types of Failure

Careful records were kept in 1978 of the type of failure in each panel. Failure types were closely associated with the type of facing rather than the core material. Most characteristically, sandwich panels failed as a result of shearing in the core material. Particularly in plywood-faced panels with corrugated paper honeycomb core, shearing would occur in the core material alongside the glue line (fig. 14). Only in one pair of plywood panels (7N1, 7S1) was there evidence of failure in the glue bond itself (fig. 15).

In the fiberboard-faced panels (3N4, 3S4), a layer of fiberboard had pulled away, with the bond between glue and fiberboard completely intact. Failure in these two panels was accompanied by wrinkling of the core material (fig. 16), which was frequently the case with the expanded type of paper core.

Aluminum-faced panels failed in local buckling in the top compression facing by suddenly bulging out from the core. Close observation revealed that when the facing had separated from the core, the adhesive had not adhered to the aluminum surface. Paperboard-faced panels also failed in compression of the top facing that resulted in local buckling (fig. 17).

Panels faced with high-density hardboard (8N2, 8S2) failed as a result of tension in the bottom facing, once at a point of load and once at the center of the panel. One of the panels faced with particleboard (8N3) failed in tension.

All other panels failed as a result of shear in the core.

Other Structural Tests

In background research prior to construction of the experimental unit in 1947, tests were conducted on potential core and facing materials, sections of sandwich assemblies, and full-size panels to gain a more comprehensive knowledge of panel performance in response to compressive and racking loads, impact loads, accelerated aging, and flatwise tension loads.

Properties of Core and Facing Materials. —Various core materials were tested in compression, and also in shear because they must take most of the shear load in sandwich panels. The results are summarized in table 2.

Facing materials were tested in compression and tension parallel to the sheet, since they must carry most of these loads in order for the panel to develop bending strength. Facing materials were also tested for impact resistance, since it is often the limiting factor in the thickness of the facing. Results are summarized in table 3.

Laboratory Aging of Sandwich Panel Specimens. —Sections of sandwich panel assemblies incorporating the final

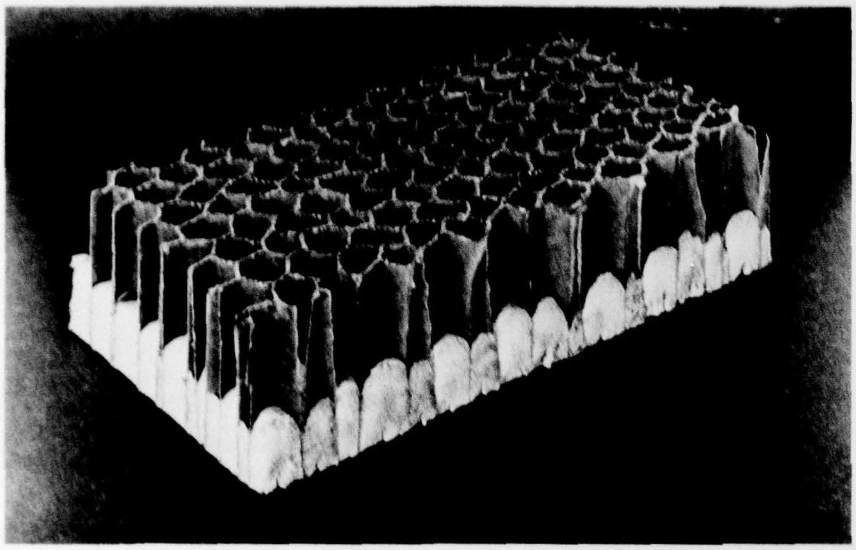

Figure 10.—Expanded hexagonal paper-honeycomb core with 1-inch polyurethane foam from one side. (M 135 580)

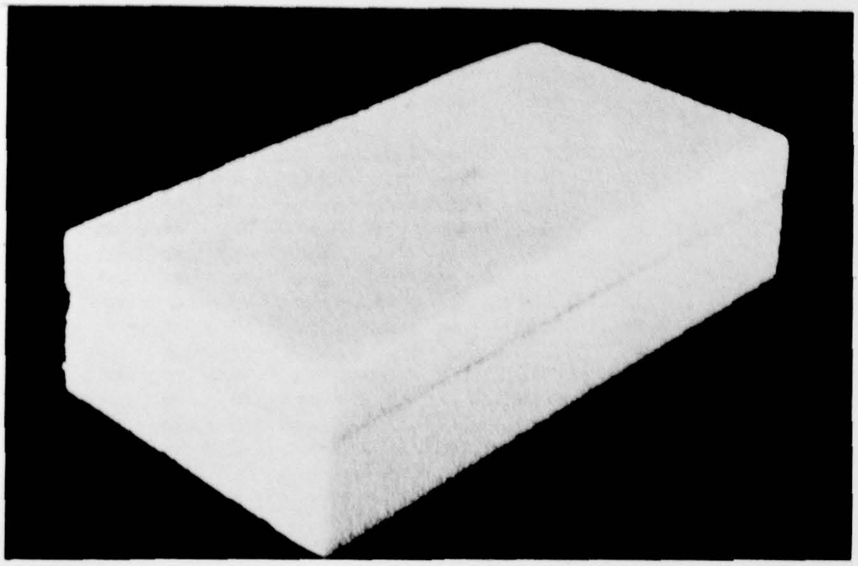

Figure 11.—Extruded polystyrene core with density of 1.9 pounds per cubic foot. (M 135 581)

Table 2.—Mechanical properties of several core materials

Core material and arrangement[1]	Phenolic resin	Compressive strength[2]	Shear properties[3]	
			Shear strength	Modulus of rigidity
	Pct	Lb/in.²	Lb/in.²	1,000 Lb/in.²
50-16 XN corrugated paper	5	30	28	—
	15	63	74	—
60-16 expanded paper	10	45	—	—
	20	95	97	10.3
125-lb expanded paper	35	360	306	20.6
112-114 glass cloth with ¼-inch cells	unknown	286	165	11.9
0.002-inch foil with ⅜-inch cells		234	152	29.1
0.002-inch foil with ¼-inch cells		436	244	41.9

[1] All paper cores tested dry.

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

[3] Cores with XN paper, shear in bending. All others, shear between two steel plates.

choice of core and facing materials were subjected to the laboratory aging process as described in (21) and equivalent to the current ASTM Standard C481-62 (3). The process consisted of six 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. Specimens were tested for bending stiffness and also for shear, according to a procedure reported in (20) which is equivalent to the present ASTM Standard C273-61 (4). The results, originally published in (20) are summarized in table 4 of this report. Comparison with unaged control specimens showed that aging reduced stiffness from 6 to 15 percent and shear strength from 18 to 32 percent.

Comparison of laboratory aging processes. —In 1947, because the results of the standard laboratory aging process had not (and still have not) been correlated with the results of actual long-term exposure, small specimens of one type of sandwich panel construction—a commercially manufactured panel with 0.02-inch aluminum facings and resin-treated paper honeycomb core bonded with a phenol vinyl glue—were subjected to a variety of different aging processes as outlined in table 5. Each specimen was then submitted to a tension test equivalent to the current ASTM Standard C297-61 (6) to determine which component of the sandwich assembly had been weakened by laboratory aging.

The results are presented in table 5 for a variety of aging processes. In processes 1 through 3, the value of tensile strength is the average of 10 specimens taken from each of 4 panels. In processes 4 through 8, the value is the average of 5 specimens taken from each of 4 panels at the end of each cycle or time interval. When exposed to a temperature of 180° F or soaked in water for 48 hours, the adhesive bond weakened appreciably. The effects of cycling under less extreme temperature conditions or varying humidity conditions were less severe.

Compression tests of sandwich panels. —The load-carrying capacity of several 8-foot high wall panels was tested by applying an edgewise compression force. Recorded deformation was negligible at loads below 500 pounds per lineal foot. Three aluminum-faced panels failed as a result of local buckling in a facing at loads from 2,300 to 3,100 pounds per lineal foot. A panel with ¼-inch plywood facings failed at 19,000 pounds per lineal foot.

Impact tests. —In one procedure followed for impact loads, panels were supported horizontally near the ends and a 60-pound sandbag was dropped on the center of the panel at increasing

Table 3.—Mechanical properties of several facing materials

Material[1]	Thickness	Dry weight	Moisture content		Absorption[3]	Linear expansion[4]		Compression and tension parallel to length of sheet						Impact puncture resistance[6]	
								Compression[5]		Tension					
			Dry	Soaked[2]		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]		
	In.	Lb/ft²	Pct	Pct	Pct	Pct	Pct	Lb/in.²	1,000 Lb/in.²	Lb/in.²	Lb/in.²	1,000 Lb/in.²	1,000 Lb/in.²	In.-lb	In.-lb
Douglas-fir plywood	¼	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	⅛	.75	4.8	36.5	11.0	.38	.37	3,420	672	3,460	1,800	669	308	198	212
"	¼	1.40	5.8	37.5	11.3	.23	.27	2,900	700	2,350	1,000	–	224	529	580
Treated hardboard	⅛	.77	5.7	30.7	9.4	.30	.37	5,260	900	4,980	3,020	855	382	206	225
"	¼	1.44	5.5	20.7	3.6	.26	.25	4,620	810	4,260	2,700	–	422	439	527
Finished hardboard	⅛	.73	7.4	67.1	29.3	.32	.33	3,300	681	4,570	990	679	93	271	252
Laminated paperboard, waterproofed	¼	.70	9.6	72.9	18.3	.24	1.12	780	313	1,840	250	293	67	231	136
"	⅜	.96	9.7	40.1	9.3	.21	1.05	780	317	1,700	420	294	79	344	276
Cement-asbestos board	⅛	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.	¼	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 cup with triangular base 2.45 inches on each side.

heights until failure occurred. The maximum height at failure was 8 feet for a plywood-faced wall panel, 7 feet for an aluminum-faced wall panel, more than 10 feet for a floor panel, and 4 feet for an aluminum-faced roof panel.

No damage resulted from a 3-foot drop on wall and roof panels or a 6-foot drop on floor panels, these heights had been suggested as minimum performance requirements for panels.

In a second procedure, a 2-inch diameter steel ball was dropped from a height of 4 inches. Dents of from 0.01 to 0.03 inch were measured in panels with various facing materials. Dents of equal depth were more noticeable in a smooth, bright aluminum facing than in facing materials with a dull finish or texture such as fiberboard.

Environmental Performance

The effect of variations in moisture content and temperature on the structural properties and dimensions of sandwich panels are discussed. Potential condensation problems associated with paper honeycomb cores are also discussed. Finally, the results of records kept on the bowing of panels due to seasonal changes in climate are presented.

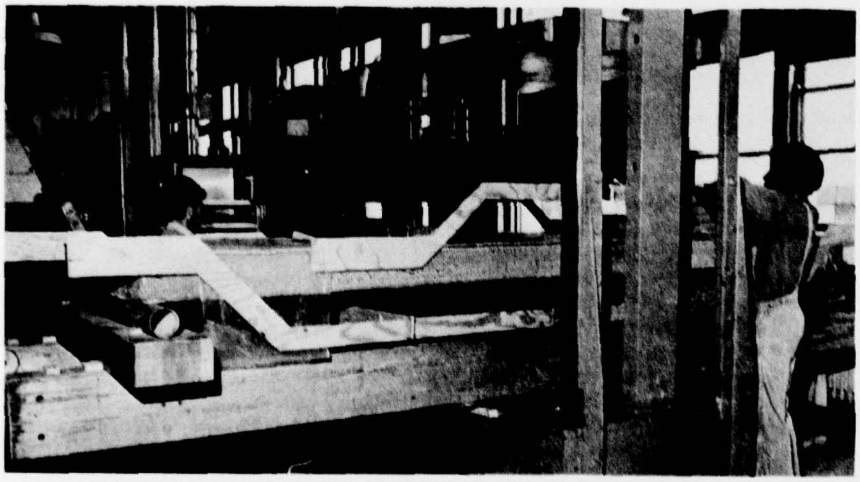

Figure 12.—Typical setup for a panel to be tested for bending strength and stiffness in 1978. (M 147 139-2)

Moisture

Moisture may affect the structural properties of core and facing materials and the dimensional integrity of the facings. Potential condensation problems must also be considered.

Table 4.—The percent retention of bending stiffness and shear strength for laboratory aged sandwich specimens compared to unaged control specimens

Core	Facings	Stiffness	Shear Strength
		Pct	Pct
XN	Three-ply, 1/4-inch Douglas-fir plywood with paper overlay	90	71
XN	Three-ply, 1/4-inch Douglas-fir plywood	86	81
XF	Three-ply, 1/4-inch Douglas-fir plywood	85	82
XN	Two-ply, 1/10-inch Douglas-fir veneer with paper overlay	85	68
XN	Single-ply, 1/8-inch Douglas-fir veneer with paper overlay	94	72

A facing composed of wood or a wood-based material is hygroscopic; that is, water vapor is absorbed by the wood facing or evaporated from its surface until an equilibrium is reached with the surrounding environment. With an increase of moisture, the dimensions of the facing increase while its structural properties are generally reduced. Table 3 summarizes the effect of moisture on the dimensions and structural properties of several facing materials used in the experimental unit. Douglas-fir plywood, for instance, expanded by 0.1 percent of its original length due to a change in relative humidity. When soaked, it lost about 18 percent of its original stiffness and strength. Impact resistance, on the other hand, is slightly affected. In comparison, hardboards and laminated paperboards expand at a greater rate than plywood, and their structural properties tend to be reduced at a proportionally greater rate.

Moisture also affects the strength of paper honeycomb core materials. The ratio of strength in a wet versus dry condition is about 30 percent for compression and 45 percent for shear.

Condensation may occur within the paper honeycomb cores of exterior wall or roof panels in cold climates. In laboratory tests, a sandwich panel was placed in an opening between a heated room maintained at 75° F, 50 percent relative humidity, and a cold room at −15° F. These conditions are more severe than would normally be encountered in a residence. The panel tested was 4 feet wide by 7 feet 6 inches high. At the end of 102 days of exposure, the panel weight had increased by about 8.5 pounds or about 12 percent of original weight, much of which was in the form of ice in the honeycomb cells.

In 1978 prior to tests for bending, all panels were visually checked for signs of biodegradation, particularly in the paper core material. None was observed.

Temperature

The effect of temperature on strength of sandwich panels is generally not critical in building construction. The strength of most wood materials changes about 0.33 to 0.50 percent from that at 68° F per degree of temperature change. 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.

In laboratory tests of sandwich panels

Table 5.—Tensile strength of one type of sandwich panel construction exposed to several different laboratory aging processes[1]

Exposure					Test results		
Reference number	Description	Total time before testing			Tensile strength[2]	Location of failure	
						In glue	In paper
		Weeks	Days	Cycles	Lb/In.^{2}	Pct	Pct
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		3	83	28	72
		12		6	50	53	47

[1] Panel constructed of *0.020-inch aluminum facings and a 2-inch-thick resin-treated paper honeycomb core bonded with a phenol vinyl* adhesive.

[2] Strength values are the average of 10 specimens taken from each of 4 panels.

under a severe temperature differential of 70° F on one side of the panel and -20° F on the other, bowing of the panels occurred immediately toward the warm side. With continuing exposure, the bowing decreased due to absorption of moisture on the cold side.

Seasonal Bowing of Panels

Bowing of sandwich panels is the bending which occurs as a result of internal forces that develop in the facings of the panel. In panels used in the exterior of buildings, these internal forces develop as a result of a difference in moisture and temperature conditions between inside and outside facings which causes an unbalance in the rates of dimensional change.

The bowing of wall and roof panels in the experimental unit was studied over a 15-year period for the original panels, a 4-year period for panels installed in 1962, and a 3-year period for those installed in 1968. In general, a cyclic pattern bowing was observed from year to year.

Plywood-faced panels with paper cores. —The north panels were flat only in July and bowed out to a maximum of about ¼ inch in February (fig. 18). South panels were essentially flat from May to November and bowed out to about 1/10 inch during the winter.

Plywood-faced panels with polyurethane foam/paper cores. —North and south panels bowed in similar patterns and reached a maximum at about 4/10 of an inch in January (fig. 19). Both panels were at a minimum during the warmer months, with the north panel essentially flat and the south panel below 1/10 of an inch.

Plywood-faced panels with extruded polystyrene cores. —North and south panels bowed in similar patterns, the north panel reaching a maximum of about 4/10 inch and the south panel 3/10 inch in January (fig. 20). Both panels bowed in slightly during the summer and early fall.

Aluminum-faced panels. —North panels bowed slightly outward during the winter months, and bowed slightly inward the rest of the year (fig. 21). South panels were essentially flat from May to October and bowed slightly inward during the colder months.

Particleboard-faced panels (2N2, 2S2). —North and south panels varied similarly with a continuous outward bow, from a minimum of about 2/10 inch in the summer to a maximum in the winter of 4/10 inch for the north panel and 3/10 inch for the south panel (fig. 22).

Particleboard-faced panels (8N3, 8S3). —North and south panels bowed in similar patterns, the north panel reaching a maximum at 4/10 inch and the south panel at 3/10 inch in January (fig. 23). Both panels bowed inward slightly during the warmer half of the year.

Paperboard-faced panels (4 inches thick). —Bow of north and south panels was almost identical with maximum outward bow during the winter months

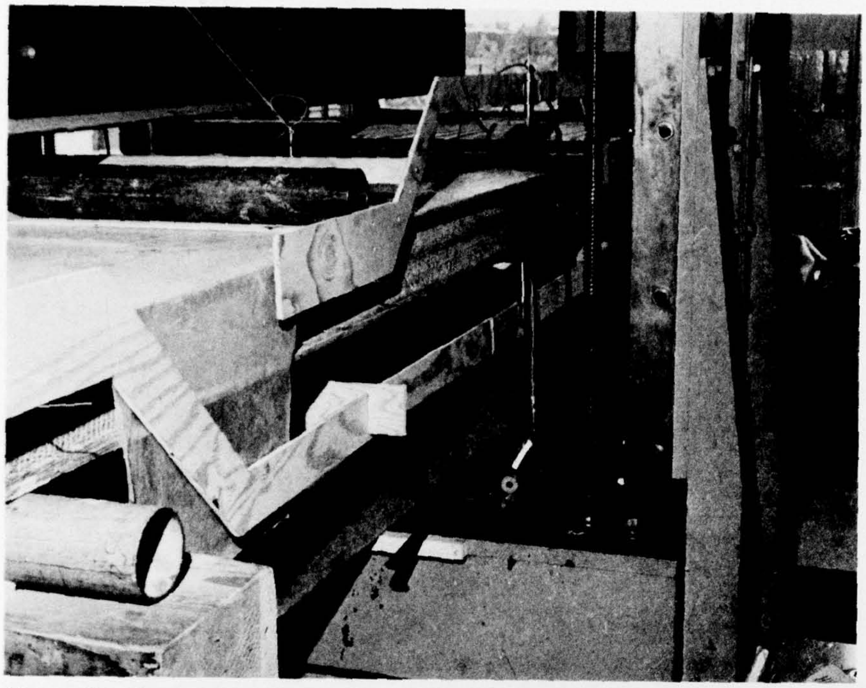

Figure 13.—View of panel ready for testing, showing both the long and short yokes with transducers for measuring midspan deflection. (M 147 139-1)

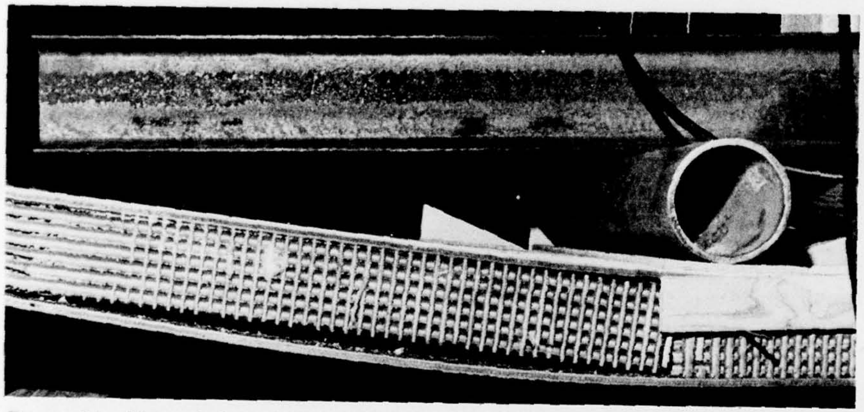

Figure 14.—View of shear failure in the paper honeycomb core material along the glue line in a panel faced with plywood (panel No. 1N1). (M 147 103-7)

of 2/10 inch and with a slight inward bow in late summer (fig. 24).

Medium-density hardboard-faced panels. —North and south panels bowed outward throughout the year in similar patterns (fig. 25). Bowing was minimal in the summer, reaching a maximum of about 4/10 inch in the north panel and 2/10 inch in the south panel during the winter.

High-density hardboard-faced panels. —North panels were flat in July and August and bowed out greatly to a maximum of ½ inch in March (fig. 26). South panels bowed out continuously throughout the year from a minimum of 1/10 inch to a maximum of 4/10 inch in the winter months.

Cement asbestos-faced panel. —The one panel on the north wall had a continuous outward bow from 2/10 inch in summer to 4/10 inch in winter (fig. 26).

Panels with unbalanced facings. — The inside facing of these panels was ¼ inch birch plywood and the outside panel was aluminum-faced hardboard (fig. 27). North and south panels varied greatly in the pattern of bowing. The north panel bowed inwardly all year within a narrow range of 1/10 to 3/10 inch. The south panel bowed outward for the most part with a maximum of 2/10 inch in April and a slight inward bow in January of 1/10 inch.

Roof panels. —The pattern of bowing of the plywood roof panels is a reverse image of that for aluminum roof panels (fig. 28). In January, plywood panels reached a maximum outward bow of 3/10 inch while aluminum panels bowed inward slightly. In July, plywood panels bowed inward to 1/10 inch, while aluminum panels bowed outward the same.

Conclusions

Structural Performance

Performance of sandwich panels in the experimental unit, for periods up to 31 years, indicates that panels of nominal thicknesses can be satisfactorily used in housing construction. Between 1947, when sandwich panels were essentially an untried innovation, and the completion of testing in 1978, there have been several commercial applications of sandwich panels to housing. With the increased emphasis on conservation of limited natural resources, sandwich panels may become more widely used due to the favorable strength-to-weight ratio.

In stiffness, panels most often remained unchanged over the exposure period. After exposure, only the paperboard-faced panels deflected more than the original design limit. Plywood-faced panels with corrugated paper cores performed best, actually becoming slightly stiffer with age.

In strength, a majority of panels remained unchanged. Only panels faced with paperboard, aluminum, and hardboard tended to decrease in strength. There is some evidence that plywood-faced panels with the corrugated paper core actually increased in strength, with the exception of two floor panels which registered a sharp decrease.

Failures did not occur in the glue bond, except in the case of aluminum-faced panels. Regardless of the type of core material, whether paper honeycomb, polystyrene, or polyurethane, failure was usually by shearing in the core.

Environmental Performance

In contrast to 1947, there is a major concern today that housing construction be able to meet rigorous insulation requirements. The unfilled paper honeycomb core provides adequate insulation in mild climates but not in colder climates. The panels with extruded polystyrene and polyurethane cores, which were installed in 1968, not only showed good structural performance but, satisfy insulation requirements for most climates.

Among panels faced with wood-based products, plywood panels with paper cores bowed the least with a maximum outward bow of about ¼ inch during the winter months. However, plywood-faced panels with polyurethane and polystyrene cores bowed much more, perhaps due to a greater moisture content differential between inside and outside facings. The average bowing thoughout the year is minimal in aluminum-faced panels.

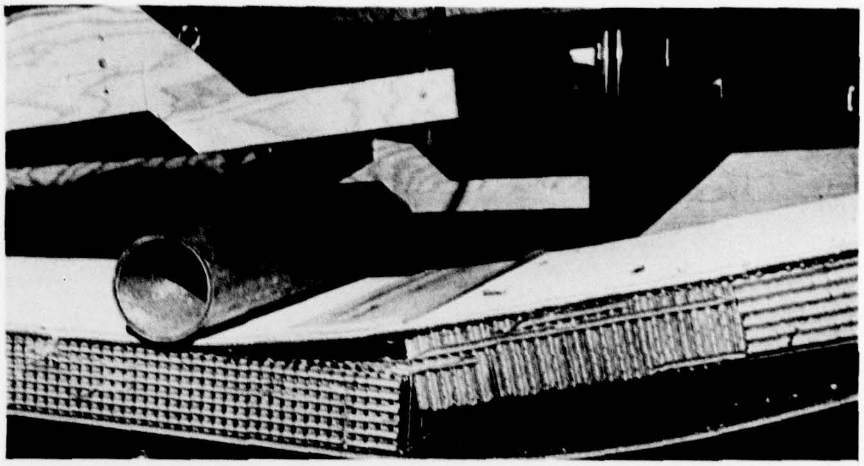

Figure 15.—View of shear failure in a panel with corrugated paper core and plywood facing. Some failure in glue bond was evident. Note that the shearing surface changes from lower inside facing to top at the point of interface between two sections of core material (panel No. TN1). (M 147 104-1)

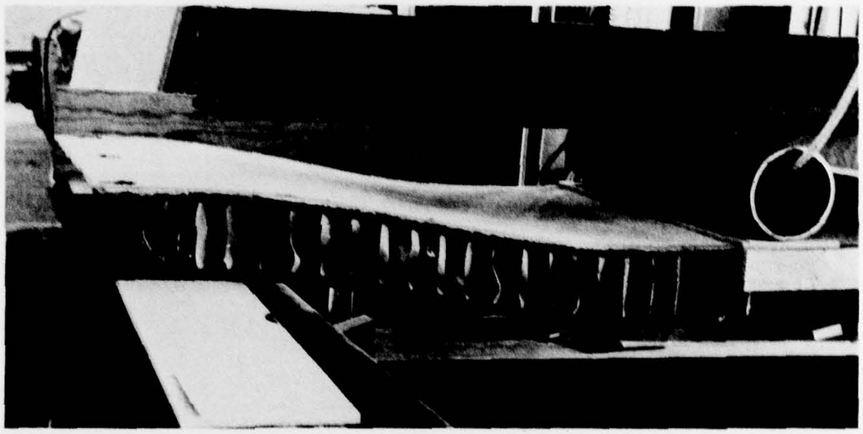

Figure 16.—View of failure due to shear in a panel with fiberboard facings and expanded type of core (Panel No. 3S4). (M 147 139-11)

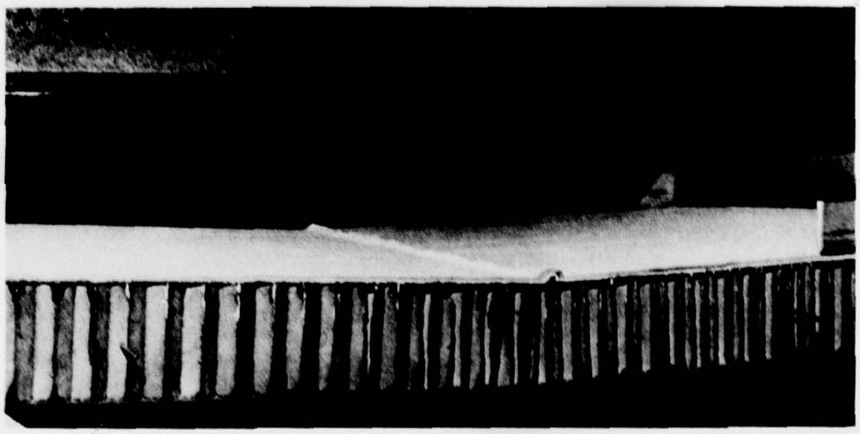

Figure 17.—View of failure in paperboard facing due to local buckling on compression side (Panel No. 1N2). (M 147 103-1)

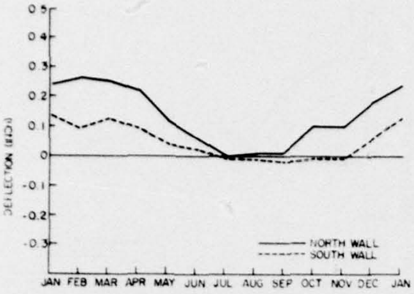

Figure 18.—Seasonal bowing of plywood-faced panels with paper cores (15-year average).

(M 146 908)

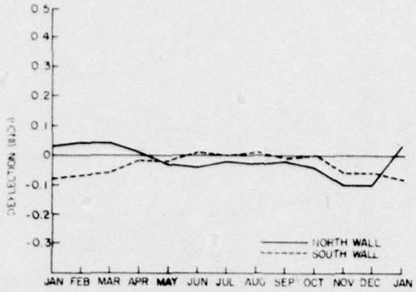

Figure 21.—Seasonal bowing of aluminum-faced panels (15-year average).

(M 146 912)

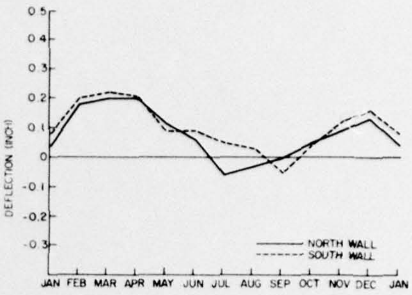

Figure 24.—Seasonal bowing of paperboard-faced panels (4-year average).

(M 146 915)

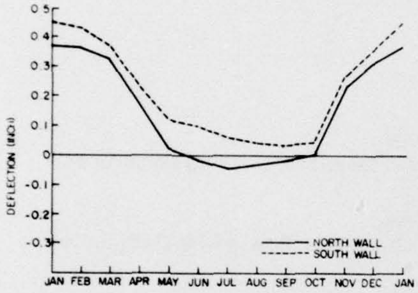

Figure 19.—Seasonal bowing of plywood-faced panels with urethane cores (9N3, 9S3) (3-year average).

(M 146 910)

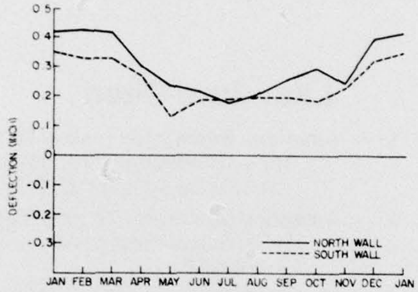

Figure 22.—Seasonal bowing of particleboard-faced panels (2N2, 2S2) (4-year average).

(M 146 913)

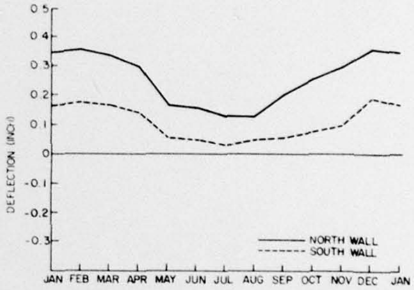

Figure 25.—Seasonal bowing of medium-density hardboard-faced panels (4-year average).

(M 146 916)

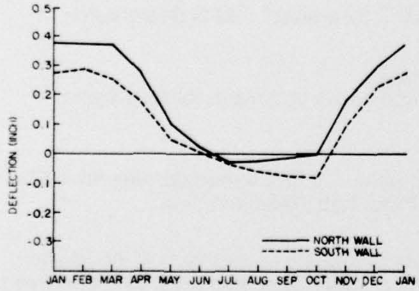

Figure 20.—Seasonal bowing of plywood-faced panels with styrofoam cores (10N3, 10S3) (3-year average).

(M 146 911)

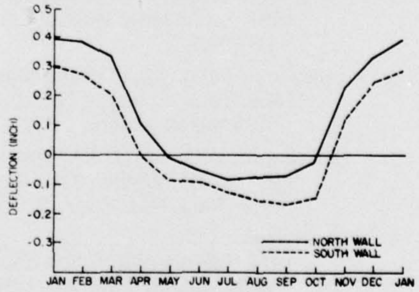

Figure 23.—Seasonal bowing of particleboard-faced panels (8N3, 8S3) (3-year average).

(M 146 914)

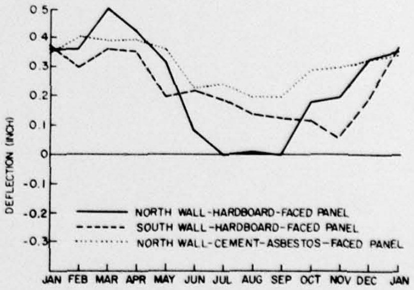

Figure 26.—Seasonal bowing of high-density hardboard- and cement-asbestos-faced panels (15-year average).

(M 146 907)

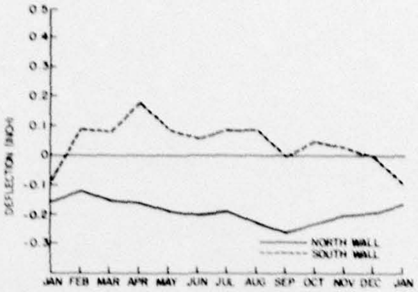

Figure 27.—Seasonal bowing of panels with plywood outside, aluminum-faced hardboard inside (4-year average).

(M 146 909)

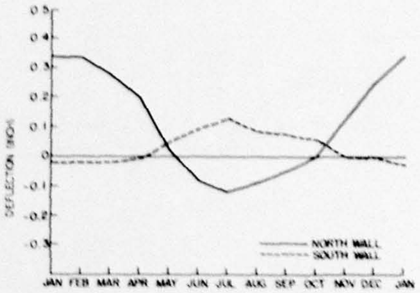

Figure 28.—Seasonal bowing of roof panels (15-year average).

(M 146 917)

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