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Structural Evaluation of Steel Faced Sandwich Panels

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nBS Building Science Series

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SI Conversion Units

In view of the present accepted practice in this country for building technology, common US units of measurement have been used throughout this paper. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the metric SI system of units in 1960, assistance is given to the reader interested in making use of the coherent system of SI units by giving conversion factors applicable to US units used in this paper.

Length

1 in = 0.0254 meter (exactly)

1 ft = 0.3048 meter (exactly)

Force

1 lb (lbf) - 4.448 Newtons (N)

Pressure

1 lbf/ft^2 = 47.88 N/m^2

1 lbf/in^2 = 6894 N/m^2

Temperature °C = 5/9 (Temperature °F - 32)

Structural Evaluation of Steel Faced Sandwich Panels

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A series of structural evaluation tests performed on components and materials intended for use in one of the Operation BREAKTHROUGH housing systems is described. Four samples of steel faced, paper honeycomb, sandwich panel material and four full size prototype roof panels were evaluated.

The samples of sandwich panel material were used to evaluate the variability of panel material properties and the effect of aging on tensile and shear strength. The roof panels were used to determine the behavior in service considering the effects of adverse environmental conditions on ultimate strength and mode of failure. In addition, the performance of one panel under sustained loading was evaluated.

Key Words: Accelerated aging; adhesive bond; ductility; flexural shear; housing systems; local buckling; material variability; moisture conditioning; Operation BREAKTHROUGH; paper honeycomb; structural sandwich; sustained load.

1.0 Introduction

1.1 Description of System.

A housing system (figure 1) proposed for the "Operation BREAKTHROUGH" program of the Department of Housing and Urban Development (sponsor) utilizes factory-produced sandwich panels for roof, floor and wall members. The wall and floor panels are attached to a steel grade-beam system as shown in figure 2. The floor panels are supported along the edges by the cold-formed steel grade beams and by joists spanning between the grade beams. All panels are 3-inches thick; the roof and wall panels consist of a 26-gage (.0179 in.) steel sheet bonded to each side of a resin-impregnated paper honeycomb core as shown in figure 3. The floor panels are similar except that the upper surface is 3/8 in. plywood. Urethane foam is pressed into the honeycomb prior to final assembly to improve thermal properties. Wood edge members are fastened around the perimeter of the panels.

Figure 1. Prototype House

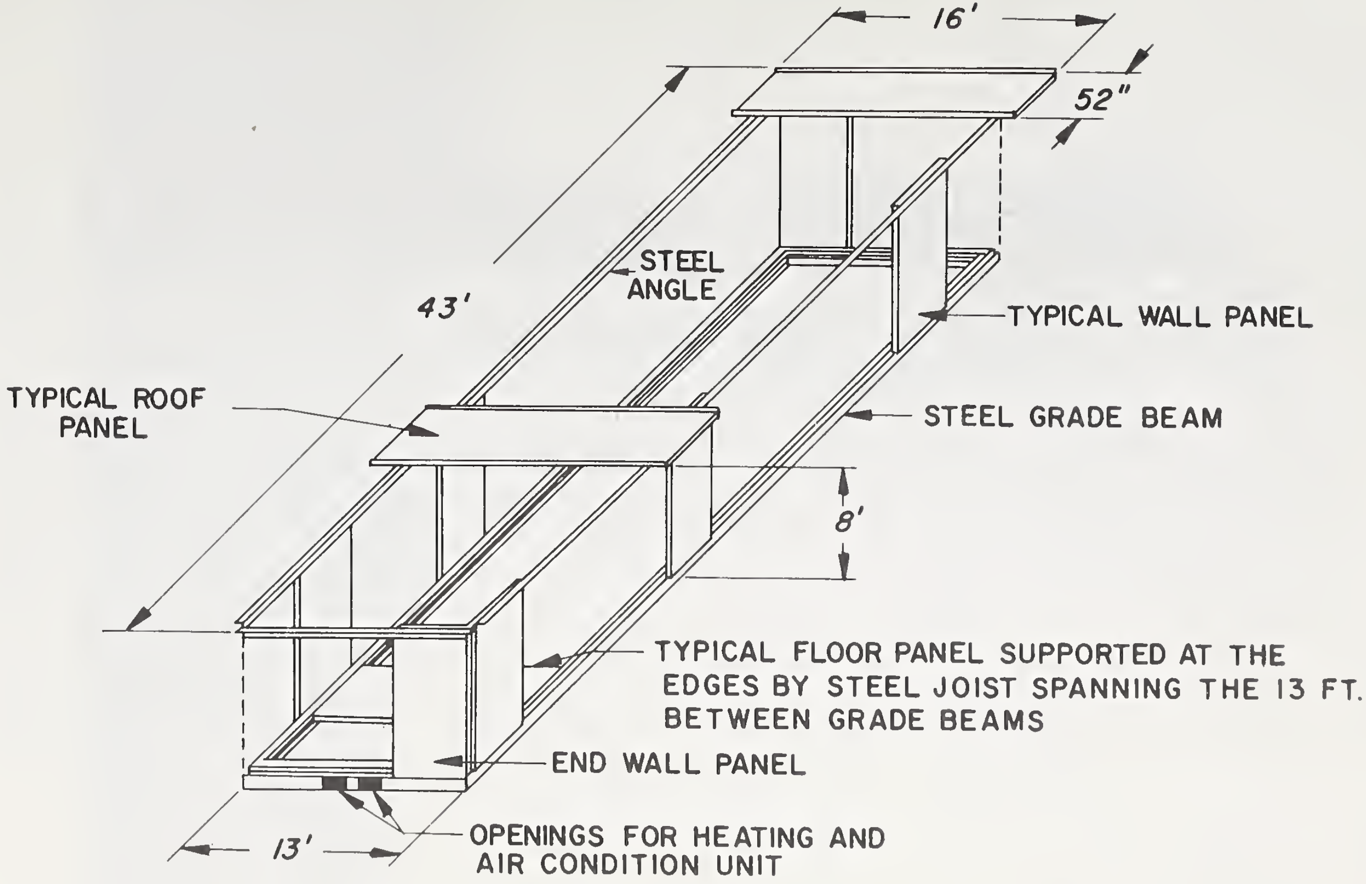


Figure 2. Structural Isometric of Housing System

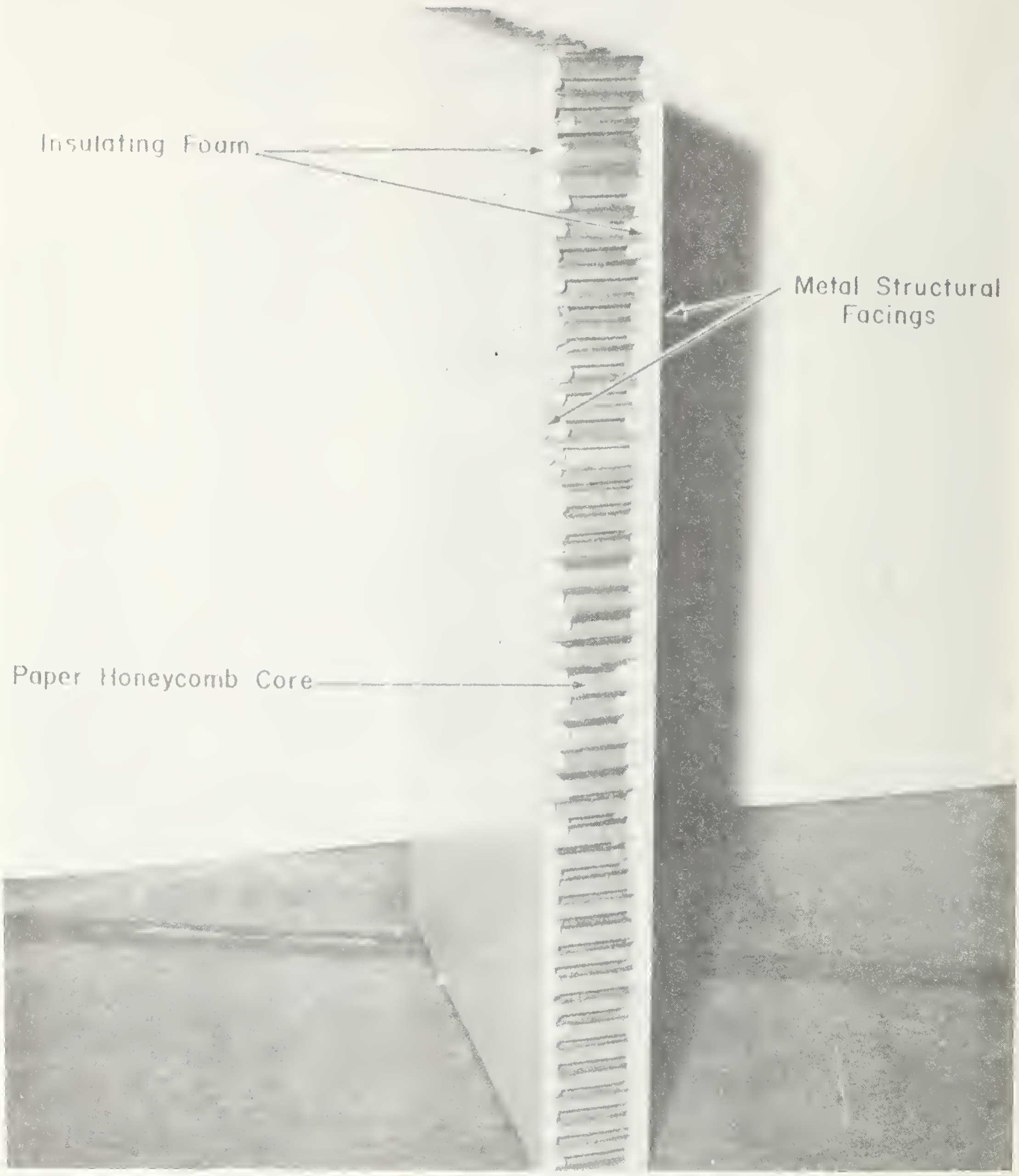


Figure 3. Section of Panel Material

1.2 Scope of Evaluation.

One phase of Operation BREAKTHROUGH is an evaluation of the structural adequacy of each proposed housing system. Two basic questions regarding structural performance must always be considered when evaluating each system. First, is it structurally safe; and second, will the structure perform adequately in service? This paper covers only the structural evaluation; however, other performance factors such as fire, acoustic, and thermal resistance have been evaluated.

An evaluation of the housing system showed the roof panel to be one of the critical elements in maintaining structural integrity during the life of the structure. The panels used on the roof are subjected to larger stresses than those used in the floors and walls. Also, the roof panels are more susceptible to weathering damage because no roofing material is applied to the roof, other than flashing and sealants at the panel joints and at the intersections with the wall panels.

The adhesive bond between the honeycomb core and the steel skins is important in maintaining both the load capacity (safety) and stiffness of the structural system (serviceability). Many adhesives that are exposed to environmental conditions, such as high humidities and elevated temperatures, are known to undergo deterioration resulting in decreased bond strength. This process is referred to as aging. The speed of the aging process is frequently dependent upon the severity of exposure conditions. To evaluate the effect of environmental conditions on the performance of the panel materials, small specimens were exposed to conditions more severe than those actually encountered in service on the premise that the more severe conditions would serve to accelerate the aging process. A description of these test procedures and the results are included in Chapter 2.

The flexural behavior of the roof panels was evaluated by testing to determine the effect of moisture conditioning on the structural performance of the panel. A description of these test procedures and the results are included in Chapter 3.

2.0 Panel Material Evaluation

2.1 Scope.

In evaluating the sandwich panel material it was assumed that, in service, moisture would accumulate within the panels and under certain conditions the temperature of the exterior facing of the roof panels would approach 180°F [1].[1/]

1/ Numbers in brackets indicate references listed at the end of this paper.

High humidities, in combination with high temperatures, are especially detrimental to adhesive bonds used in sandwich panels [2]. Therefore, evaluation of the panel material included a determination of the effect of moisture and high temperature on strength.

Four samples of panel material were evaluated. All samples were fabricated by the producer and were similar except for the adhesive and bonding procedure used in making the panels.

Sample A was a preliminary design bonded with a poly (vinyl acetate) adhesive. Test specimens were fabricated to the required size. Testing on this sample was not completed (See 2.3.1.1)

Sample B was a preliminary design bonded with a neoprene-phenolic contact adhesive. Test specimens were fabricated to the required size.

Sample C was cut with a fine-tooth band saw from a prototype roof panel which was bonded with an epoxy adhesive.

Sample D was a wall panel taken at random from the production line which was bonded with an epoxy adhesive. Test specimens were cut to size with a fine-tooth band saw.

The shear (parallel to the plane of the sandwich) and flat-wise tensile (normal to the plane of the sandwich) strengths of specimens taken from each sample were determined before and after accelerated aging.

2.2 Test Procedures

2.2.1 Flexural Shear Test.

The shear strength of the honeycomb cores was determined by ASTM C 393-62 [3] using quarter point loading. The test span (18-in) was chosen so that failure would be either by shear buckling of the core or by shear along the core-facing interface. The specimens for samples B, C, and D were 6 in wide x 23 in long. Figure 4 shows a typical test setup and a Sample A specimen following the test. The rate of loading was approximately one-third the expected maximum load per minute.

The shear strength values determined by this test method will be approximately those determined by other methods (for example, ASTM C 272). These values vary with test span, thickness of core and facings and other test variables. One such variable is the size and thickness of the plates used to distribute the loads into the specimen and to prevent local crushing

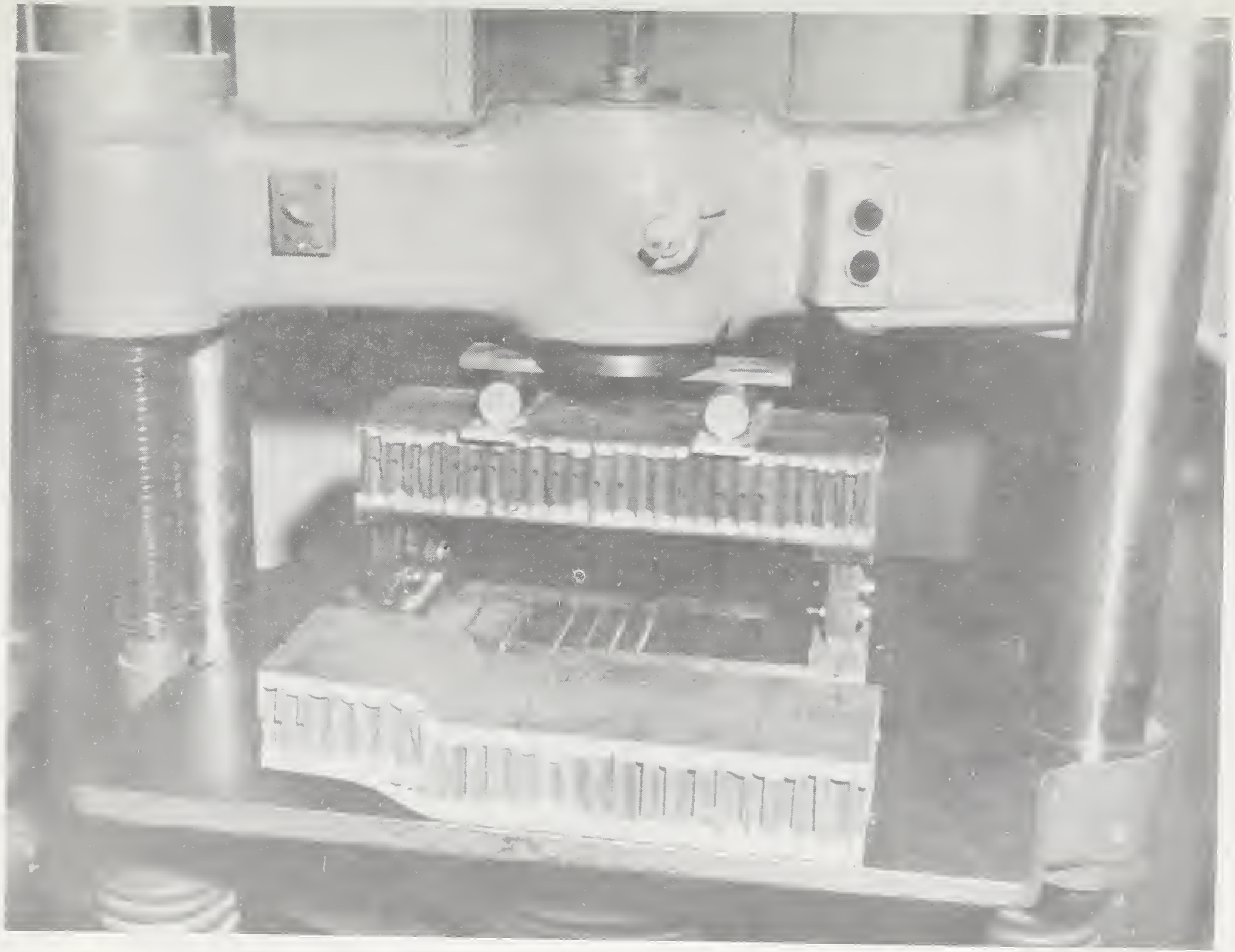


Figure 4. Flexural Shear Test

under the load points. The load distribution plates used in this test were 6 x 2 x 1/4 inches and the reaction plates were 6 x 2 x 1/2 inches and oriented as shown in figure 4.

2.2.2 Flatwise Tensile Test.

The test method of ASTM C 297-61 [3] was used to determine the flatwise tensile strength of the panel material. The 4 in x 4 in specimens were tested as shown in figure 5. The steel loading blocks (2 in thick) were bonded to the specimen with a hot-melt adhesive.[2/] The pull rods were connected to the hydraulic testing machine through spherical seats. The loading rate was approximately one-third of the expected maximum load per minute.

The purpose of this test is to determine the tensile strength of the weakest link in the sandwich. Thus, the core will fail if the tensile strength of the core is less than the tensile strength of the adhesive bond.

The purpose of this study was to determine the mode of failure as well as the strength values before and after accelerated aging.

2.2.3 Conditioning and Aging of Specimens.

All specimens were tested after being brought to equilibrium with laboratory conditions (73° ± 3°F and 50 ± 3% rh). Half of the specimens from each sample were stored in the laboratory until tested while the other half were artificially aged using the standard procedure of ASTM C 481-62, Cycle A [3] before testing.

This procedure consists of 6 repetitive cycles of warm water soaking, steam spraying, freezing and dry-heating. Although, this arbitrary procedure is widely used in evaluating sandwich materials there is as yet no acceptable correlation with natural aging.

2.3 Test Results

2.3.1 Accelerated Aging (ASTM C 481).

Specimen appearance after the aging procedure was noted with significant observations as follows:

2/ This adhesive had enough fluidity at approximately 325°F for this bonding operation. This temperature did not degrade the adhesive used in producing the panels.

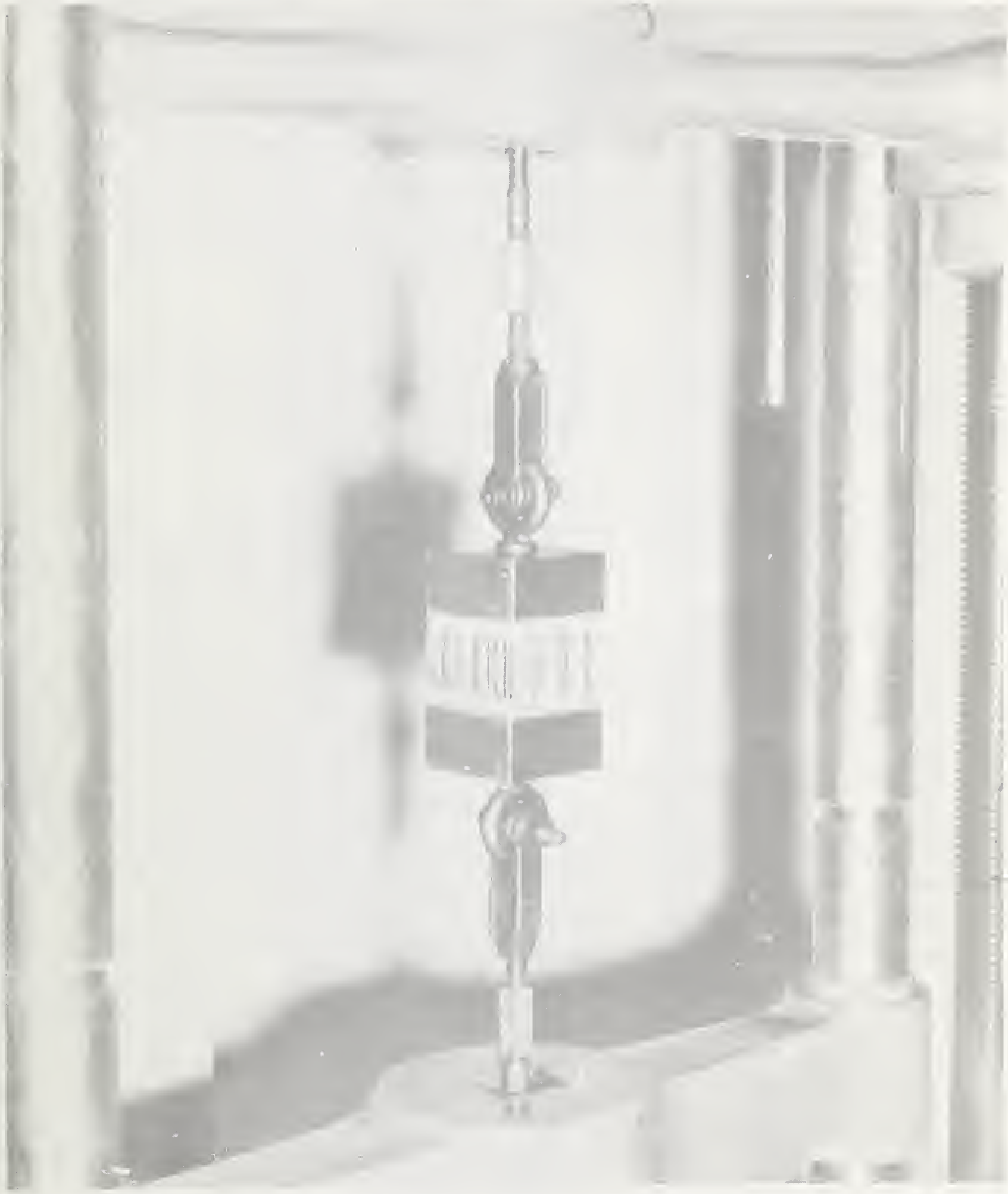


Figure 5. Flatwise Tensile Test

2.3.1.1 Sample A.

The first step of the aging procedure was to immerse the specimens in warm water (120°F) for one hour. At the end of this step all specimens from Sample A were showing signs of delamination. Most specimens had at least one facing completely delaminated from the core. Figure 6 is a picture of a flexural-shear specimen (6 in x 23 in) after water soaking. The stresses set up in the core from the moisture expansion were sufficient to completely separate the facings from the core. Note, in this photograph, that the core had expanded until it was about 1 in longer than the facing. Sample A material was rejected and testing terminated because the adhesive was water soluble.

2.3.1.2 Samples B, C, and D.

The accelerated aging procedure darkened the color of the paper honeycomb, but no other significant changes were observed.

2.3.2 Flexural Shear Test Results (ASTM C 393).

The results of the shear tests are presented in table 1. The core in the sandwich panels is oriented (see figure 7) so that the core shear strength in the "W" direction is the critical parameter. [The paper ribbons of the core run perpendicular to the span of the panel]

The shear strengths and the relationship between the strengths in the "W" direction and the "L" direction depend to a large extent on the shape of the honeycomb cells. If the core is 100 percent expanded in the sandwich, the cell shape is a true hexagon and the "W"/"L" shear strength ratio would be approximately 0.6. Most paper honeycomb sandwich cores are either over or under expanded and the expansion usually varies within a panel. Thus, some variability of core strength values should be expected when testing small specimens cut from the same panel.

The primary interest in this evaluation was in the "W" direction shear values and in the effect of the aging on these values. It can be seen from the data in table 1 that the shear strength of the unaged core in the "W" direction varied from 20.9 to 28.9 psi and that the aging reduces this strength 18 to 20 percent.

All the flexural shear specimens failed by shear buckling of the core indicating that the strength of the adhesive bond was sufficient to develop the shear capacity of the core. (See figure 4)

2.3.3 Tensile Test Results (ASTM C 297).

The tensile test results presented in table 2 show a wide variance in the tensile strength values between samples and, in the case of Sample C,

Figure 6. Sample A Specimen Following 1-Hour Soak in 120°F Water

Table 1. Flexural Shear Test Results[1]

Sample	Specimen	Shear Strength, "L" Direction[2]		Shear Strength, "W" Direction[3]	
		Aged Specimens psi	Unaged Specimens psi	Aged Specimens	Unaged Specimens psi
B	1	---	---	22.1	27.1
	2	---	---	23.3	28.9
	3	---	---	22.8	28.7
	Avg.	---	---	22.7	28.3
C	1	38.2	37.3	17.9	23.8
	2	38.4	42.8	20.5	23.5
	3	37.9	43.1	21.0	24.9
	4	36.5	---	---	---
	Avg.	37.7	41.1	19.7	24.1
D	1	---	30.6	---	20.9
	2	---	31.6	---	25.7
	3	---	32.6	---	23.5
	Avg.	---	31.6	---	23.4

1 All specimens failed by shear buckling of honeycomb core.

2 "L" direction indicates that the paper ribbons of the core ran parallel to the length of the specimen.

3 "W" direction indicates that the paper ribbons of the core ran perpendicular to the length of the specimen.

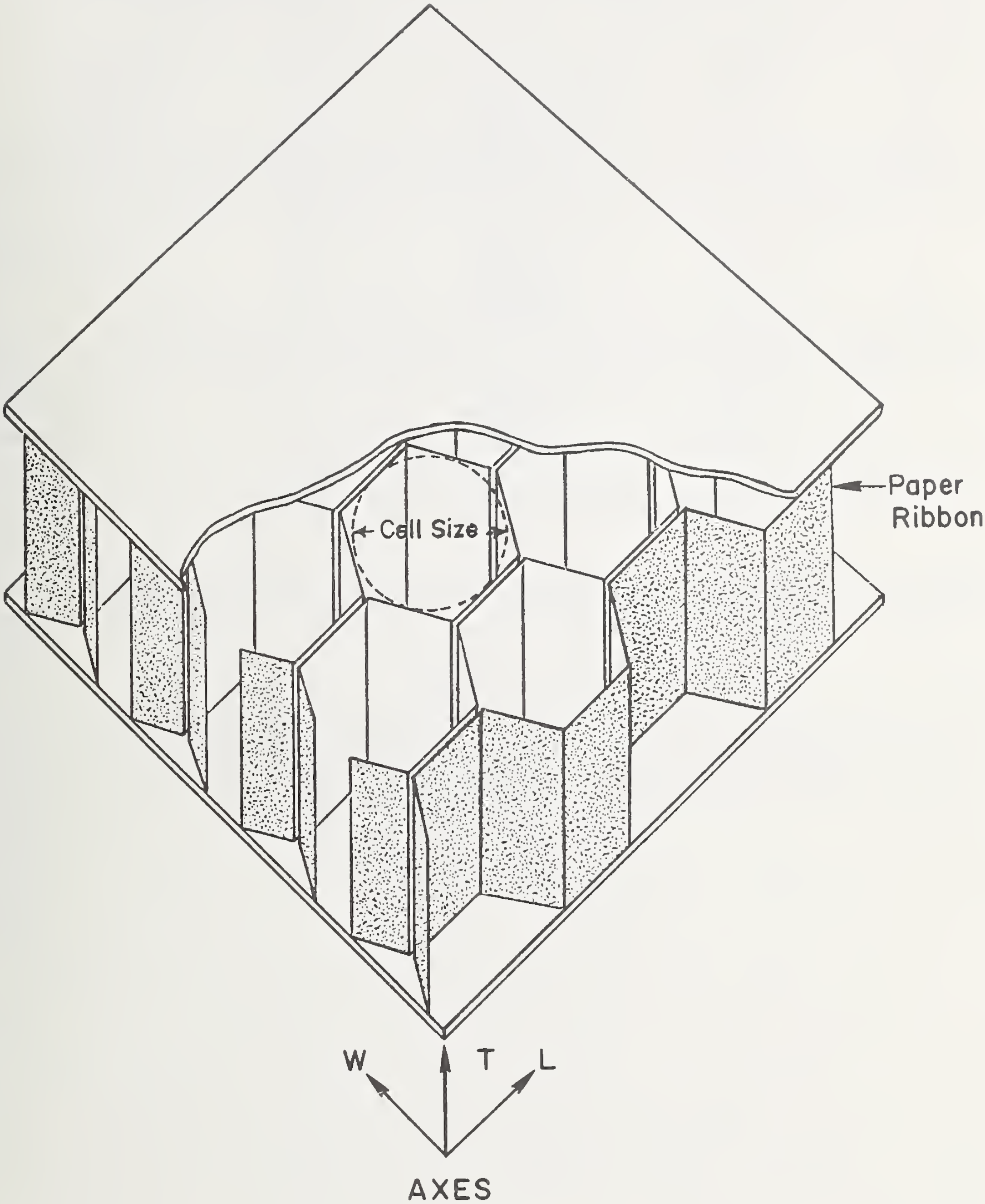


Figure 7. Hexagonal Honeycomb Orientation

Table 2. Tensile Test Results

Sample	Specimen	Aged Specimens Tensile Strength psi	Aged Specimens Failure Mode[1]	Unaged Specimens Tensile Strength psi	Unaged Specimens Failure Mode[1]
B	1	32.2	100% Bond	31.5	100% Bond
	2	26.0	100% Bond	33.8	100% Bond
	3[2]	32.6	100% Bond	33.5	100% Bond
	4[2]	31.4	100% Bond	28.0	100% Bond
	5[2]	31.6	100% Bond	27.0	100% Bond
	Average	31.0		31.0	
C	1	9.1[3]	90% Bond	50.0	5% Bond
	2	10.0[3]	75% Bond	74.7	5% Bond
	3	22.5[3]	40% Bond	54.0	5% Bond
	4[2]	33.4	10% Bond	---	
	5[2]	37.1	1% Bond	---	
	Average	22.4		59.6	
D	1	22.6	35% Bond	36.3	0% Bond
	2	23.0	50% Bond	26.3	0% Bond
	3	28.3	65% Bond	38.8	0% Bond
	4	23.1	50% Bond	46.3	0% Bond
	5	39.7	60% Bond	31.6	0% Bond
	Average	27.3		35.9	

[1]Failures were classified as either bond or core failures. Bond failure generally was at the primer-bonderized steel interface except for Sample B specimens where the adhesive failed cohesively.

[2]Specimen cut from flexural shear specimen.

[3]Specimen was cut from an area of the panel where there had been relative movement between the core and one facing during fabrication. This movement had "squeegeed" the adhesive so that certain areas were starved for adhesive. (See Fig. 8)

within the sample. Observations made following each test helped in explaining this variance.

These observations as well as the strength data indicated that the specimens of Sample C were different from those of Sample D. Essentially, failure occurred in the core of all unaged specimens from both samples. However, observations indicated that the adhesive for Sample D was bonded mostly to fibers on the edges of the paper core (resulting from surface sanding of core) rather than to the solid portion of the paper as it was for Sample C. It can be concluded that the actual tensile strength of the dry, unaged core is probably at least 50 psi. However, because of the fabrication practice the tensile strength should be considered to be no more than 35 psi.

There is insufficient data to properly judge the effect of the aging on the tensile strength of the core. However, from a comparison of the Sample C data for aged specimens 4 and 5 with the unaged specimens, it appears that the aging may reduce the tensile strength by as much as 40 percent. A comparison of the Sample D data for the aged with the unaged specimens indicate a reduction of only 24 percent in bond strength.

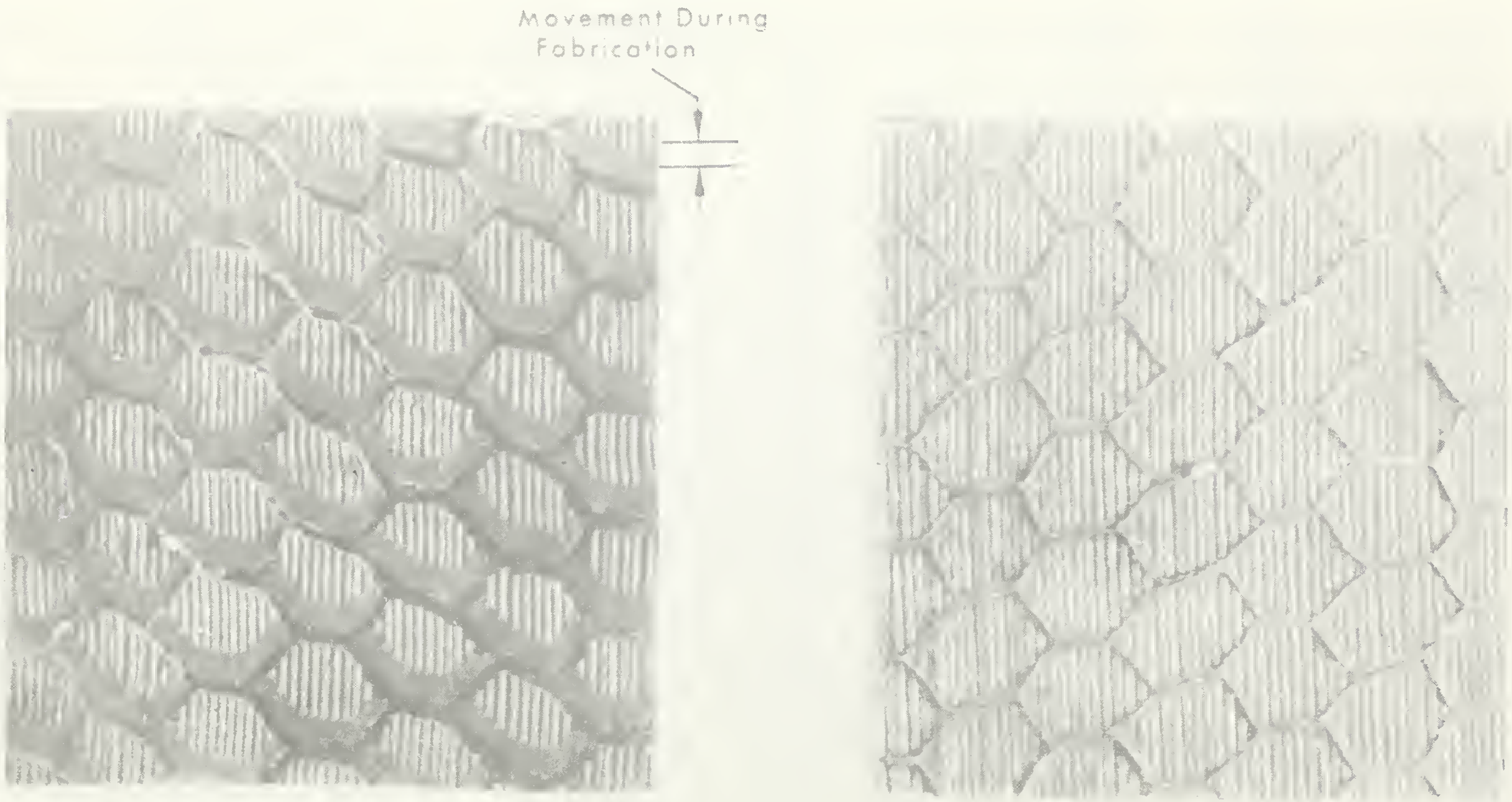
The data indicate that the aging had little if any effect on the tensile strength of the adhesive (neoprene-phenolic) of Sample B. It is also noted that the bond strength of the adhesive of Samples C and D is greater than that for Sample B. However, the strength of the adhesive bond after aging was less for Sample C and D than for B.

Observations made on the Sample C specimens after the tensile tests emphasize the effect that fabrication techniques can have on the test results. Aged specimens No. 1, 2 and 3 of Sample C had been taken from an area of the panel where there had been a relative movement between one facing and the core during mating. This movement, which can be seen in figure 8, "squeegeed" the adhesive in front of the cell edges so that the areas behind the edges were starved for adhesive. The data for these three specimens indicate a greatly reduced bond strength as a result of this movement during fabrication.

Most bond failures for Samples C and D occurred at the interface of the steel facing and a primer which had been applied prior to application of the adhesive. Since significant bond failures occurred only on the aged specimens it seems reasonable to assume that the durability of the primer bond to the steel is the weak link in the system and not the adhesive. However, it would appear from the low results for the "squeegeed" aged specimens 1, 2 and 3 of Sample C that the adhesive does furnish some protection for the primer.

3.0 Structural Testing of Full Size Roof Panels

The reliability of the procedure for predicting the structural behavior for the type of construction in the roof panel was not known. Consequently,



Aged by ASTM C-481
Mostly Bond Failure

Aged in Laboratory Air
Mostly Core Failure

Figure 8. Facings From Sample C Specimens Following Tensile Test

a testing program was undertaken to verify structural performance. Various moisture conditioning procedures were used to simulate in-service conditions since the panel may be susceptible to water penetration during service life. Four full-size, prototype production panels were obtained from the producer and three were subjected to short-term load testing and one to a 24-hour sustained load test.

3.1 Description of Moisture Conditioning Procedures.

Each of the three short-term test panels was moisture conditioned by a different procedure before being subjected to the flexural tests. The three procedures were:

1. 50% relative humidity at 73 ± 3°F for five days.
2. 95% relative humidity at 73 ± 3°F for five days by storage in a fogroom with the panel draped with a plastic film to prevent the deposition of liquid water.
3. Complete submersion in a water bath at 73 ± 3°F for 7 days and a subsequent 9 day drying period, under procedure 1 conditions and without forced air.

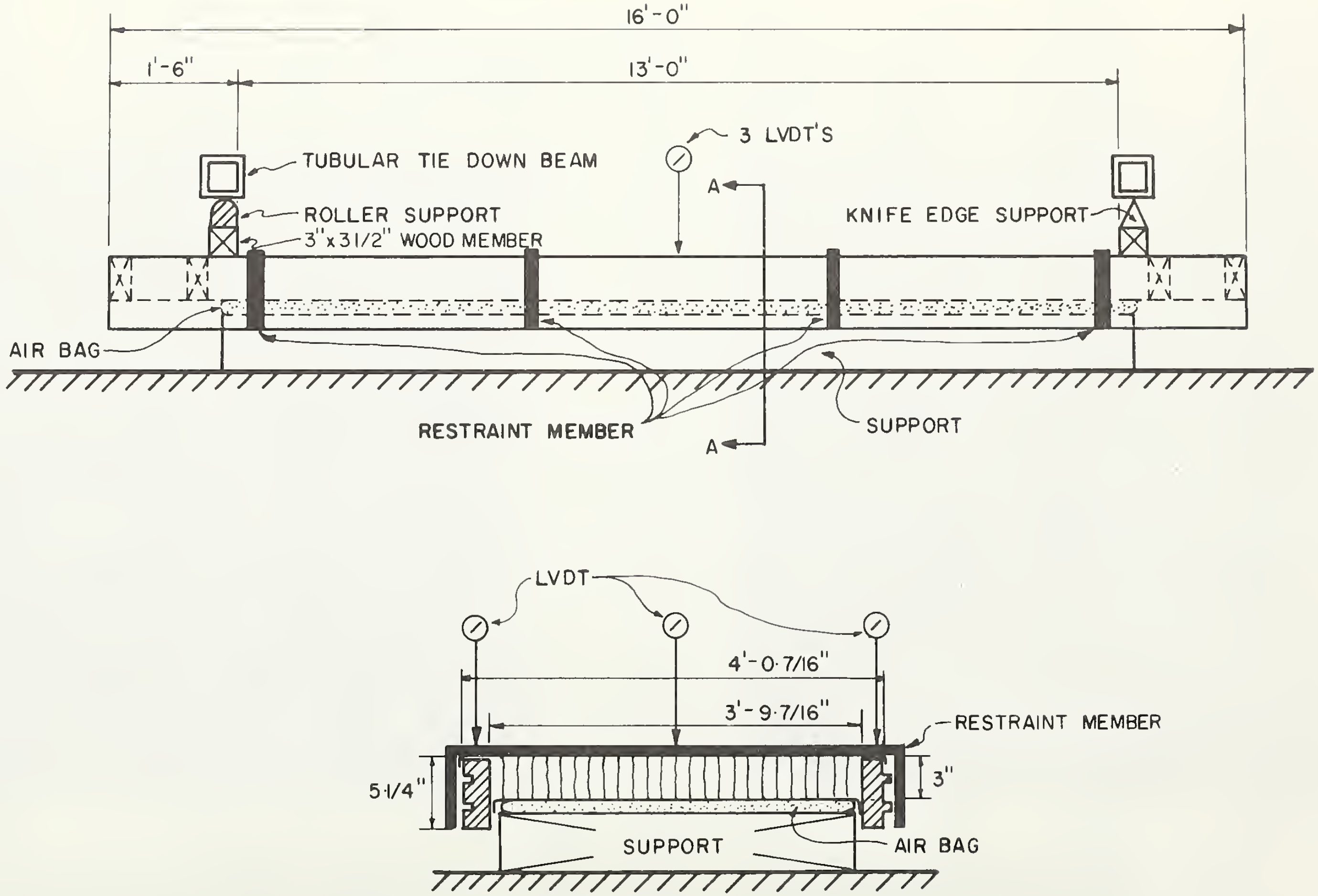
The fourth roof panel for the 24-hour sustained load test was conditioned using procedure 1.

3.2 Description of Test Setups.

3.2.1 Short-Term Flexural Test.

The roof panel was tested in the horizontal inverted[3/] position with an air bag sandwiched between it and a wood support placed on the laboratory floor as shown in figures 9 and 10. The support members were 3 in x 3 1/2 in wood blocks to simulate the actual wall support condition. The overall panel length was 16 ft 0 in and inside-to-inside dimension of the supports was 13 ft 0 in. The specimen supports were square tubular tie down beams with a roller at one end and a knife edge at the other. Four steel bracing members were placed between supports in an attempt to simulate lateral restraint provided by adjacent panels to the edge members in a completed roof structure.

[3/] Normal position refers to panel orientation in service. Inverted position refers to panel turned upside down.



SECTION A-A

Figure 9. Schematic of Test Setup for Short-Term Flexural Tests on Full-Size Roof Panels

Figure 10. Short-Term Flexural Test on Full-Size Roof Panel

Three linear variable differential transformers (LVDT) were placed at midspan to record vertical movement with one over each edge beam and one at the centerline of the specimen. X-Y recorders plotted air bag pressure versus midspan deflection.

3.2.2 Twenty-Four Hour Sustained Load Test.

The roof panel was tested in the normal position with sand bags applied between supports as shown in figures 11 and 12. The overall panel length was 16 ft 0 in and inside-to-inside dimension of the support was 13 ft 0 in. A single deflectometer was placed at centerline of midspan to record vertical movement.

3.3 Description of Test Procedure.

All loads discussed under testing are equivalent applied loads. For the short term tests where the panels are tested in the inverted position, the equivalent applied load is determined by taking the applied air bag load minus twice the panel weight minus the weight of the loading apparatus. The equivalent applied load for the 24-hour sustained load test is the actual load since the panel was tested in the normal position.

3.3.1 Short-Term Flexural Tests.

For each of the three short-term tests a preload of 20 psf was applied to the panel and then removed in order to seat the specimen in the test fixture. Load was then applied in 5 psf increments to 30 psf and then removed. Load was then applied in 5 psf increments to failure. Deflection readings were taken at each increment.

3.3.2 Twenty-Four Hour Sustained Load Test.

Sand bags were distributed uniformly between panel supports to provide a load of 45.7 psf (0.2 DEAD + 1.5 LIVE). Load was maintained for 24 hours and removed. Deflections were periodically recorded during the 24 hour period, immediately after load removal, and 24 hours thereafter.

3.4 Test Results - Short Term Flexural Tests.

3.4.1 Panel Conditioned by Procedure 1.

This panel failed at an equivalent applied load of 135 psf with elastic load-deflection behavior up to failure. The specimen was then unable to sustain any significant load. Figure 13 shows the load-deflection history of the midspan LVDT's located at a side beam and at the centerline. Failure occurred by local buckling (wrinkling) of the compressive facing in a straight line transversely across the panel approximately six inches from, and parallel to, a splice in the honeycomb core (see figure 14).

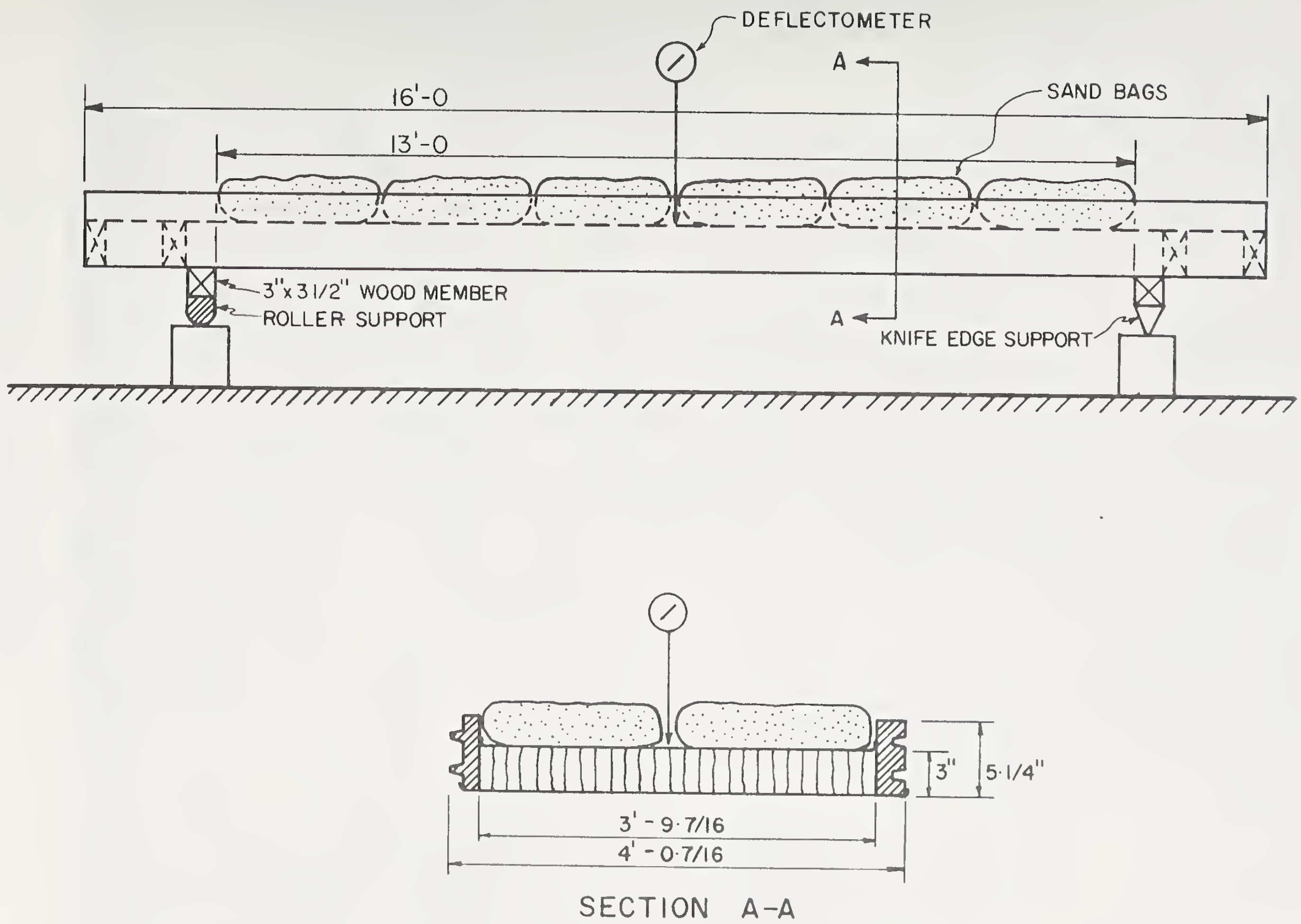


Figure 11. Schematic of Sustained-Load Test on Full-Size Roof Panel

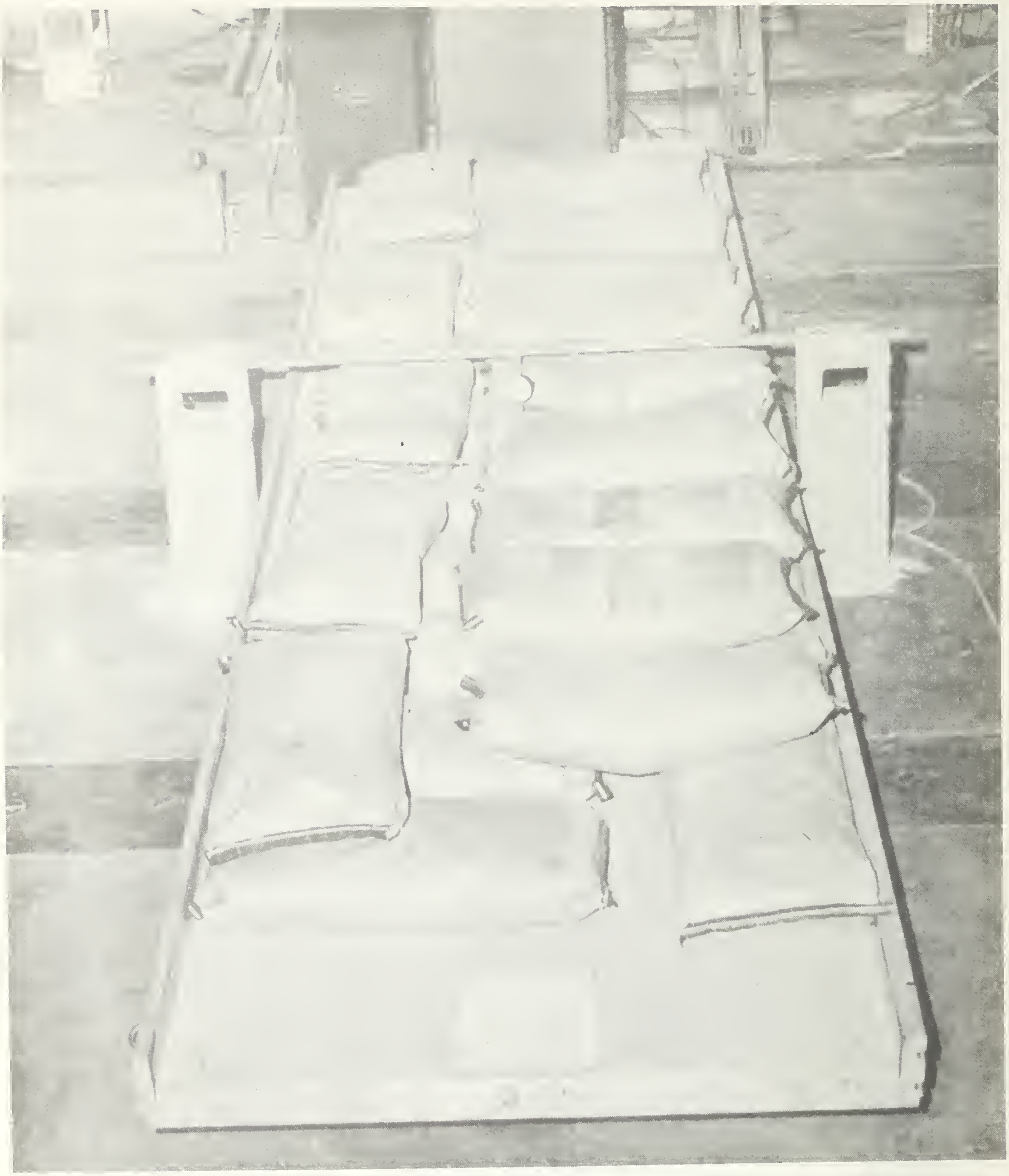


Figure 12. Sustained Load on Full-Size Roof Panel

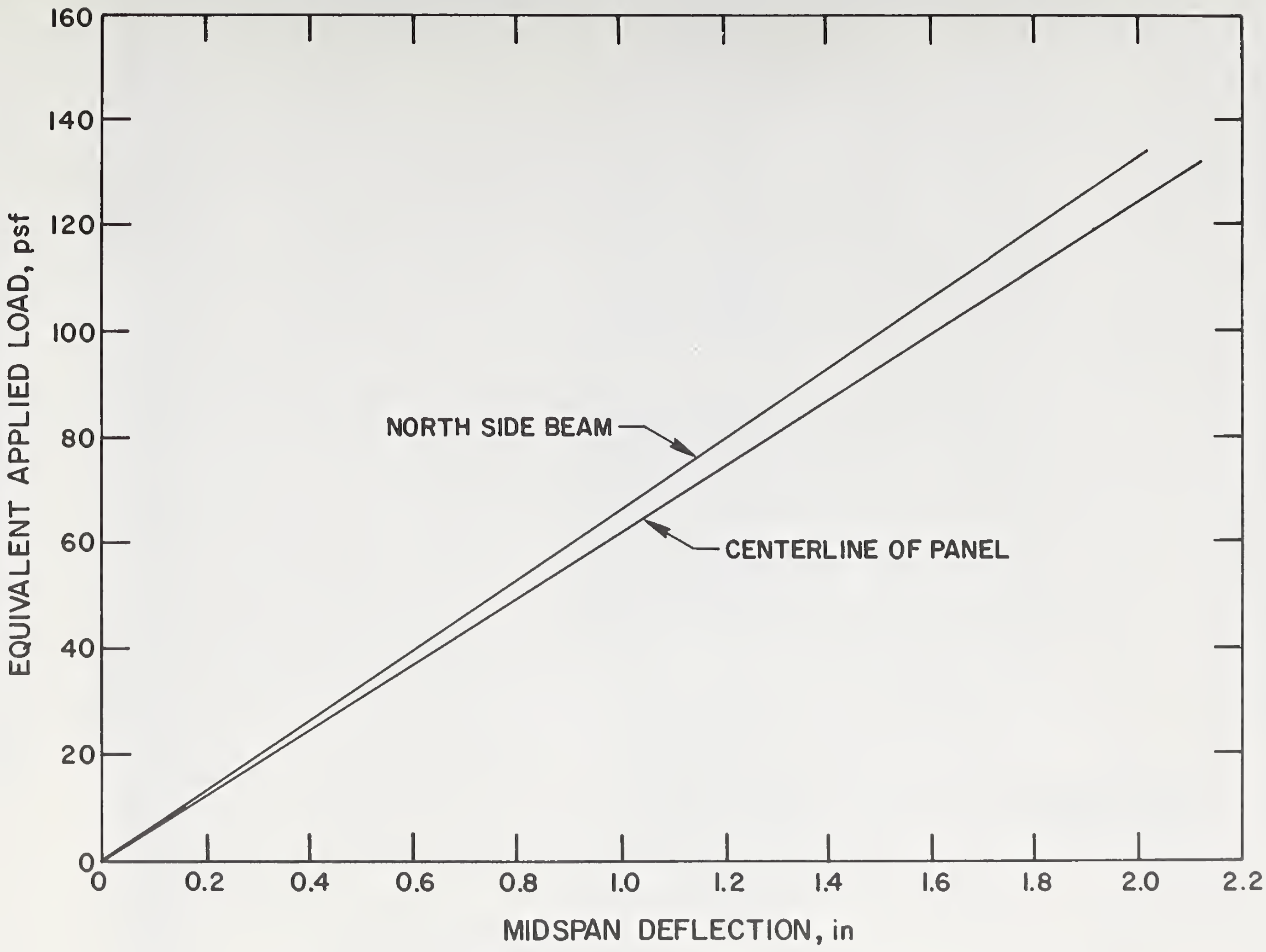


Figure 13. Short-Term Flexural Results on Specimen Conditioned by Procedure 1

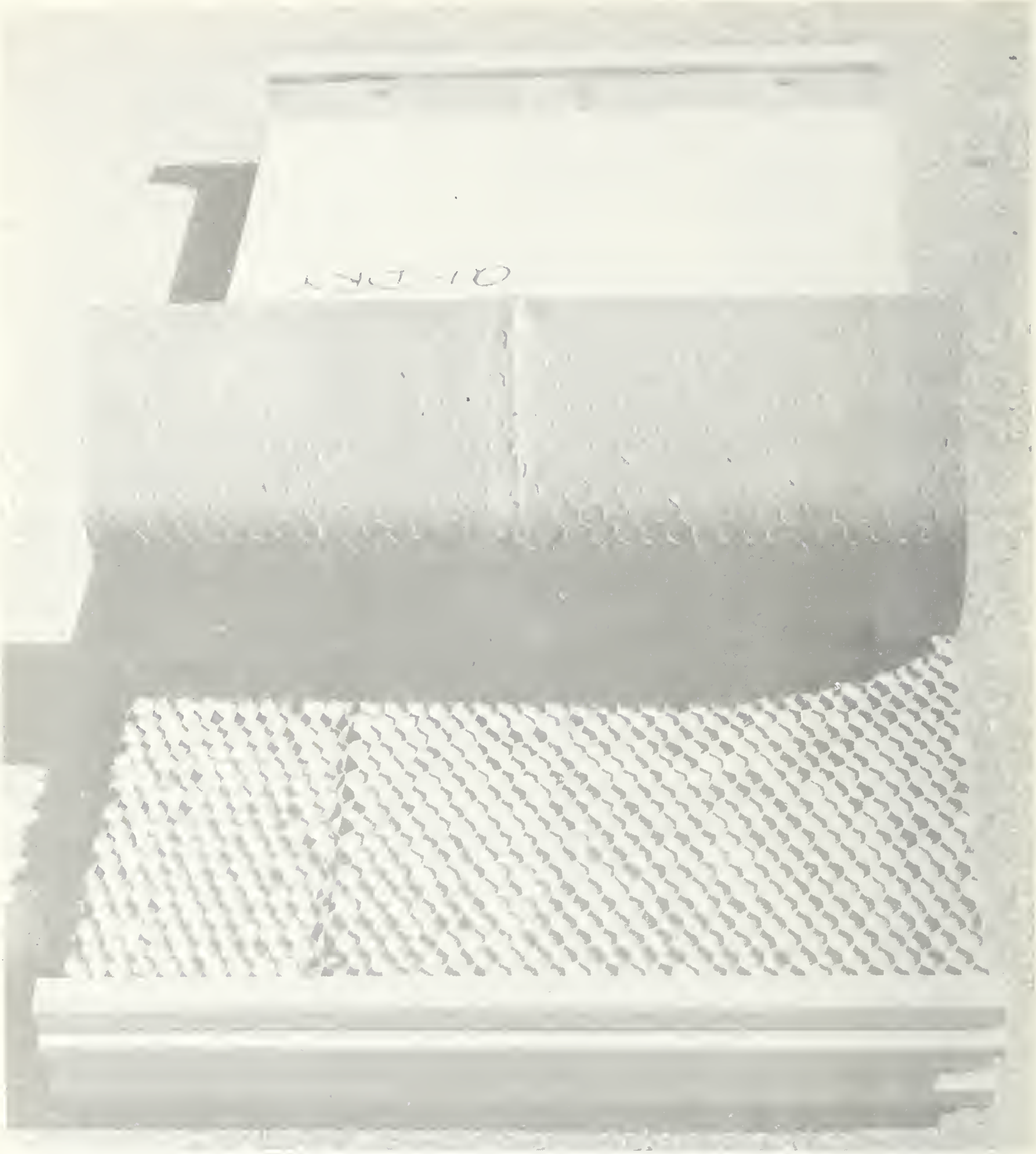


Figure 14. Portion of Short-Term Flexural Specimen Conditioned by Procedure 1 Showing Buckling of Compressive Facing

3.4.2 Panel Conditioned by Procedure 2.

This panel failed at an equivalent applied load of 155 psf with elastic load-deflection behavior up to failure. The specimen was then unable to sustain any significant load. Figure 15 shows the load-deflection history of the midspan LVDT's located at the side beam and at the centerline. Comparison of figures 13 and 15 indicate an inconsistency in relative movements of the north side beams and the panel centerlines. However, this is not unexpected since the panels are not exactly symmetrical (see difference in edge members in figure 9). Because they are not symmetrical, the panels will warp slightly under uniform load. Failure occurred by local buckling of the compressive facing in a straight line transversely across the panel at, and parallel to, a splice in the honeycomb core (see figure 16).

3.4.3 Panel Conditioned by Procedure 3 (Soaked).

The panel behaved elastically up to an equivalent applied load of 80 psf when a sudden drop in load occurred (see figure 17). This was believed to be caused by readjustment of the air bag and with a slight increase in effective loaded area. The panel was again able to take load linearly with respect to deflection.

Failure occurred at an equivalent applied load of 104 psf and was apparently initiated by fracture at a knot in the edge member as is shown in figure 18. This was followed almost immediately by a local buckling of the compressive facing and a complete loss of load carrying capability. The buckling occurred in a straight line transversely across the panel at, and parallel to, a splice in the honeycomb core as shown in figure 19.

Water had entered the panel during the soaking period at the wood edge members and traveled along the honeycomb sheet edges and splices. The panel weighed 207 pounds before placing in the water and 240 pounds on the day of test. The panel was taken apart after the test and the moisture content was determined on portions of the material taken from an area which appeared to be the dampest portion of the panel. This area was at the intersection of the edge member and core splice. The moisture contents, listed below, are based on oven-dry (220°F) weights.

Foam Insulation	129%
Honeycomb Core	41%
White Fir Edge Beam	24%

Inadequate adhesive bonding between the honeycomb and steel facings to the right of the core splice is evident in figure 19. It apparently was caused by a difference in the thickness of the two adjacent core pieces.

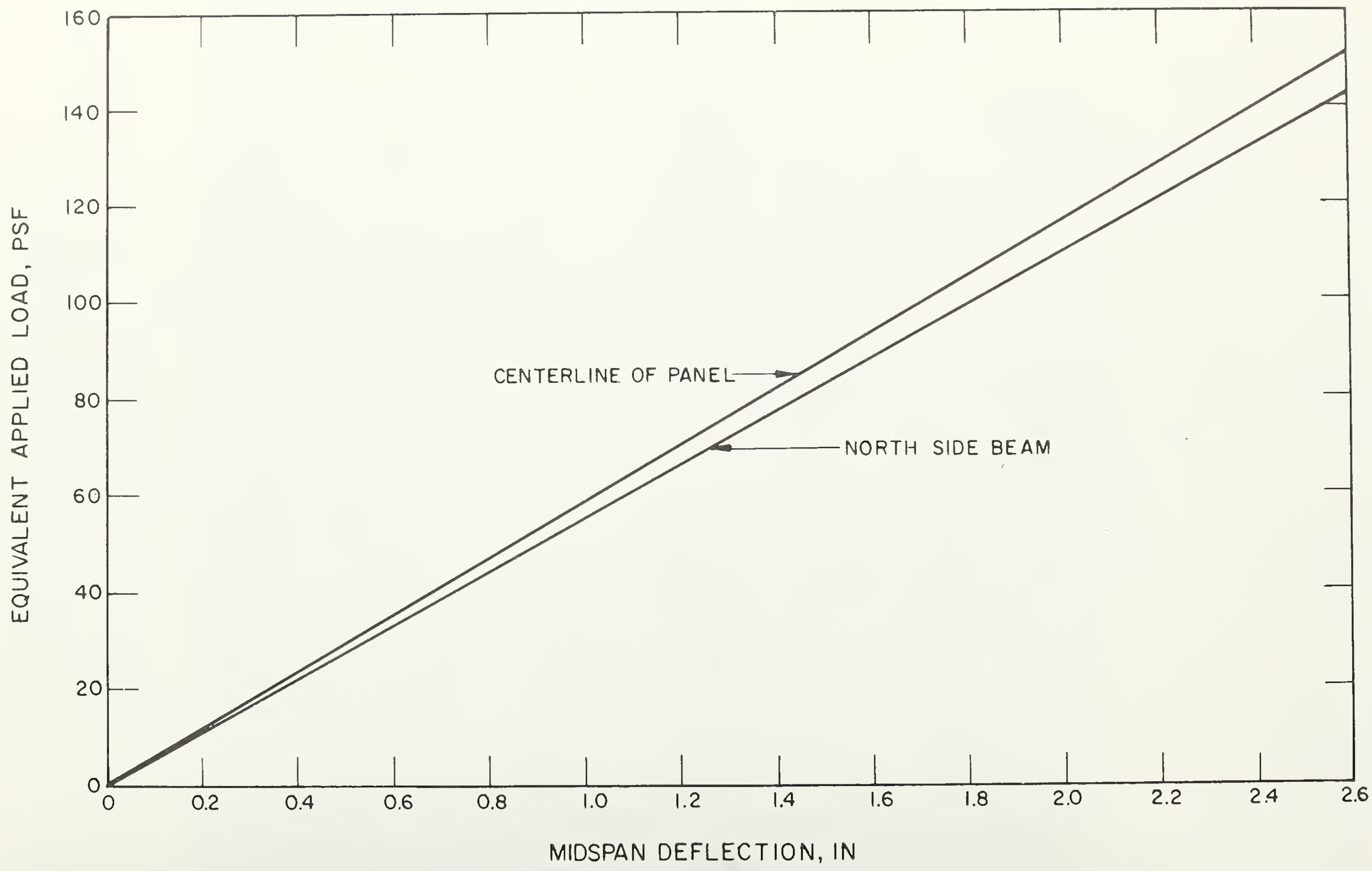


Figure 15. Short-Term Flexural Test Results on Specimens Conditioned by Procedure 2

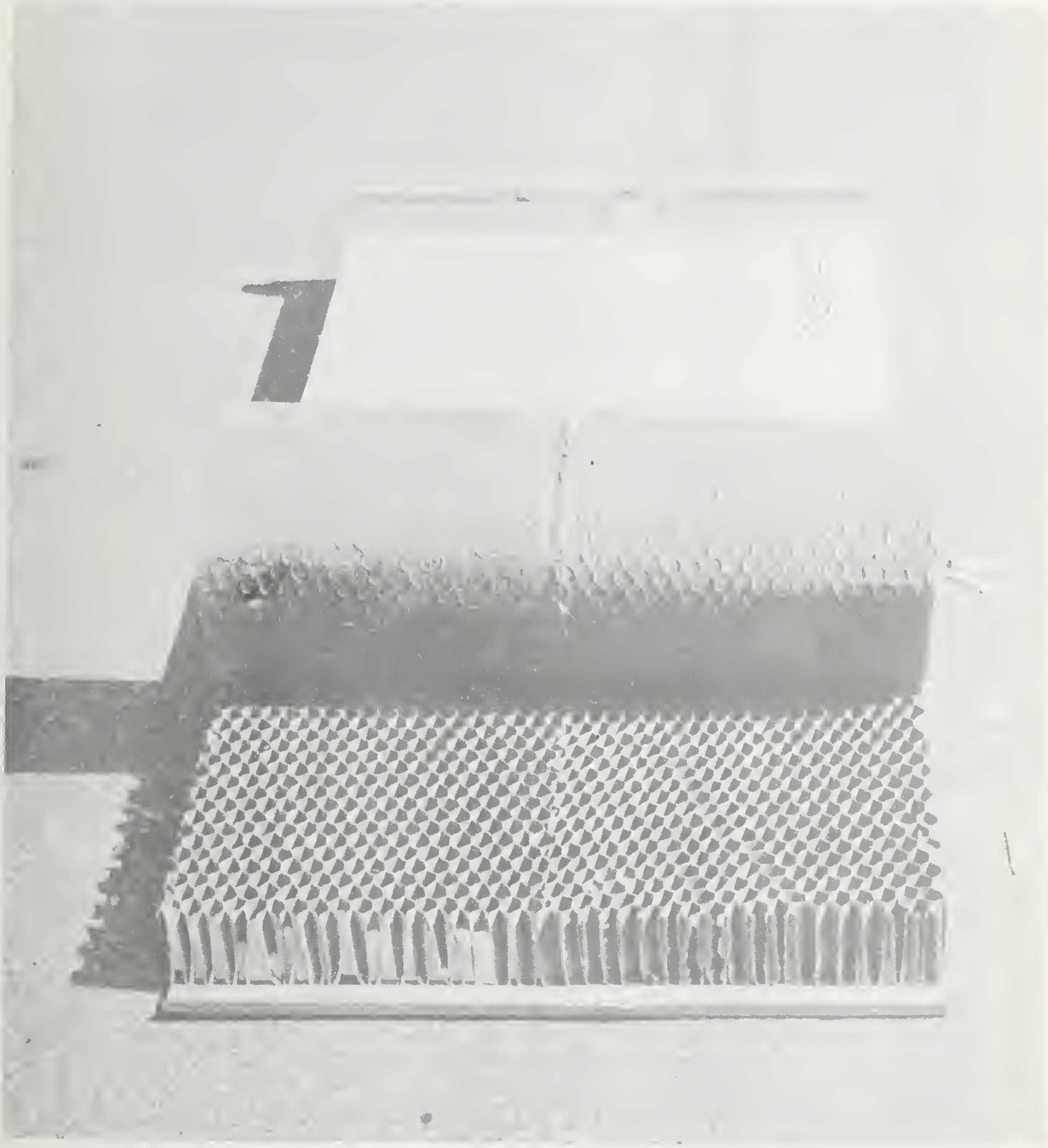


Figure 16. Portion of Short-Term Flexural Specimen Conditioned by Procedure 2 Showing Buckling of Compressive Facing

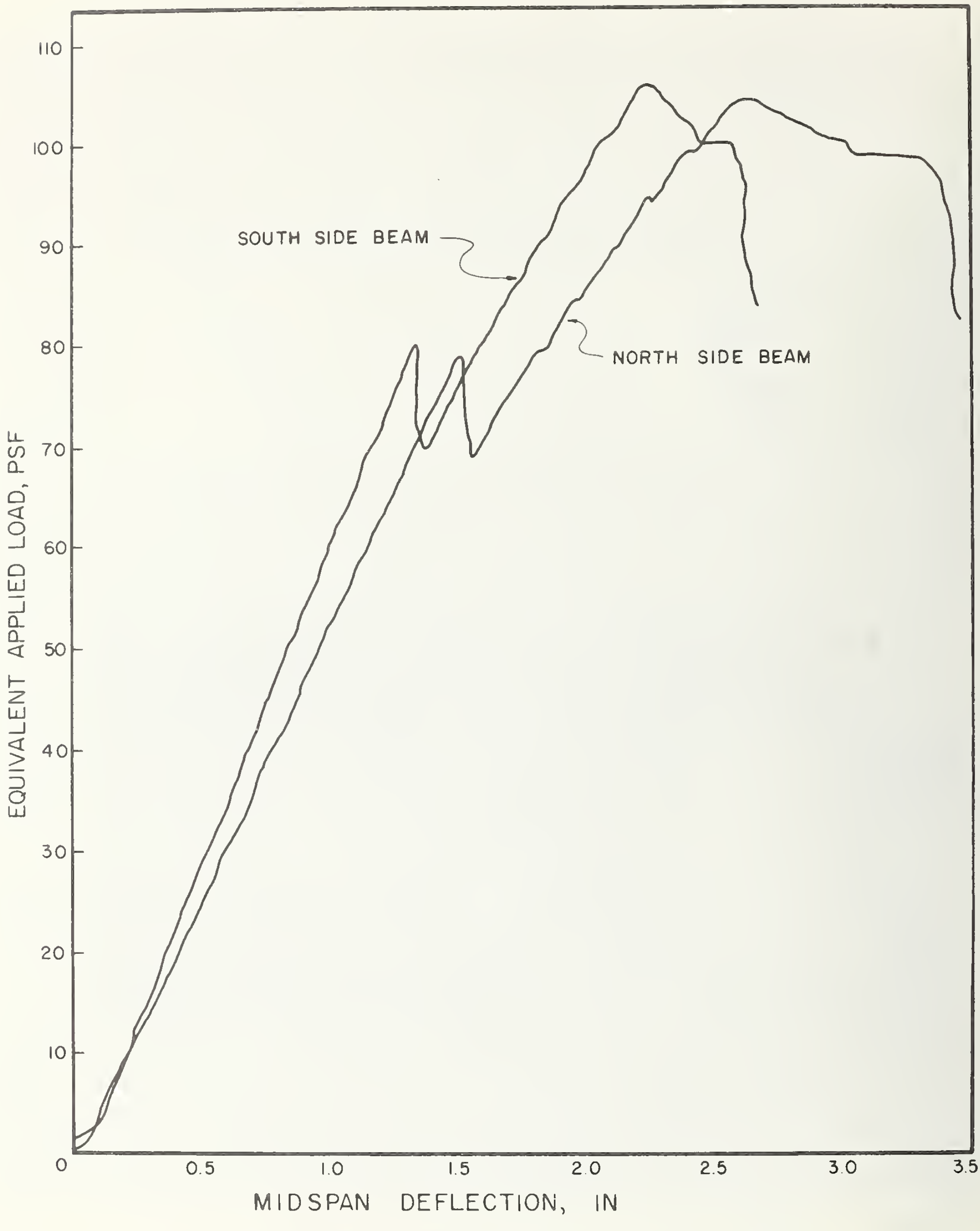


Figure 17. Short-Term Flexural Test Results on Specimen Conditioned by Procedure 3.

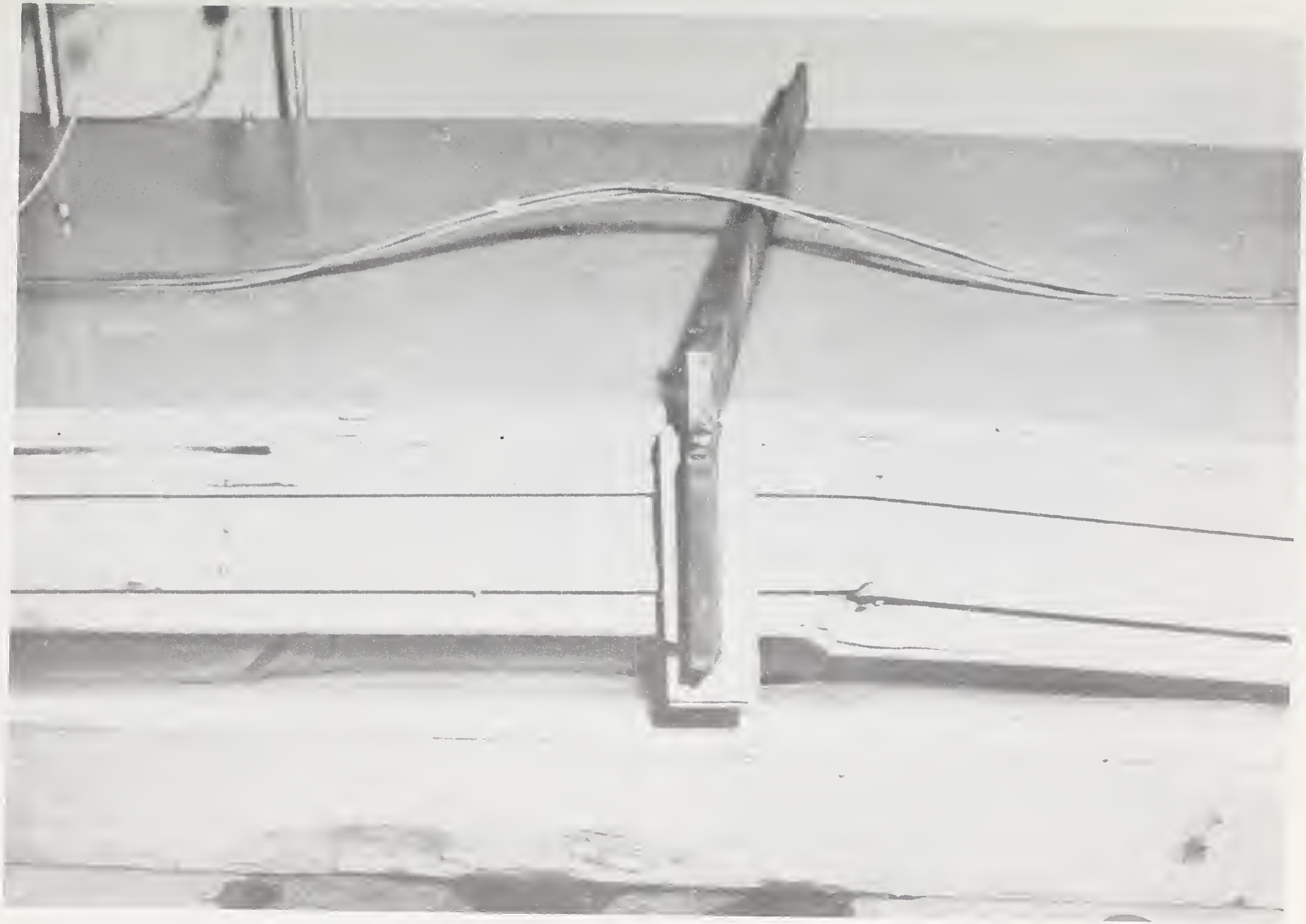


Figure 18. Short-Term Flexural Test Specimen Conditioned by Procedure 3 Showing Initial Failure at Knot in Edge Member

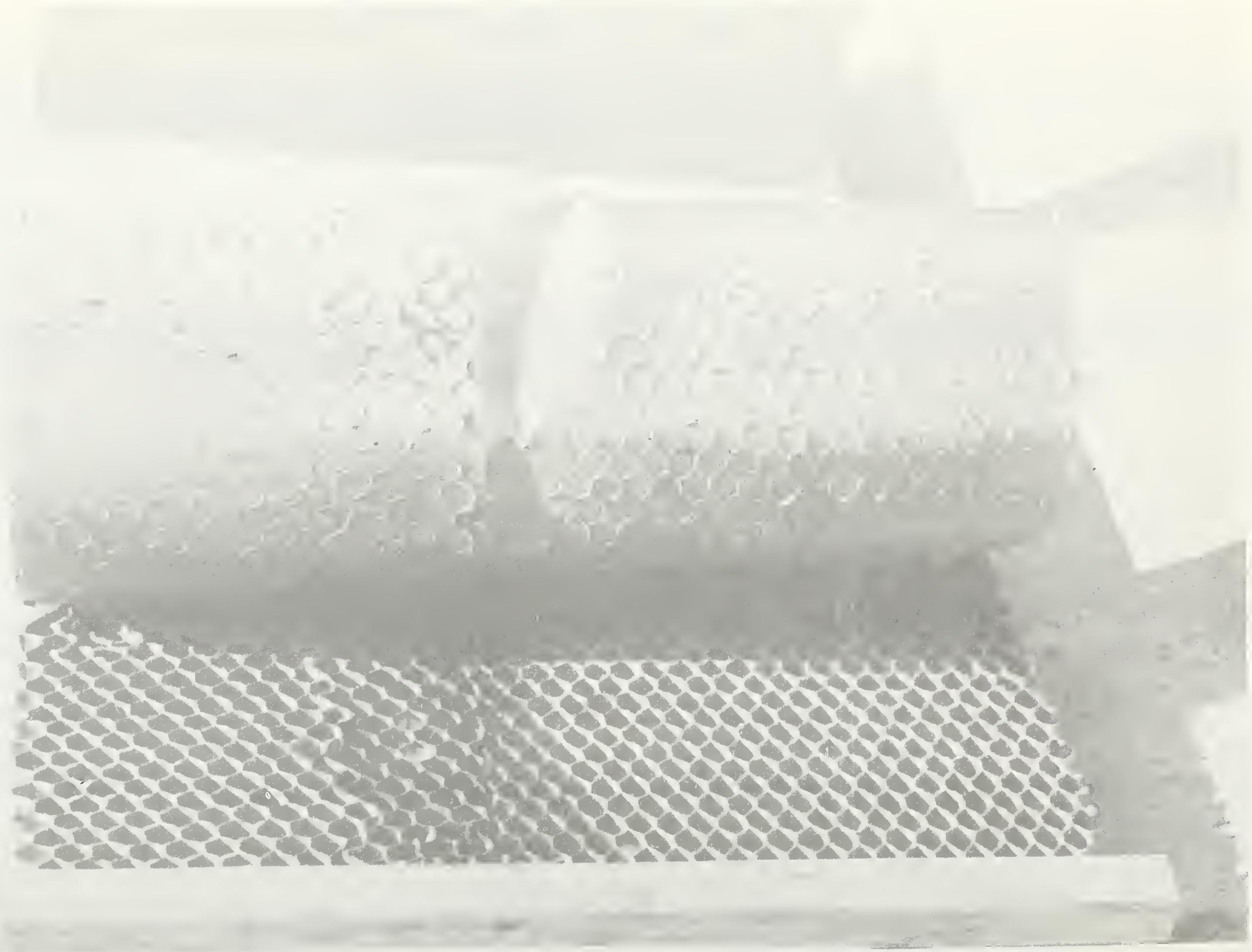


Figure 19. Portion of Short-Term Flexural Specimen Conditioned by Procedure 3 showing Buckling of Compressive Facing

3.5 Test Results - Twenty-Four Hour Sustained Load Test.

A uniform load of 45.7 psf (0.2D + 5L) was applied to the panel with sand bags (D = 3.5 psf; L = 30 psf). The panel deflected 0.77 in at midspan upon load application and increased to 0.81 in after 24 hours. The residual deflection immediately after removal of load was 0.050 in and recovered to 0.037 in after 24 hours. Figure 20 shows this time-deflection history.

4.0 Discussion of Results

4.1 Test Performance of Roof Panels.

It was computed that the shear stress in the roof panel with a live load of 30 psf would be 6.5 psi neglecting the contribution from the edge members. The method of attaching the edge members to the panel (stapling) did not appear sufficient to justify computations assuming complete composite behavior.

The measured shear strength for the unaged specimens of Samples C and D averaged about 23.9 psi. Aging reduced the strength to about 19.7 psi (Sample C). These strengths appear to be adequate when compared with the computed 6.5 psi shear stress for the 30 psf roof load. However, these strengths were obtained in dry specimens when in fact it must be assumed that the core will be damp at some time in service.

Jenkinson [4] and others have shown that honeycomb similar to that used in this panel material will lose about 50 percent of its dry (50 percent rh) shear strength when conditioned at 100 percent rh. Thus, the shear strength of the core when reduced 50 percent for dampness would be 12 psi for the unaged and 9.9 psi for the aged core.

The above discussion shows how the shear capacity of the core in the roof panel would affect its load carrying capacity. However, the flexural tests on the full-size roof panels indicate that the shear capacity of the core is not a controlling factor and that the edge members do contribute to the flexural strength of the panel. The three roof panels tested to failure with short-term uniform loads show that the failure mode is facing buckling rather than shear. This means that the tensile (or compressive) strength of the panel materials in the flatwise plane is the controlling factor in the roof panel. The computed test shear stress for the soaked roof panel, assuming no edge members, was 18.8 psi at the failure load of 104 psf. This computed stress when compared with the 12 psi shear strength for wet unaged core indicates that for this test the edge members contributed about 36 percent to the shear resistance of the damp roof panel. The same type of comparison indicates that the edge members contributed only about 10 percent to the shear resistance of the dry panel. However, these roof panel tests did not reveal the effects of aging or variability in the properties of the panel material.

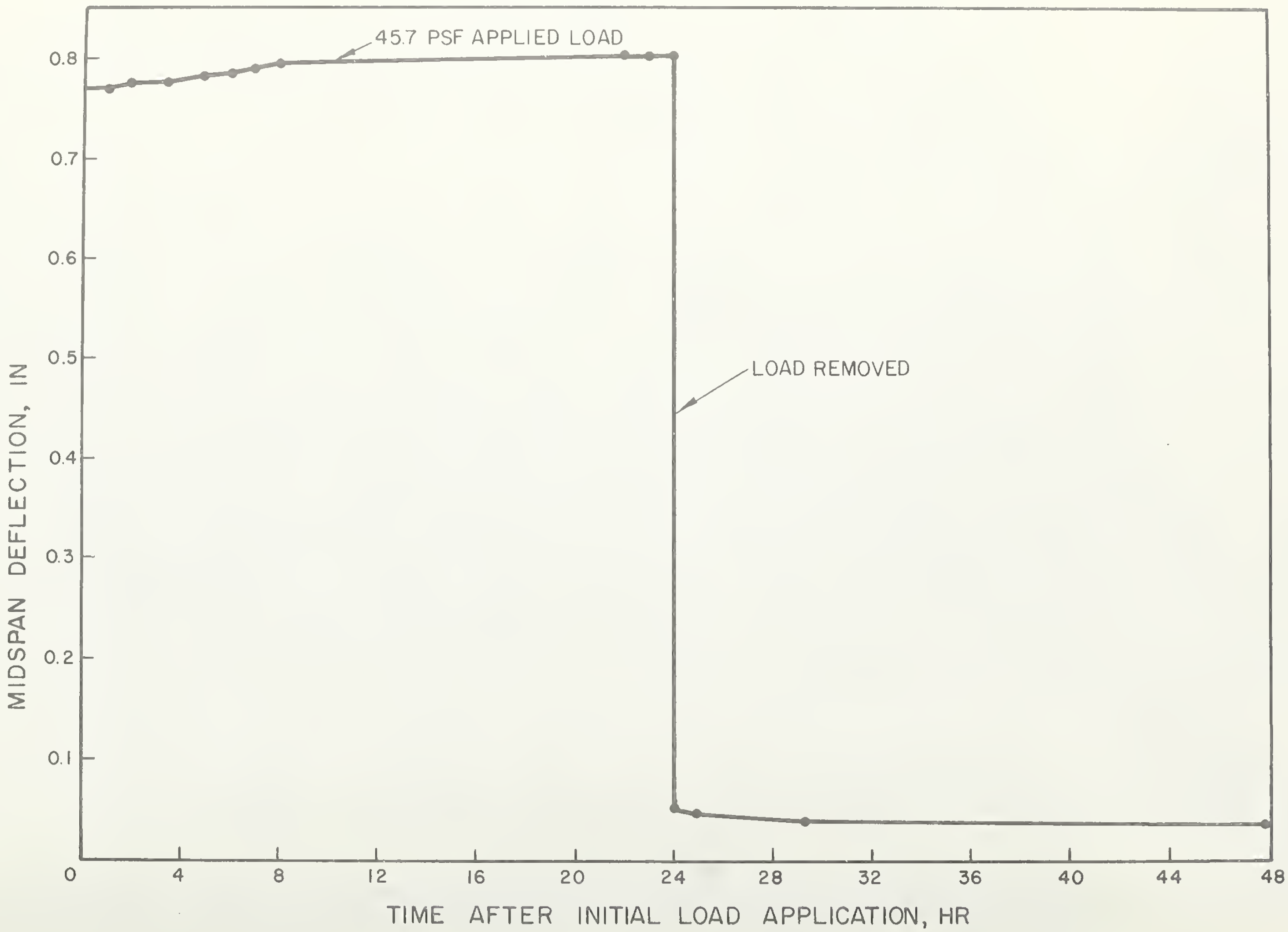


Figure 20. Sustained-Load Test Results on Specimen Conditioned by Procedure 1

The minimum failure load of 104 psf, for these panels, when adjusted down for the aging effect of 24 percent (see section 2.3.3) is 79 psf.

A variability factor (ν) of 0.41, computed from the tensile test data for Samples C and D, could be used because of the failure mode in all the full-scale, roof-panel tests. Adjusting the load capacity of the wet and aged roof panel (79 psf) for this variability reduces the rated capacity to 49 psf [79 $\left(\frac{1}{1 + 1.5\nu}\right)$].[4/] This variability factor of 0.41 may be conservative, but present knowledge concerning localized buckling failure in sandwich panels is insufficient to justify a lower value.

The sponsor recommends that the design ultimate load be 1.4D + 1.7L after allowance for aging, environmental effects and variability. From the discussion above and this recommendation the design live load should not exceed 26 psf.

Normally it is expected that a structural component will exhibit some ductility; that is, support a significant load while undergoing inelastic deformation. This was not exhibited by these sandwich roof panels.

The sudden buckling failure which occurred near, and parallel to, the core splice was typical for all short-term flexural panels and appeared to be in part caused by inadequate adhesive bonding between the honeycomb and steel facings. This inadequate bond was apparently caused by a difference in the thickness of the two core pieces and is an indication of a quality control consideration. As a result, it was recommended either: (1) core splices be eliminated by using full length core sheets; or (2) core material be chosen for consistent thickness and splices made such that the shear strength of the splice and that of the bond near the splice be equal to that of the honeycomb core without a splice.

5.0 Summary and Conclusions

This paper describes a series of structural evaluation tests performed on components and materials intended for use in one of the Operation BREAKTHROUGH housing systems. Four samples of steel faced, paper honeycomb, sandwich panel material and four prototype roof panels were evaluated.

The samples of sandwich panel material were used to evaluate the variability of panel material properties and the effect of aging on tensile and shear strengths. The roof panels were used to determine the probable behavior in service considering the effects of adverse environmental conditions

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4/ Assuming a normal distribution, the requirement that structures be designed for an overcapacity of (1 + 1.5ν) times the required capacity would mean that approximately 95 percent of that population of structures would have at least the factored load capacity.

on ultimate strength and mode of failure. In addition, the performance of one panel under sustained loading was evaluated.

The following conclusions can be made from the test results:

1. The roof panels, when loaded uniformly, will fail in flexure rather than in shear even when the core is damp.
2. The uniformly loaded roof panels failed suddenly by local buckling of the compressive skin and exhibited very little ductility.
3. The flatwise tensile strength of the sandwich panel material is a controlling factor in the strength of the roof panels.
4. Aging of the sandwich material reduced the flatwise tensile strength about 40 percent in the prototype panel specimens (Sample C), but only 24 percent in the production panel specimens (Sample D). This difference in the aging effect is attributed to the disruption of the adhesive film, which offers some protection to the metal facing, in the prototype panel.
5. The coefficient of variability for the tensile strength of the small specimens was 41 percent. This includes variability in the adhesive bond as effected by fabrication techniques.
6. The maximum uniform load which a wet and aged roof panel should be expected to support is 49 psf.
7. A wet and aged roof panel will meet the sponsor's recommendations for 26 psf live load using a variability of 0.41.
8. Defects in the wood edge members, such as large knots, may affect the load capacity of the roof panels.
9. The long-term performance of the panel material would be affected by the following quality control items:

   a. Thickness of adhesive relative to the condition of the edges of the paper honeycomb core. If the edges of the core has been roughened by sanding or some other method prior to lamination the adhesive may have to be thicker in order to bond to the solid portion of the paper.

b. Relative movement between facing and core during, or after, lamination. This movement will "squeegee" the adhesive away from one side of the core cell edge.

c. The bond between the primer and the basic steel sheet.

d. Difference in thickness between two pieces of core used in the same panel. The thicker piece prevents good contact of the thinner piece with the adhesive.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

A series of structural evaluation tests performed on components and materials intended for use in one of the Operation BREAKTHROUGH housing systems is described. Four samples of steel faced, paper honeycomb, sandwich panel material and four full size prototype roof panels were evaluated.

The samples of sandwich panel material were used to evaluate the variability of panel material properties and the effect of aging on tensile and shear strength. The roof panels were used to determine the behavior in service considering the effects of adverse environmental conditions on ultimate strength and mode of failure. In addition, the performance of one panel under sustained loading was evaluated.

17. KEY WORDS (Alphabetical order, separated by semicolons) Accelerated aging; adhesive bond; ductility; flexural shear; housing systems; local buckling; material variability; moisture conditioning; Operation BREAKTHROUGH; paper honeycomb; structural sandwich; sustained load.

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