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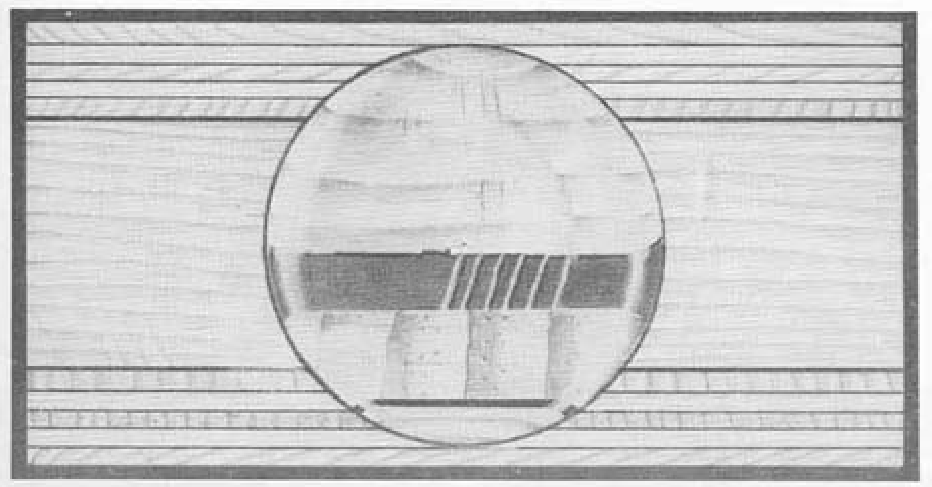
BEHAVIOR OF AN EPOXY-POLYSULFIDE ADHESIVE IN WOOD JOINTS EXPOSED TO MOISTURE CONTENT CHANGES



CONTENTS

SUMMARY

The mechanical behavior of a flexible epoxy-resin adhesive system was observed in joints of plywood to lumber. The joints were subjected to internal swelling stresses caused by an increase in moisture content. Previous experimental work at the U.S. Forest Products Laboratory has shown that this adhesive system acts as a strain-absorbing cushion and thus has a significant stress-relieving effect in the joint.

An attempt was made to use this adhesive as a calibrated tool for measuring shear strain as a function of lumber size, lumber specific gravity, and glueline thickness in a plywood-to-lumber joint. The strain was then converted to shear stress.

Photographic results showed that the adhesive acted as a strain-absorbing component by straining in shear up to 0.625 inches per inch without failure.

The calibration of the adhesive was complicated because the adhesive performed viscoelastically rather than elastically under a sustained load. Even with this difficulty, certain stress relations were obtained by calibrating the adhesive on a viscoelastic basis using an average sustained load.

The technique of using a calibrated adhesive has great potential in studying adhesive behavior; however, it is necessary to have an adhesive system whose performance would he primarily elastic under a sustained load.

BEHAVIOR OF AN EPOXY-POLYSULFIDE ADHESIVE IN WOOD JOINTS EXPOSED TO MOISTURE CONTENT CHANGES

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INTRODUCTION

When a glue joint between two pieces of wood is subjected to changes in moisture content, swelling or shrinkage of the wood occurs and the resulting dimensional changes exert internal mechanical stresses on the glue joints. The magnitude of these stresses would be expected to become more severe as the specific gravity of the wood increases, as the range of moisture content change increases, and as the angle of grain between the two wood pieces increases from 0° to 90°. If the internal stresses exceed certain levels, failures may occur in either the glueline or in the wood adjacent to the glueline. Typical wood glues are quite rigid and tend to concentrate internal stresses in the wood at the glueline, often resulting in checks in the wood. This essentially amounts to joint failure; however, if a glueline could partially deform under such internal stresses, some of the stress would be relieved and premature joint failure would be delayed or prevented. An ideal adhesive film would recover elastically when the stresses were relieved and not be subject to significant creep deformations.

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

The present study was intended to observe the performance of one such deformable glueline, based on an experimental formulation of epoxy and polysulfide resins that has been under study at the U.S. Forest Products Laboratory. A test specimen of lumber to plywood was used with the grain of the two adjacent wood surfaces at right angles to each other at the glueline. A recent study[2] with this type of specimen suggested significant advantages in a lower modulus adhesive of this type, presumably because of the ability to partially deform under stress. To gain an insight into the nature of the improved performance, it was considered imperative that the actual mechanical behavior of the flexible glue beobserved under swelling stress conditions.

In addition to the observations taken during a cycle of increasing humidity, the adhesive was used for another purpose. The shear stress-strain-time relationship was determined for the adhesive by a recently devised method[3], so that by reversing the process the measurement of strains during swelling could be converted to stress in the glueline. In effect then, the adhesive becomes a precalibrated mechanical tool or strain gage for determining stresses induced in a glueline as a result of the moisture change in the wood adherends.

The primary objective was to use thetechnique described to determine the distribution and intensity of the stress induced in the glueline between plywood and lumber, as well as to determine the dependence of this stress on lumber size, lumber specific gravity, glueline thickness, and amount of moisture content change in the wood.

MATERIALS USED

Basic Components

The three material components used in the study were lumber, plywood, and adhesive.

The lumber was high quality, West Coast Douglas-fir of C and Better finish grade. The material was flat sawn, straight grained, and free from hots or other major defects. Originally, this lumber was reported to have been kiln dried to 8 to 12 percent moisture content by the lumber manufacturer.

The plywood used was a commercial, Douglas-fir plywood panel. The material was selected from 3/4 inch, A-C exterior type 5-ply stock.

The adhesive was a laboratory formulationthat had been used in prior studies. Its apparent elastic modulus of rigidity had been determined as 15,000 pounds per square inch[3]. The chemical composition of the adhesive was as follows:

100 parts by weight of a commercial bisphenol-A-epichlorohydrin epoxy resin.

70 parts by weight of a commercial polysulfide rubber (used as a modifier).

10 parts by weight of diethylenetriamine catalyst.

Specimen

The specimen that was used for observations and stress measurements consisted of a relatively thin slice of the original bonded panel. The original panel consisted of 3/4-inch plywood bonded on the top and bottom of a board (either 2 by 6 by 30 or 2 by 10 by 30 inches) with the face ply of the plywood oriented at 90° to the longitudinal grain of the lumber. The slice, 5/32 inch wide, was cut on a plane perpendicular to the longitudinal grain of the lumber.

A very thin width of the section was chosen so that a condition of two-dimensional stress and strain could be assumed without appreciable error.

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[2] Krueger, G.P., and Blomquist, R. F. Performance of a rigid and a flexible adhesive in lumber joints subjected to moisture content changes. U.S. Forest Serv. Res. Note FPL-076, Forest Prod. Lab., Madison, Wis., 1964.

[3] Krueger, G.P. A method for determining the modulus of rigidity of an adhesive in a timber joint. Materials Flea. and Stds. 2(6):479-484. 1962.

Specimen Variables

The objectives of the study required that six panels be prepared, each to represent one of the test variables. The variables of size, specific gravity, and glueline thickness are shown diagrammatically in figure l.

Since a photographic technique was used to record the strains, a permanent visual record was provided, For this reason one specimen for each variable was considered sufficient for strain measurements, although replications were observed during the test.

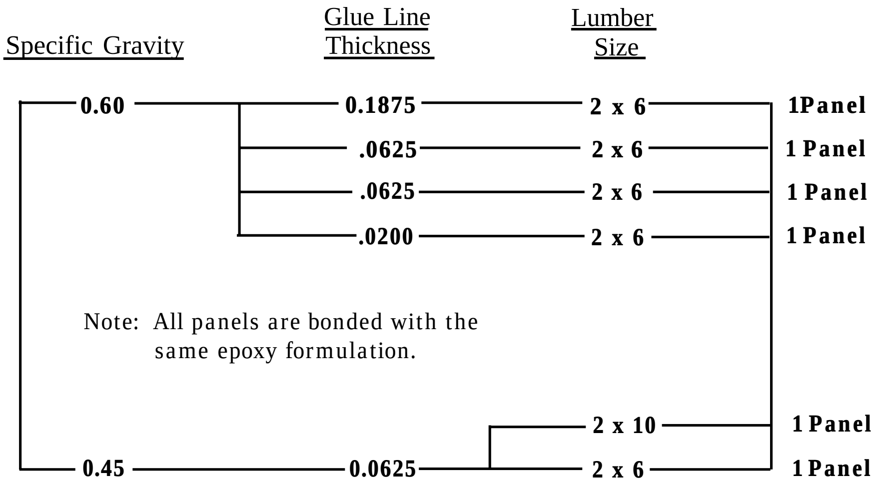


Figure 1.--Diagram of test variables.

PREPARATION OF SPECIMENS

To provide sufficient material of the specific gravity range indicated in figure 1, four Douglas-fir boards were cut into 30-inch lengths designated A–B, C–D, or E–F. At the end of a conditioning period at 80° F. and 30 percent relative humidity, specimens were cut from the ends of the boards for determination of the specific gravity of the material. Table 1 gives a tabulation of the average specific gravity and moisture content values of the nine board sections.

On the basis of these data, boards 1 A–B, 1 C–D. and 1 E-F were selected for use as the three specimens of constant specific gravity and varying glueline thickness; boards 2 A–B and 2 C–D for use as the size variable at constant specific gravity and glueline thickness; and board 3 A–B to represent either a specific gravity variable or a replication of one of the higher density specimens.

The six board panels that had been selected for the test were prepared for gluing by surfacing both sides with a planer and jointer within 24 hours or less before gluing. After planing both sides to a uniform thickness, the boards were further

Table 1.--Summary of moisture content and specific gravity of 4 Douglas-fir boards prior to selection for test

Board number	Section number	Average specific gravity[1]	Average moisture content
1	A-B	0.597	5.93
	C-D	.594	6.14
	E-F	.607	6.33
2	A–0	.446	6.26
	C-D	.460	6.26
3	A–B	.570	6.00
	C-D	.594	6.71
4	A–B	.477	6.65
	C-D	.490	6.75

prepared by gluing 1/16 by 3/16, 1/50 by 3/16, and 3/16 by 3/16-inch-veneerspacers around the periphery of each hoard on both gluing surfaces. The thickness of spacer used corresponded to the respective glueline thickness specified for each board.

All equipment and adhesive components had been maintained at 80° F. and 30 percent relative humidity for at least 7 days prior to gluing. Gluing and subsequent curing also took place at 80° F.

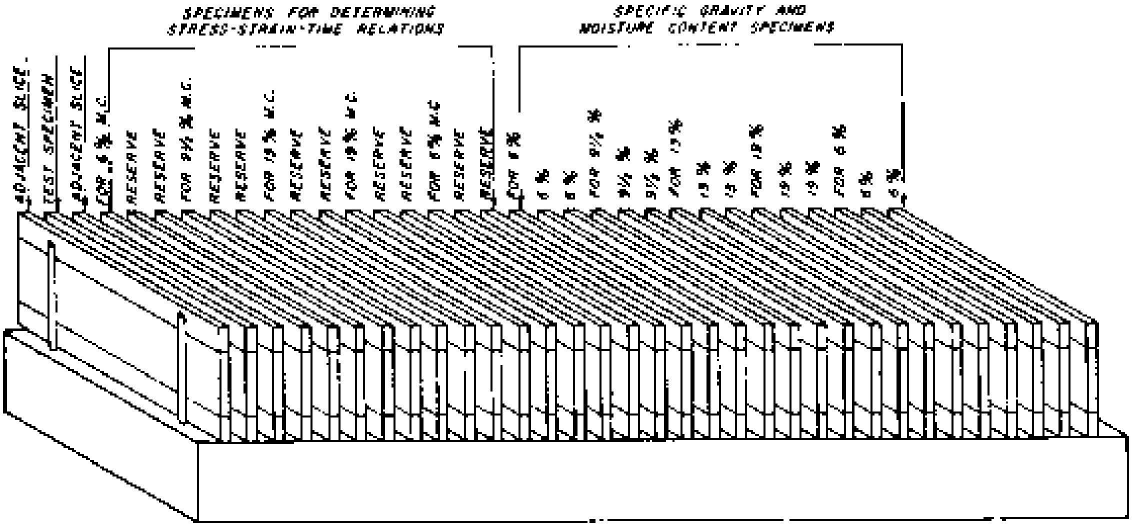
Adhesive mixing and bonding procedures were selected for bonding the six panels onthebasis of previous experience with this experimental adhesive formulation. The adhesive was poured into the voids created by the spacers and spread smooth with a spatula. The adhesives were essentially cast in place and the clamping procedure induced no external pressure on the glueline.

The panels were unclamped 24 hours after the gluing process and then stored at 80° F. and 30 percent relative humidity for a 24-hour period. Following this, one-half the length of each panel was sliced transversely on a bandsaw into a series of 5/32-inch-wide specimens. Inspection showed the individual panels to be properly bonded, with no unbonded areas occurring; however, a considerable number of small air bubbles were evident in the gluelines of all panels.

Thirty-three 5/32-inch slices were selected from the center section of each panel for test purposes. Absence of air bubbles in the gluelines was the principal criteria for selection.

One slice per panel was selected for the actual test specimen on which strains were to be measured on the basis of uniformity of grain, glueline thickness, andspecimen width. The slices on each side of the test slice were retained for the usual comparison with any failure that might occur in the test slice, when subjected to the same moisture changes as the test specimen. Fifteen additional slices (calibration specimens) were retained for determination of the stress-strain-time relations of the adhesive at the first moisture content level. Another 15 slices were retained for a specific gravity and moisture content check at various humidity levels during the course of the experiment. Figure 2 shows the arrangement of the slices in a storage rack

After the specimens were selected. the adhesive faces of the test slices and calibrationspecimens were scribed with reference lines for strain



SPECIMENS USED PER PANEL PER TEST VARIABLE

(M 124 949)

Figure 2.--Diagram of specimens used in swelling test, showing number used per panel per test variable and general arrangement in storage rack

measurements on both sides of each glue film. These lines are shown in photographs of the test specimens, and appeared. the same on the calibration specimens. The lines were scribed on the adhesive face with a razor blade under a 40-power stereomicroscope. The specimens for stress-strain-time relation or calibrationwereprepared and teated in the manner previously described[2]. It is important to nota that all the assumptions made regarding the performance and stress distributions of the specimen described in earlier work[2] also apply to this test. The procedure used for recording and measuring the strains was to photograph the scribe lines on 35-millimeter-color film, project the slide (approximately 100x magnification) on white paper, and compare the relative shear displacements by marking the scribe line positions for successive load increments. The same photographic equipment and lighting arrangement was used for both the swelling test specimens and the stress-strain-time specimens. The dimensions of the test specimens and positions of the strain reference areas are shown in figure 3.

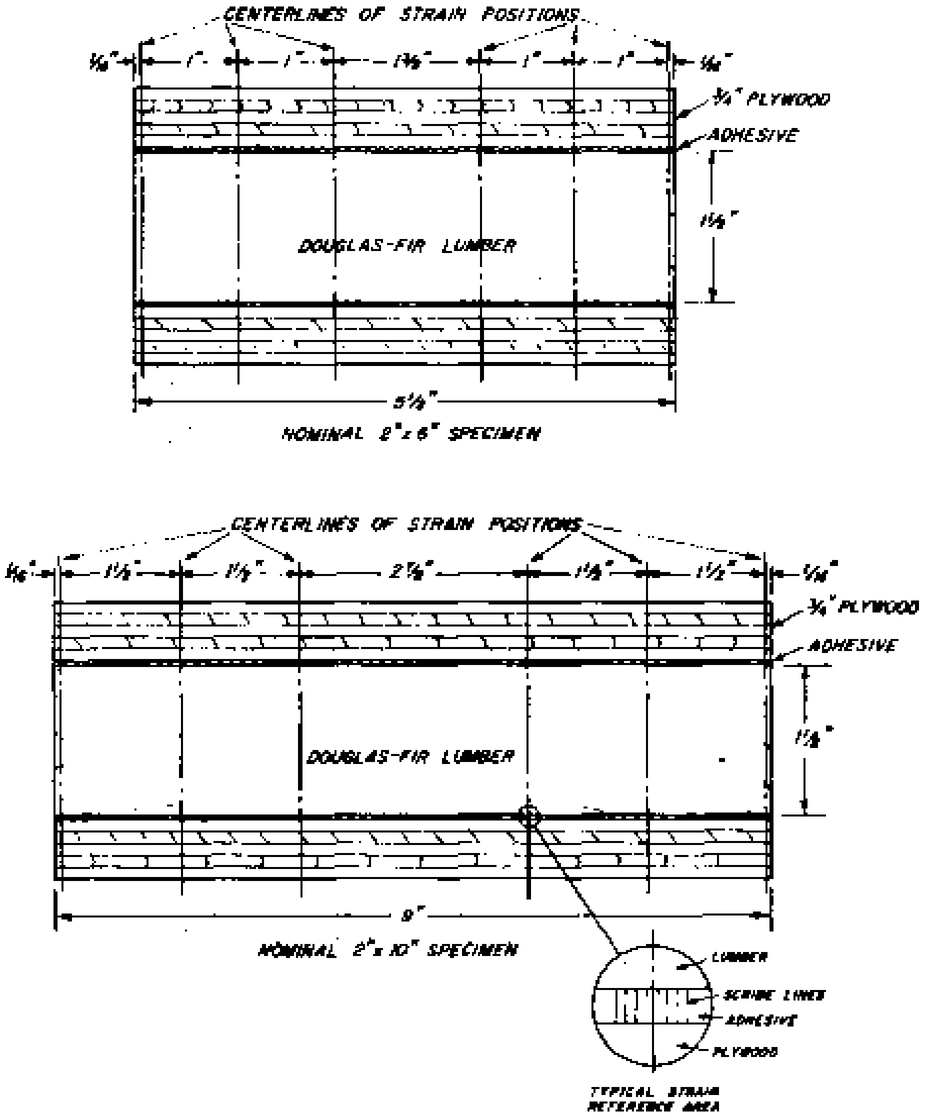


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Figure 3.-- Dimensions of test specimens and positions of strain reference areas.

The swelling test began by photographing and recording the zero strain condition of the test specimens at 6 percent moisture content. This constituted the base reference reading. At this time, the specific gravity was determined on the basis of ovendry weight and volume for three random samples for each test specimen. The results of these determinations are tabulated in table 2. The specific gravity data indicated that there were two 2 by 6 specimens with a glueline thickness of 0.0625 inch which had the same average specific gravity of 0.58.

The entire group of 33 specimens in the racks (fig. 2) for each test panel was conditioned at 80° F. and 65 percent relative humidity for 6 days, and the strains recorded photographically. The specimens were then conditioned at 80° F. and 80 percent relative humidity for 7 days and again photographed Finally they were moved to an 80° F. and 97 percent relative humidity room for 6 days, after which the specimen strains were photographed for the last time. From the 80° F. and 97 percent relative humidity mom the specimens were brought back successively through the 80° F. and 80 percent relative humidity

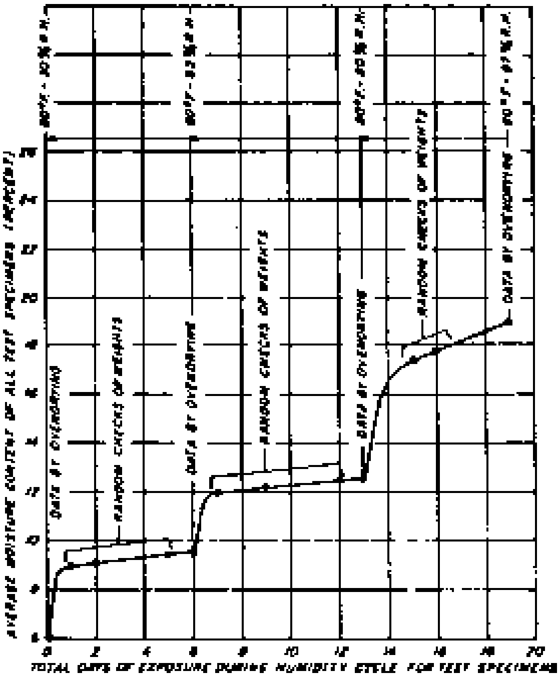

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Figure 4.--Summary chart showing increase in average moisture content of specimens during humidity exposure cycle.

Table 2.--Summary of specific gravity data for swelling test specimens

Specimen size	Glue line thickness	Board no.	Section no.				
				Sample no. 1	Sample no. 2	Sample no. 3	Average
In.	In.						
2 by 6	3.0200	1	A–B	0.62	0.60	0.61	0.61
2 by 6	.0625	1	C-D	.59	.59	.58	.59
2 by 6	.1875	1	E-F	.61	.60	.60	.60
2 by 6	.0625	3	A–B	.58	.58	.58	.58
2 by 6	.0625	2	A–B	.44	.44	.43	.44
2 by 10	.0625	2	C-D	.44	.44	.45	.44

and 80° F. and 65 percent relative humidity rooms at intervals of 7 days and finally stored at 80° F. and 30 percent relative humidity. The specimens were not photographed at the final storage conditions.

At each of the four moisture content levels (including the 6 percent level), three additional wood samples per test specimen were ovendried to establish an average moisture content. The moisture content data are tabulated in table 3. Random checks on the moisture content at various stages of exposure were made by weighing samples and computing the moisture content on the basis of the previous ovendry data. Figure 4 shows how the average moisture content increased during the humidity exposure cycle. It was not intended that the specimens reach equilibrium moisture content at each relative humidity but rather that the observed straining was decreasing at a very slow rate.

Table 3.--Summary of moisture content data

Sample no.	Initial moisture content at 80° F. and 30% relative humidity	Moisture content after successive exposure for		
		6 days at 80° F. and 65% relative humidity	7 days at 80° F. and 80% relative humidity	6 days at 80° F. and 97% relative humidity
		Percent	Percent	Percent
glueline thickness 0.0200 inch; specific gravity 0.610				
1	6.0	9.5	12.2	18.7
2	6.0	9.7	12.4	18.5
3	6.0	9.5	12.5	18.5
Average	6.0	9.6	12.4	18.6
ire 2 by 6; glueline thickness 0.0625 inch; specific gravity 0.587				
1	6.0	9.3	12.2	18.8
2	6.0	9.5	12.0	18.8
3	6.75	9.4	12.2	18.2
Average	6.25	9.4	12.1	18.6
Size 2 by 6; glueline thickness 0.1875 inch; specific gravity 0.603				
1	6.0	9.9	12.3	18.6
2	6.0	9.7	12.8	19.0
3	6.0	9.6	12.3	18.7
Average	6.0	9.7	12.5	18.8
Size 2 by 6; glueline thickness 0.0625 inch; specific gravity 0.580				
1	6.67	9.6	13.0	18.5
2	6.25	9.9	13.0	18.5
3	6.50	9.6	13.0	18.6
Average	6.47	9.7	13.0	18.5
Size 2 by 6; glueline thickness 0.0625 inch; specific gravity 0.437				
1	7.67	9.4	12.6	20.6
2	7.67	9.3	12.8	20.3
3	7.50	9.3	12.8	20.1
Average	7.61	9.3	12.7	20.3
Size 2 by 10; glueline thickness 0.0625 inch; specific gravity 0.443				
1	6.25	9.9	13.0	19.2
2	6.33	9.9	13.0	20.6
3	6.33	9.8	13.0	18.8
Average	6.30	9.9	13.0	19.5

ADHESIVE CALIBRATION FOR SUSTAINED LOAD

As the specimens were observed during the increasing moisture content cycle, it became apparent that the adhesive behavior was not highly elastic. Previous short duration creep studies (1 hour in length) showed no appreciable creep of this adhesive under relatively high shear loads applied parallel to the longitudinal grain of the lumber.[4] The extreme creep characteristics under 6-day sustained internal stresses of the present study, due to swelling of the wood, were indicated when the analysis of strains at 9-1/2 percent moisture content would have been comparable to over 2.000 pounds per square inch shear stress based On the elastic stress-strain relationship. This intense stress, of course, could not be possible in a joint with the adherend orientation used in this study as the strength of the material would be exceeded.

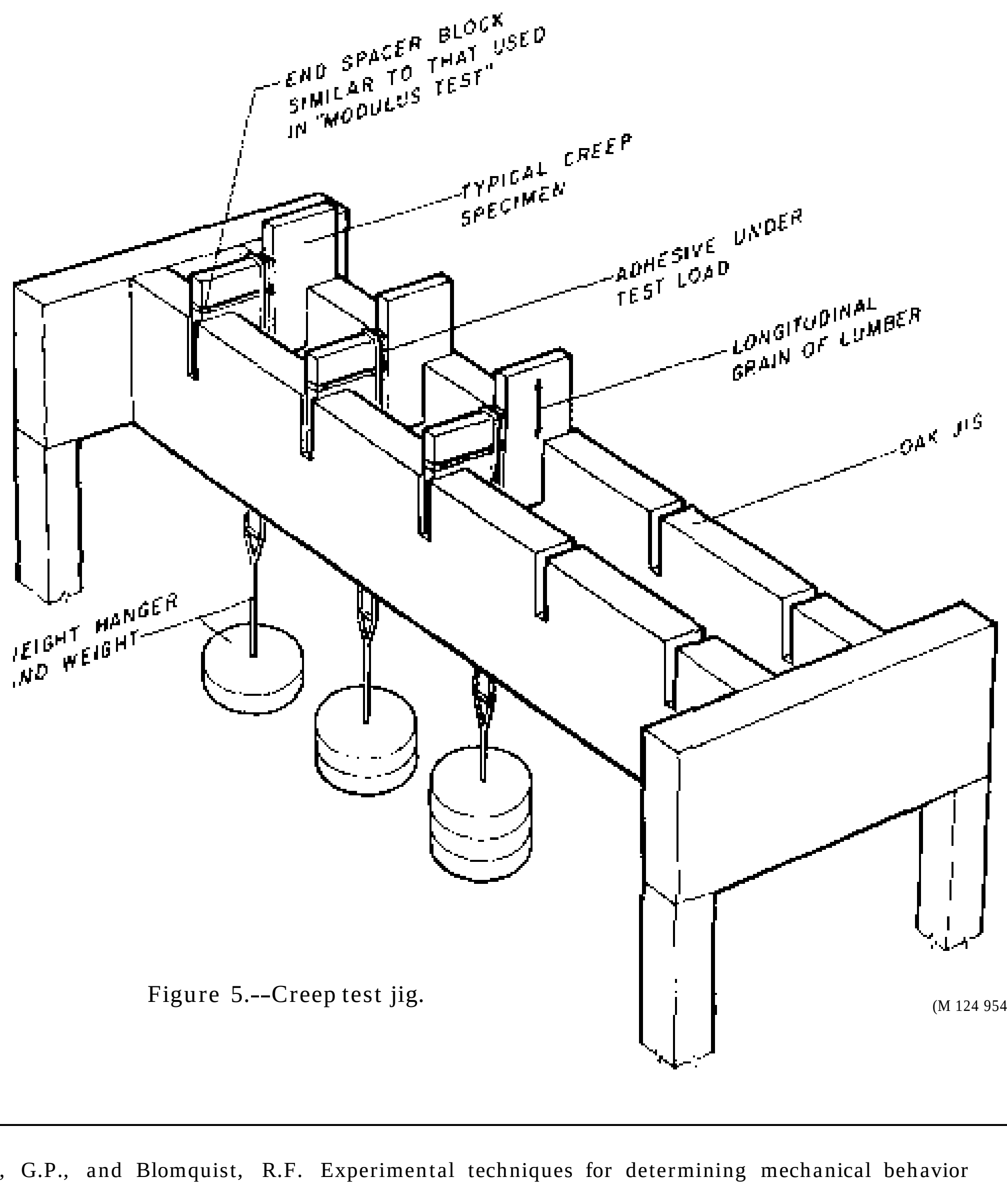

Figure 5.--Creep test jig.

(M 124 954)

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[4] Krueger, G.P., and Blomquist, R.F. Experimental techniques for determining mechanical behavior of flexible structural adhesives in timber joints. U.S. Forest Serv. Res. Paper FPL 21, Forest Prod. Lab., Madison. Wis., 1965.

At this time, an attempt was made to calibrate the adhesive on a viscoelastic basis. The purpose of the creep calibration test was to establish a sustained stress-deformation curve for an applied load over approximately the same length of time as the first humidity exposure increment in the swelling test (6 to 7 days). The rate of stress application during the swelling test could not he determined, but the proposed calibration system would give some indication of the average applied stress necessary to produce an equivalent average viscoelastic deformation in the adhesive after 6 days.

The specimens for the creep study were prepared end scribed in exactly the same manner as those for the elastic modulus of rigidity test[2]. The strains were recorded photographically as previously described. An oak jigwasdesignedand built to hold five creep specimens at a time, each with a different applied load. Figure 5 illustrates how the creep specimens were mounted in the jig and loaded by suspended weights.

Since five of the six panels were bonded with the same adhesive batch, only the adhesives of the two panels that were similar with respect to the other variables in the test (glueline, size, and specific gravity) were calibrated in thecreep study. If the results of the creep calibration study were the same, this would provide a good check of the method.

For each of the two selected panels, five creep specimens were loaded in the jig with weights of 2.71, 5.42, 8.13, 10.84, and 13.55 pounds(at 80° F. and 65 percent relative humidity). These weights provided an approximate range of average stress from 130 to 650 pounds per square inch Before the sustained load had 'reached the sixth day at 80° F. and 65 percent relative humidity, the three heaviest weights (8.13. 10.84, and 13.55 pounds) caused failure in the wood of three specimens from one panel, and the two heaviest weights caused failure in the wood of two specimens from the other panel. Several attempts were made to maintain a stress of over 250 pounds per square inch for a period of 6 days at 80° F. and 65 percent relative humidity, but it was found impossible even with a slightly larger specimen and with additional wood strips glued on forreinforcement of the cantilever part of the specimen. The wood ultimately sheared perpendicular to the grain in each instance.

The technique described, however, provided satisfactory photographic calibration data up to 250 pounds per square. inch for the first 6 days at 80° F. and 65 percent relative humidity.

EXPERIMENTAL RESULTS

The results of the swelling tests at the various moisture contents and adhesive calibrations are shown in figures 6 through 21. In each of the photographs (figs. 6. 10, 13, 15, 17, and 19), the actual test specimen subjected to the moisture changes is shown in the center. On either si& is shown the two adjacent specimens from the same glued panel that were also subjected to moisture changes but were observed only visually during such exposuretocomparewiththebehavior of the actual test piece. The six reference lines on both the upper and lower gluelines of the center test specimen were numbered as shown. The actual photographs of the specimen at each reference line are then shown when recorded at each of the moisture content levels. The photographs for the upper glueline are shown above the center photographs and for thelowerglueline. below, as indicated. The opposite si& of each specimen wasalsophotographedat12corresponding strain positions so that any longitudinal variations could be detected; however the datae were almost identical to those shown for each specimen and, therefore. are not presented here.

Figure 6 shows the data for a high-density 2 by 6 specimen with a 0.0625-inchglueline. The photograph of the specimensshowslumberfailure occurring at positions 1 and 6ofthetest specimen. This failure began at position6whenthespecimen had a moisture content of 13 percent. Most of the failure shown occurred between13 and 19 percent moisture content. The slices adjacent to the test slice developed the failures observed between 13 and 19 percent moisture content. It is interesting to note that the failures are not exactly alike in adjacent slices.

Figure 10 shows the data for the second high-density 2 by 6 specimen with a 0.0625-inchglueline. This specimen is a close replication of that shown in figure 6 although they are from two separate panels. Since no serious failures occurred in the specimen at 13 percent moisture content, a record was made at 19 percent moisture content. The specimen in figure 10 shows that the adhesive in this panel exhibited an unusual ability and capacity for deformation without loss of strength. The glue for this panel was mixed in a separate batch from that used for the rest of the panels, but the records show no reason for the highly viscoelastic nature under sustained load.

Figure 13 is the record for a high-density 2 by 6 with a glueline of 0.020 inch. In this instance, the adjacent slices had exactly the same type of failure which began in the adhesive at 13 percent moisture content, although there appeared to be yielding at 9-1/2 percent. It was noted that the start of the yield zone and subsequent failure was due to the presence of a relatively large bubble at the transverse extremity of the glueline.

Figure 15 is the record for the high-density 2 by 6 with 0.1875-inch glueline. The test slice shows a 3/4-inch length of wood shear (position 7) which developed at 19 percent moisture content. One adjacent slice shows no damage, and the other shows a tangential tension failure in the wood. This is particularly interesting since three slices from a panel, within 1/8 inch of each other, show three entirely different performances.

Of the three glueline thicknesses, the strain generally decreased with increased glueline thickness, except for the one 0.0625-inch specimen with unusual deformation properties (fig. 10).

Figures 17 and 19 give data for the 2 by 6 and 2 by 10 specimens respectively, both with specific gravity of 0.45 and 0.0625-inch gluelines. Here, in the lower density material, there were no joint failures and the photographic recording was continued up through 19 percent moisture content.

Strain Distribution

Following each photograph of the swelling strains is a graph of the measured strains in the gluelines (figs. 7, 11, 14, 16, 18, and 20). These curves show shear deformation in inches per inch plotted at the relative horizontal position of the strain recording point in the glueline. The curves above and below zero represent the glueline at the top and bottom of the specimens as numbered. The curves are the averages of the two sides of the specimen.

Figure 8 is the viscoelastic stress-strain curve which was obtained from the sustained load creep test and served as a calibration curve for the adhesive.

The stress-strain relations from the creep test were used to convert the strains in figures 7 and 11 to equivalent stresses in the cycled specimens. These stresses are shown in figure 9 and 12 for the adhesives of the specimens from the two panels that were calibrated for creep. The procedure here was to read a stress from the calibration curve (fig. 8) corresponding to a given strain on the strain variation graphs for the cycled specimens (figs. 7 and 11). The calibration stress-strain curve in figure 8 was also used to convert maximum strain of the four other cycled specimens from the four other panels to a maximum stress value. These are not plotted, since the stress conversion is practically linear with strain, and the strain graphs in essence represent the stress variation to a given scale. As previously stated, the adhesive properties (for the adhesive in fig. 10) were so obviously different from those properties in the other panels that its calibration curve was only used for computing the stresses for the specimen from that panel.

The computed stresses in figures 9 and 12 show the average stress in the adhesive over the 5-1/2 days of exposure at 80° F. and 65 percent relative humidity necessary to produce the observed average strains. In reality, the stress was probably higher during the beginning of the exposure cycle and then decreased toward the end of the cycle, since the deformation in the adhesive probably relieved some of the force after some time of sustained load.

Upon drying these test slices back to 6 percent moisture content, the specimens that bad failed at a high humidity resumed their original shape, and any separations in the wood were closed.

The specimens that had not failed during swelling developed radial drying checks, so that the forces tending to return the adhesive to its original position were relieved and, consequently, the adhesive did not fully recover the plastic deformation.

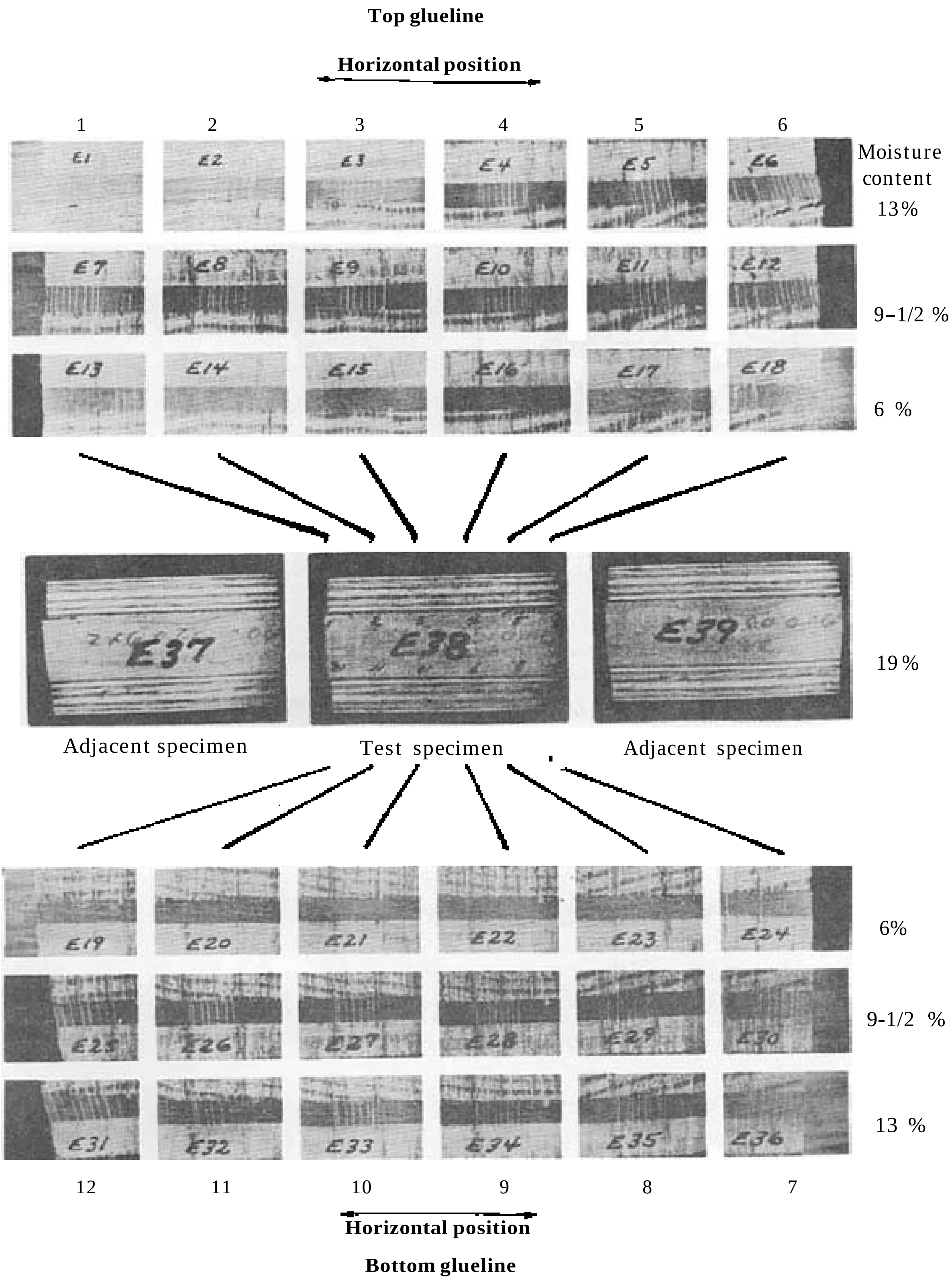

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Figure 6.--Adhesive strains in a 2 by 6 specimen having a specific gravity of 0.60 end a glueline thickness of 0.0625 inch. Example No. 1.

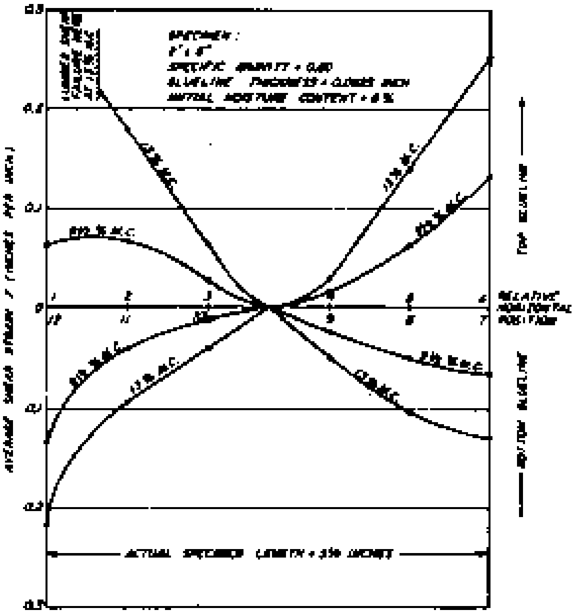

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Figure 7.--Strain distribution in a 2 by 6 specimen for 3-1/2 and 7 percent increases in moisture content. Example No. 1.

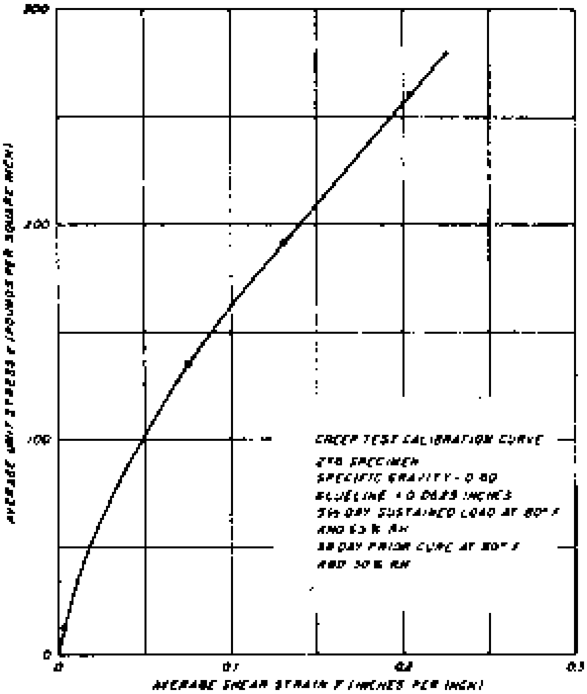

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Figure 8.--Calibration curve for the adhesive.

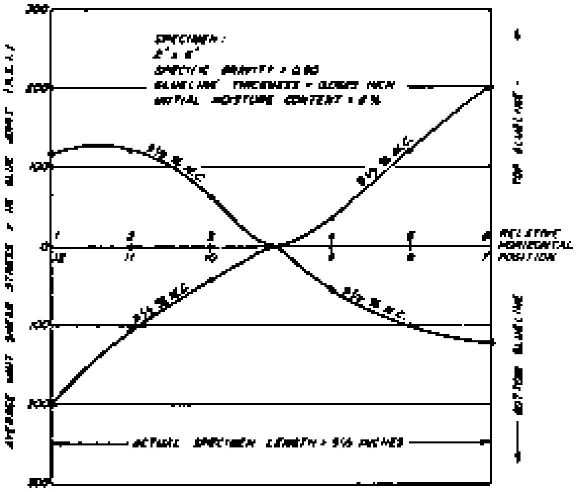

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Figure 9.--Shear stress distribution in a 2 by 6 specimen for 3-1/2 percent increases in moisture content. Example No. 1.

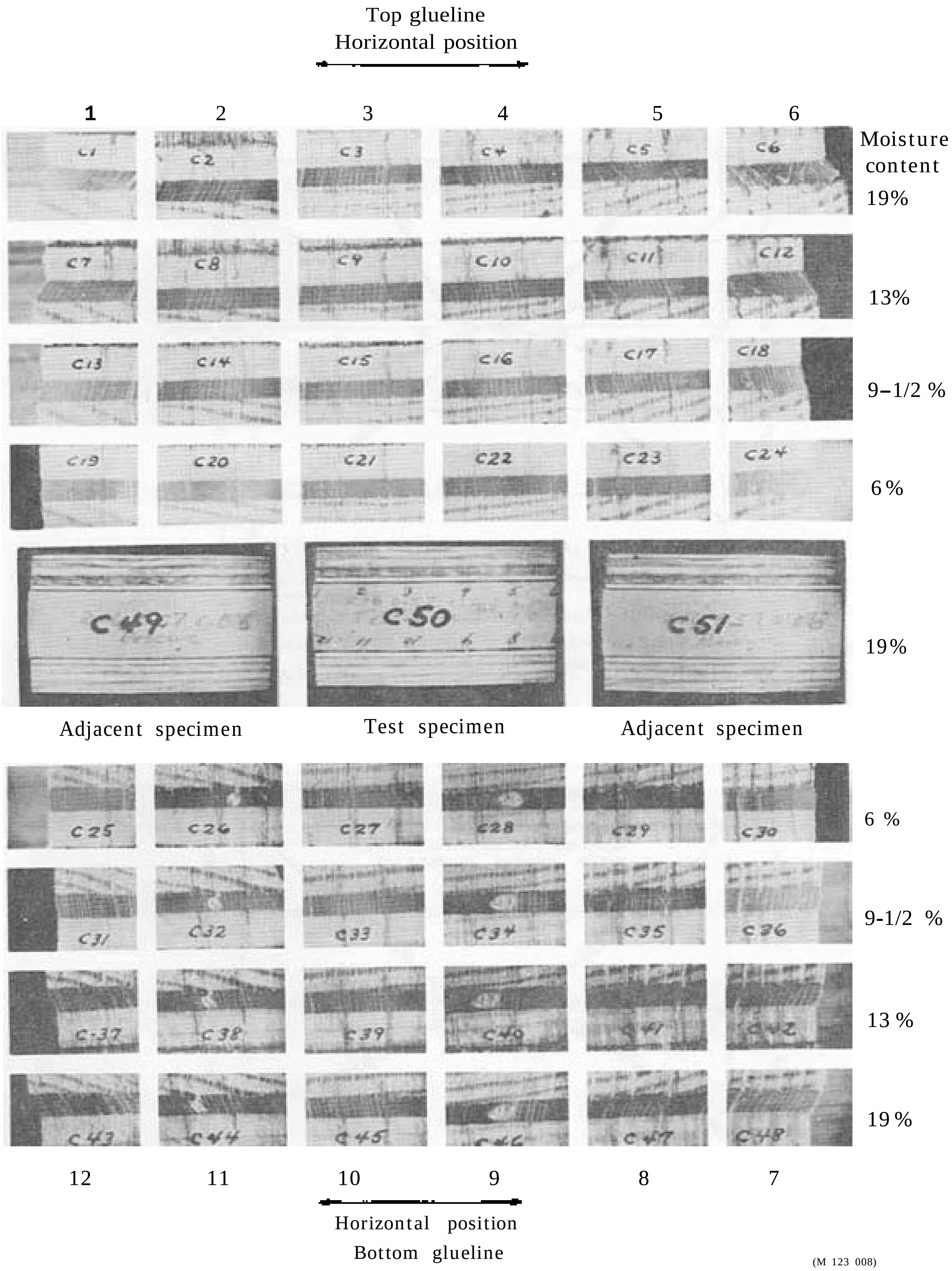

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Figure 10.--Adhesive strains in a 2 by 6 specimen having a specific gravity of 0.60 and a glueline thickness of 0.0625 inch. Example No. 2.

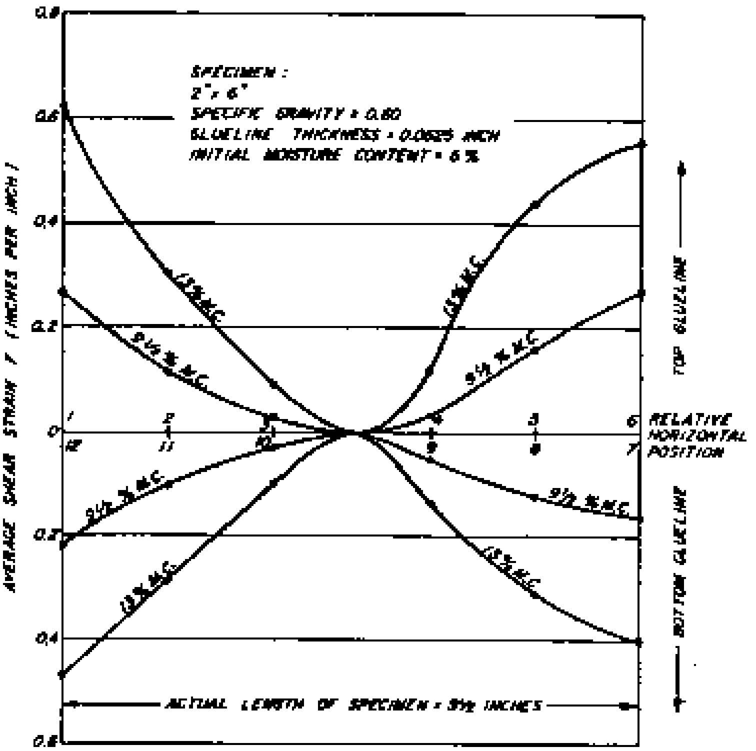

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Figure 11.--Stran distribution in a 2 by 6 specimen for 3-1/2 and 7 percent incresses in moisture content. Example No. 2.

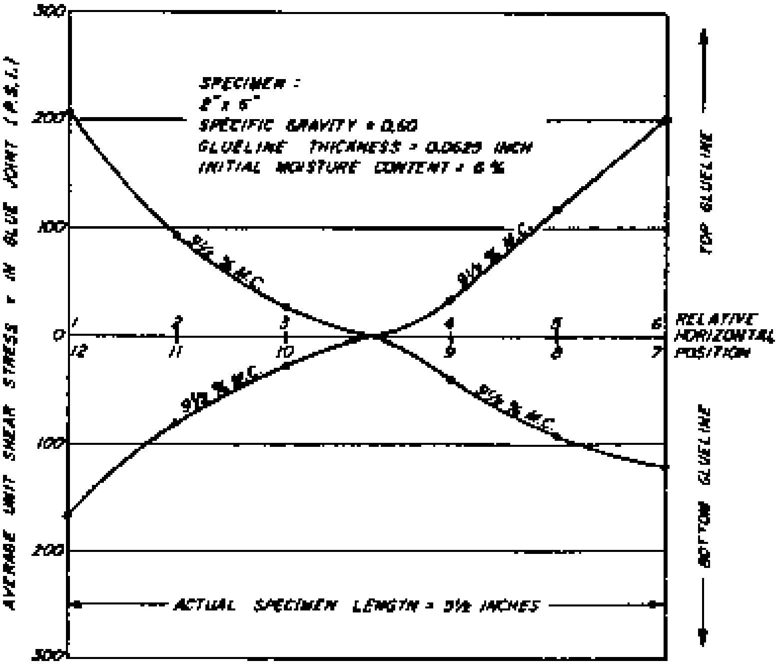

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Figure 12.--Shear stress distribution in a 2 by 6 specimen for 3-1/2 percent increase in moisture content. Example No. 2.

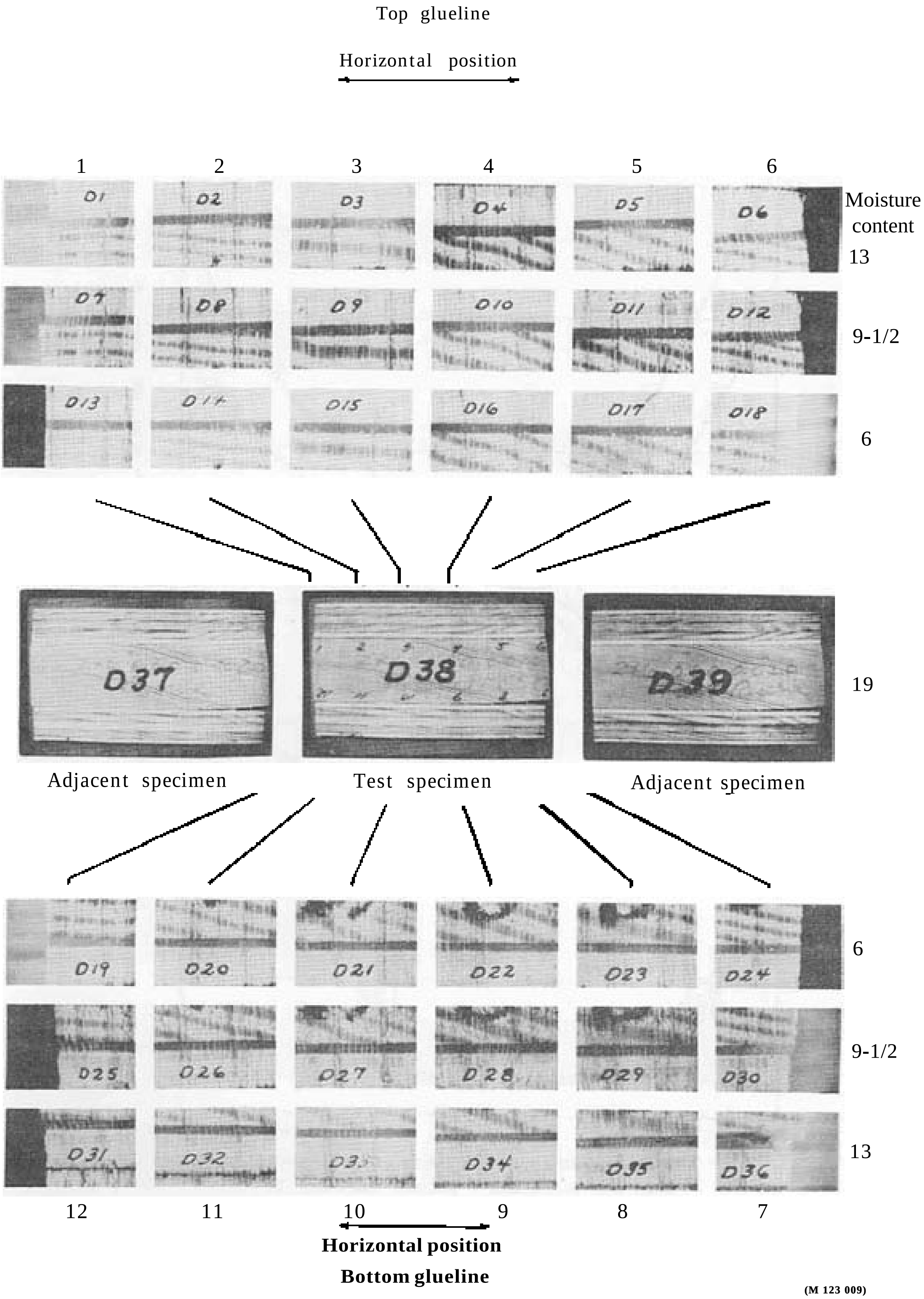

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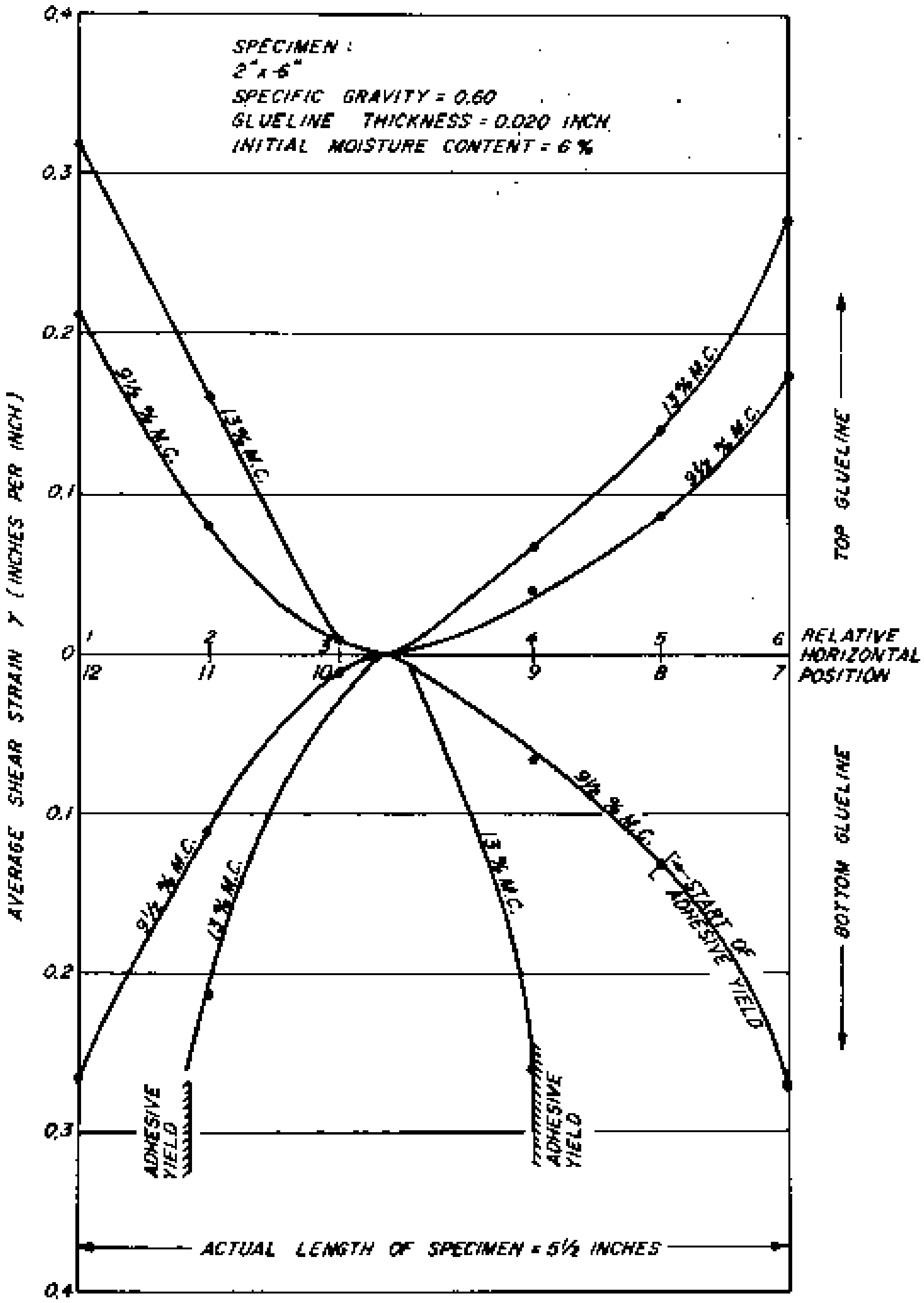
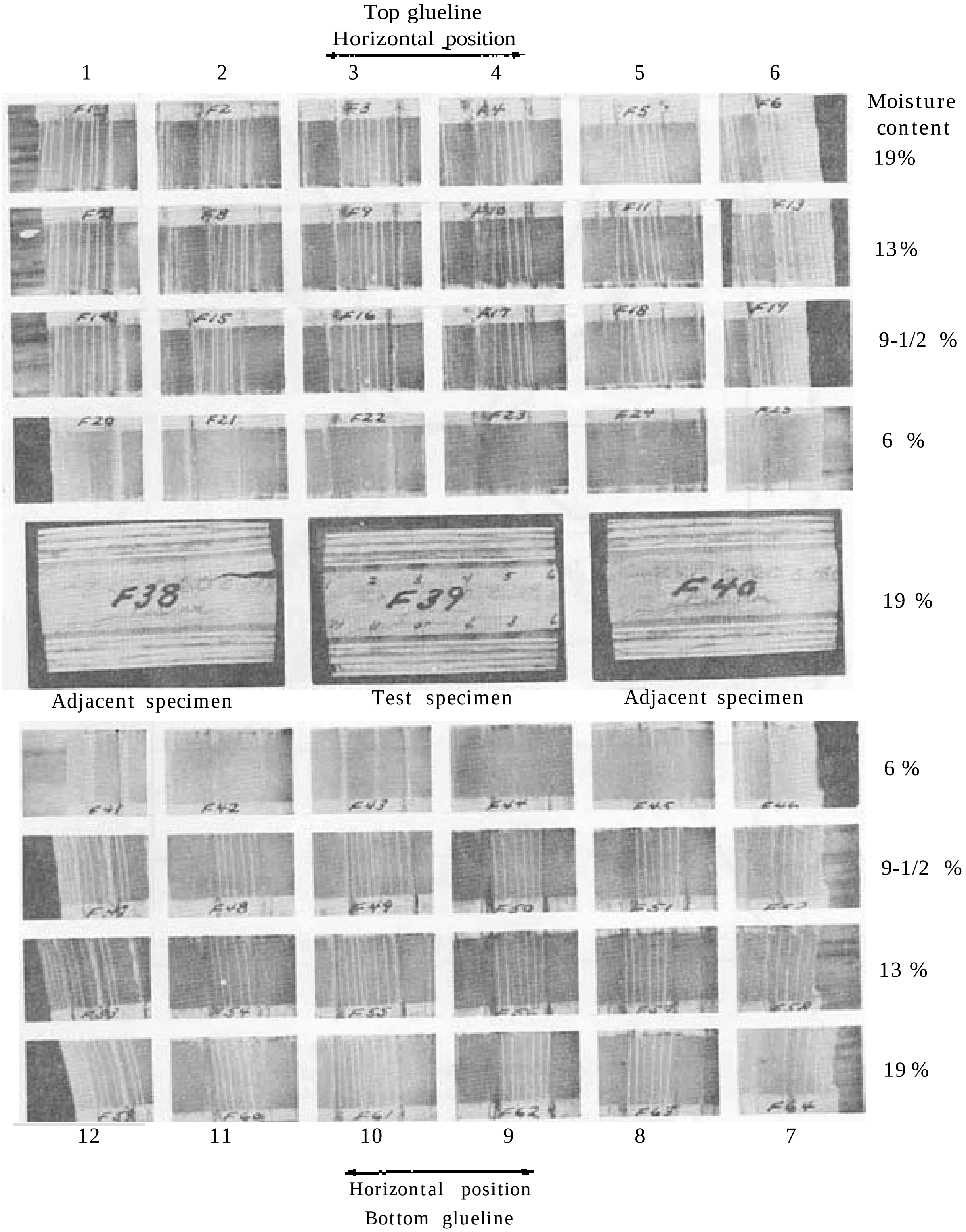
Figure 13.--Adhesive strains in a 2 by 6 specimen having a specific gravity of 0.60 and a glueline thickness of 0.020 inch



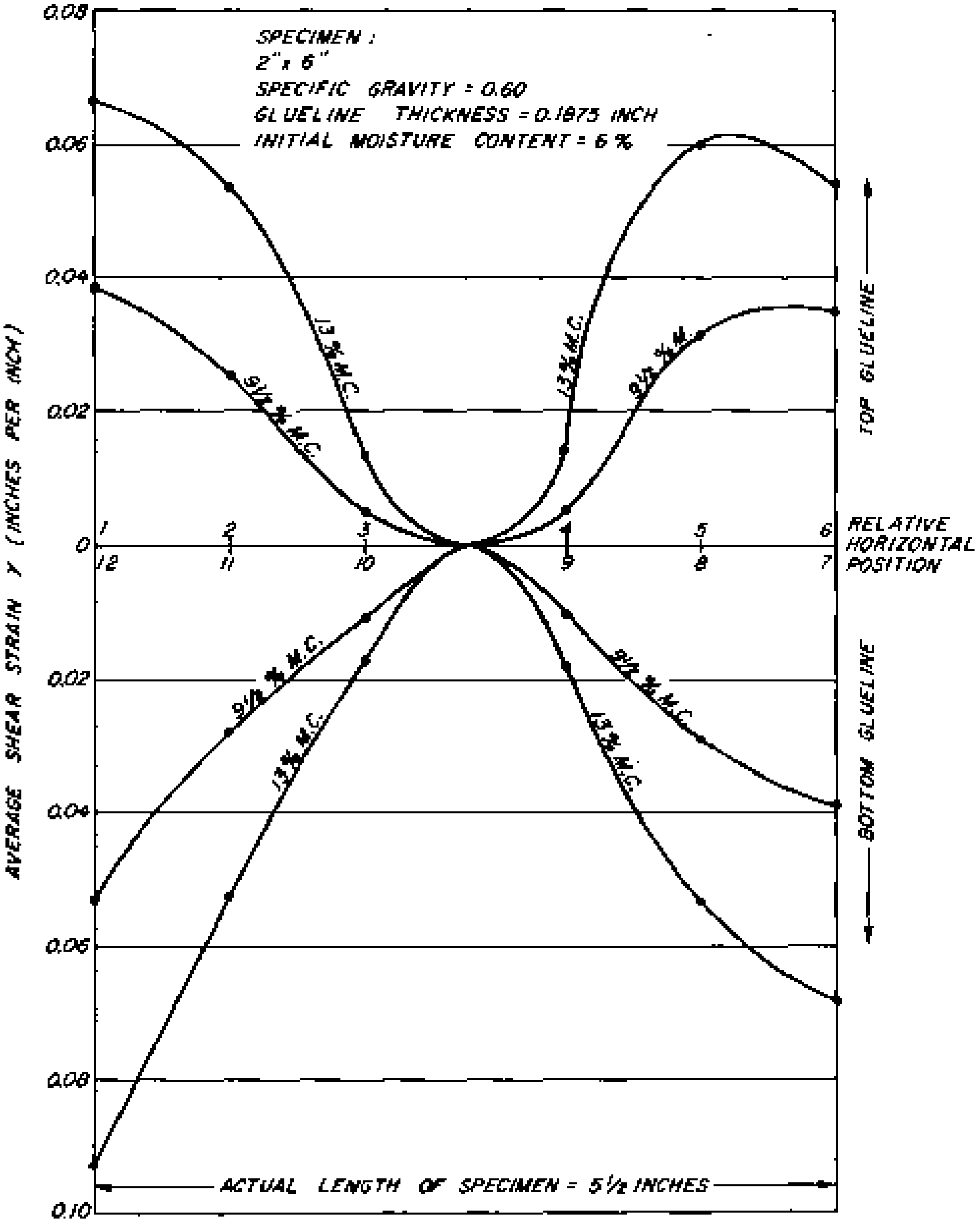
(M 124 953)

Figure 14.--Strain distribution in a 2 by 6 specimen for 3-1/2 and 7 percent increases in moisture content. Specific gravity of specimen = 0.60 and glueline thickness = 0.020 inch.



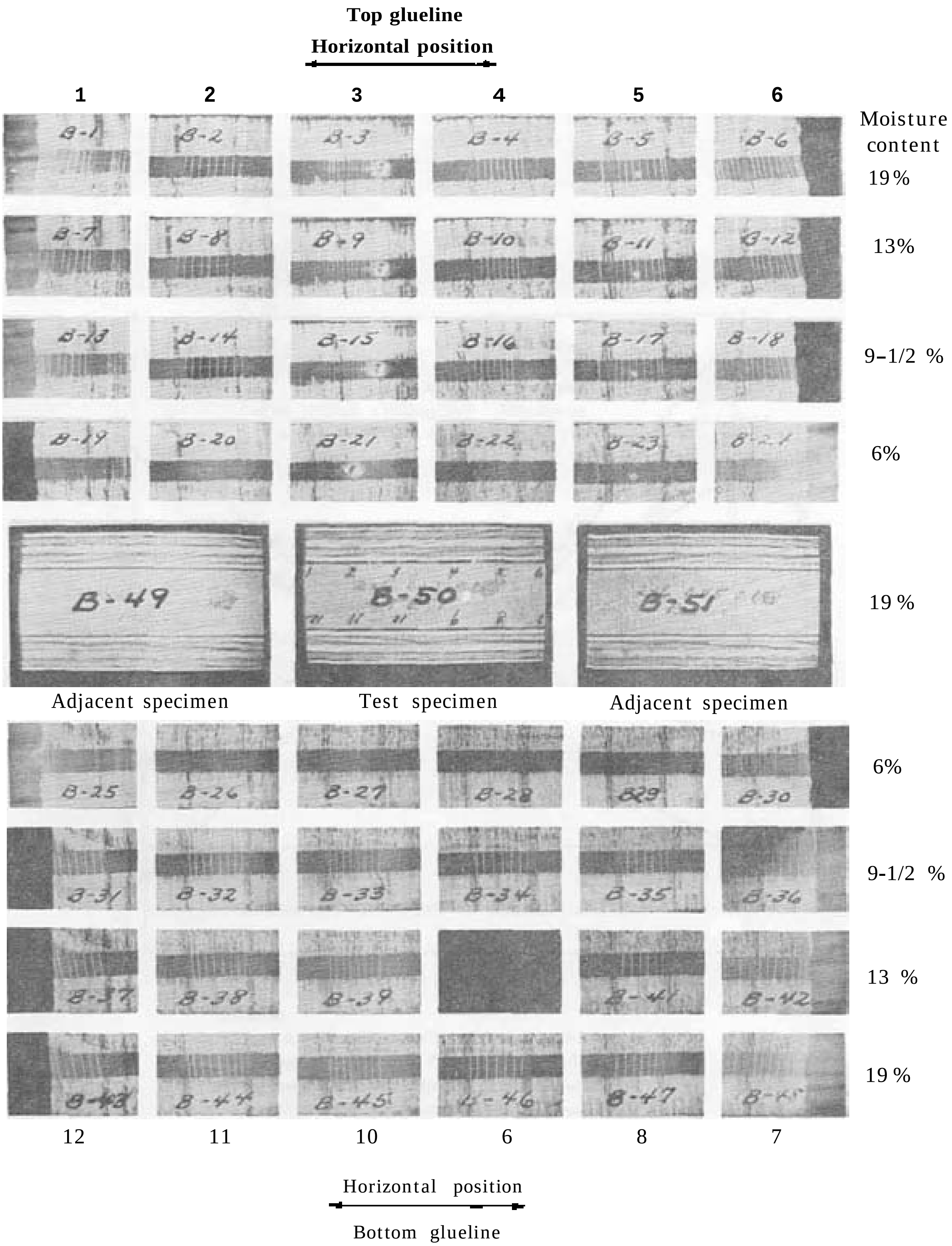
(M 123 011)

Figure 15.--Adhesive strains in a 2 by 6 specimen having a specific gravity of 0.60 and a glueline thickness of 0.1875 inch.



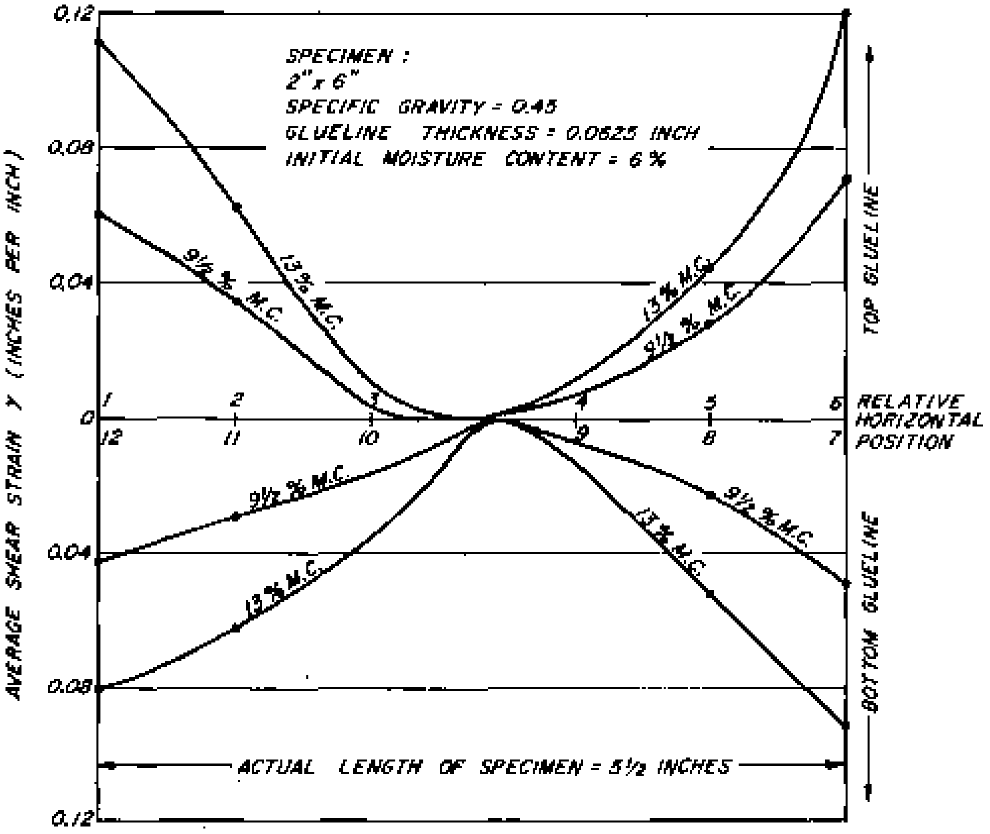
(M 124 942)

Figure 16.--Strain distribution in a 2 by 6 specimen for 3-1/2 and 7 percent increases In moisture content. Specific gravity of specimen = 0.60 and glueline thickness = 0.1875 inch.



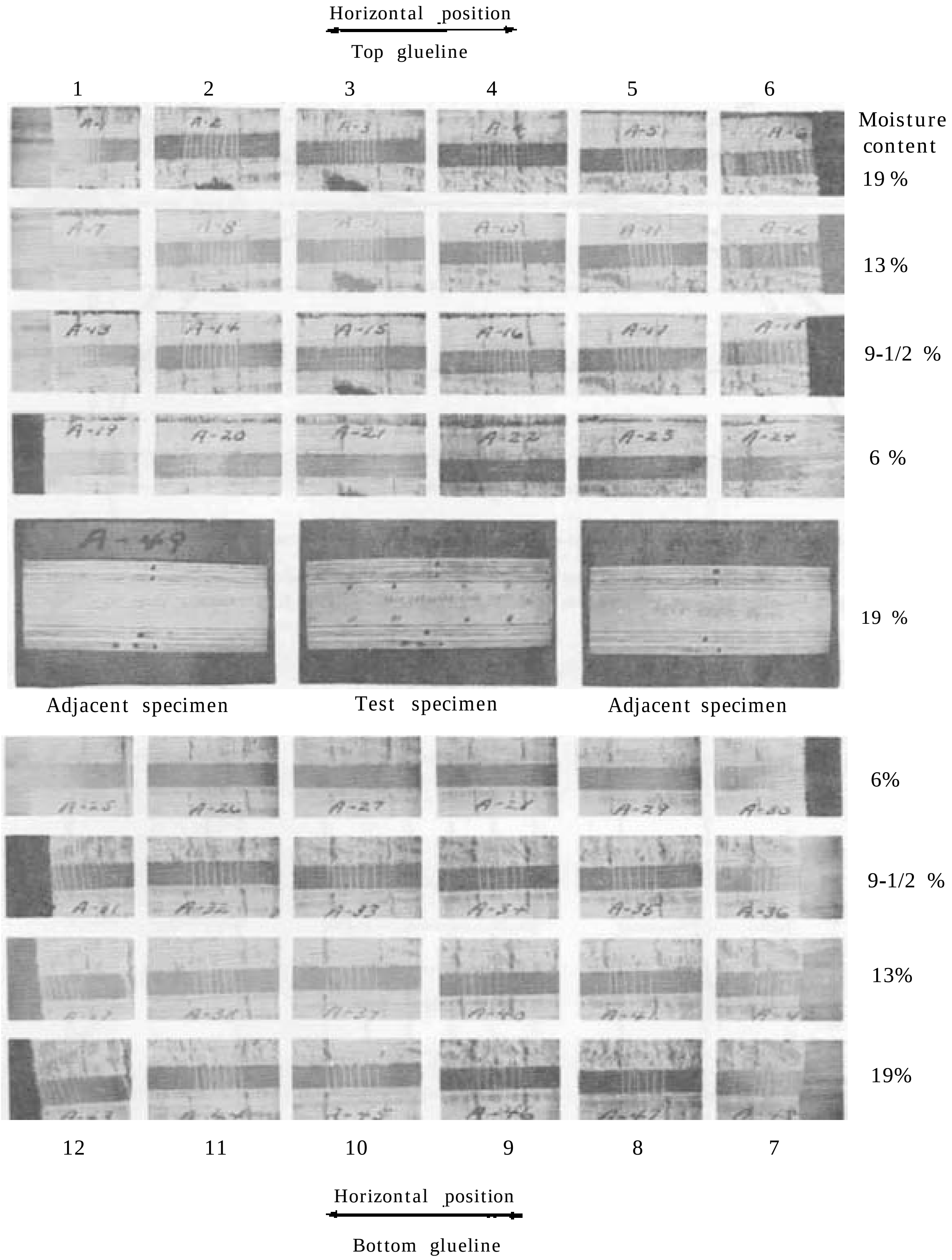
(M 123 007)

Figure 17.--Adhesive strains in a 2 by 6 specimen having a specific gravity of 0.46 and a glueline thickness of 0.0625 inch



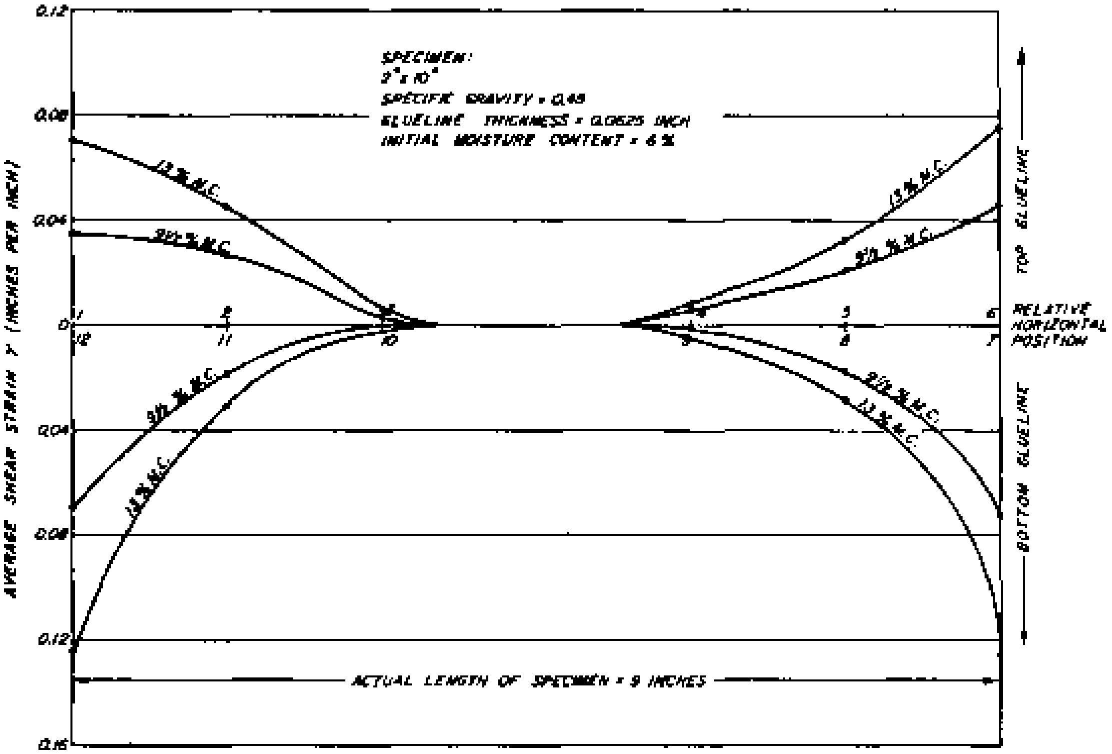
(M 124 947)

Figure 18.--Strain distribution in a 2 by 6 specimen for 3-1/2 and 7 percent increases In moisture content. Specific gravity of specimen = 0.45 and glueline thickness = 0.0625 inch



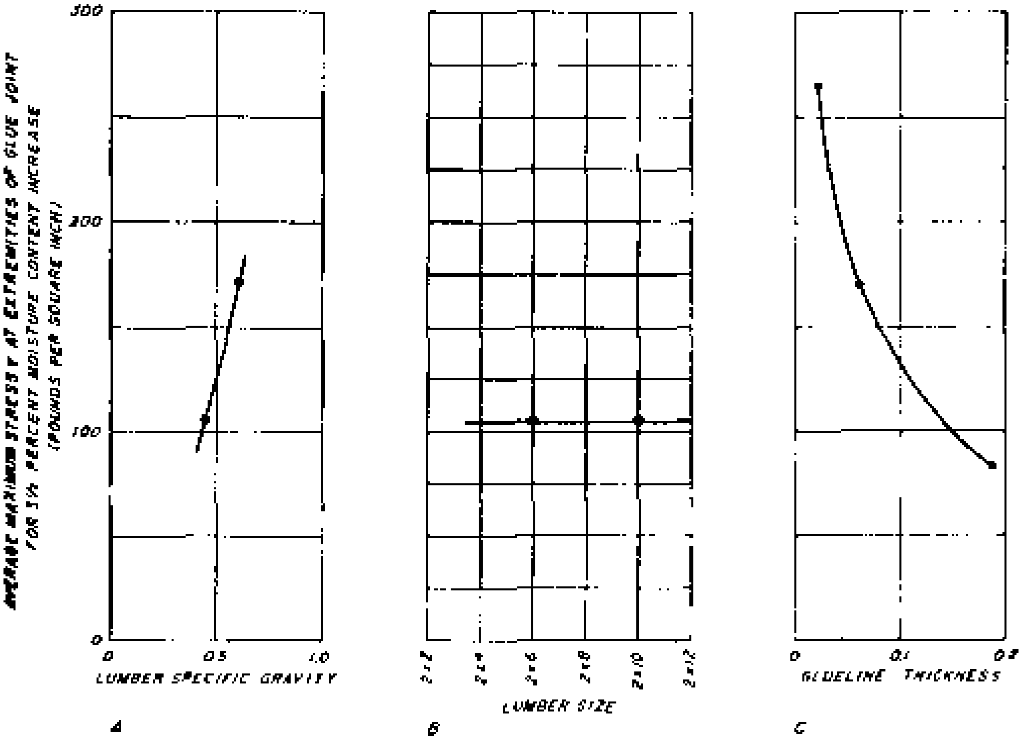
(M 123 006)

Figure 19.--Adhesive strains in a 2 by 10 specimen having a specific gravity of 0.45 and a glueline thickness of 0.0625 inch.



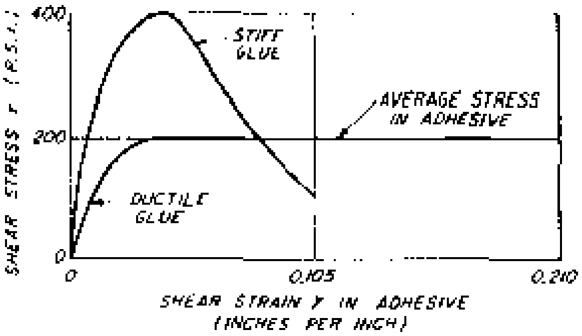
(M 124 941)

Figure 20.--Strain distribution in a 2 by 10 specimen for 3-1/2 and 7 percent increases in moisture content. Specific gravity of specimen = 0.45 and glueline thickness = 0.0625 Inch



(M 124 943)

Figure 21.--Summary of test data showing variation in average maximum stress versus: A, lumber specific gravity: B, lumber size: and C, glueline thickness.



(M 124 940)

Figure 22.--Hypothetical stress-strain relations.

DISCUSSION AND CONCLUSIONS

An analysis of the results obtained and any conclusions drawn must be based entirely on the observations of the strain photos and the calibration curve for one moisture content.

The most important observation is that the particular adhesive formulation tested has the ability to deform up to 0.625 inches per inch under a sustained load for 6 days without failure. This is a very desirable characteristic because it allows the wood adherends to move an amount almost equal to its unrestrained swelling deformation without fracturing the wood or the adhesive layer.

The concept of a flexible adhesive acting as a strain-absorbing component is in fact demonstrated in the photographic data presented.

The nature of the stress-absorbing capacity can take at least two forms. First, it would be desirable from a predictability standpoint to have an adhesive that would deform almost 100 percent elastically to meet any swelling condition. The specified modulus of rigidity for the adhesive would be a function of the shear strength and maximum anticipated unrestrained swelling strain of the adherend. Since the wood and adhesive must be in equilibrium with respect to total shear force and the deformations in the adhesive and the wood are identical, equilibrium must be reached at some point between the theoretical extremes of zero restraint (no stress in the wood) and infinite restraint (zero strain in the glue and maximum stress in the wood).

The modulus of rigidity of the adhesive must be such that this equilibrium will be reached before a critical or failing stress is induced in either the adhesive or wood, within the range of maximum swelling strain.

A second form of absorbent material would be one similar to that demonstrated here, in which the adhesive deformation is essentially visco-elastic or time dependent. The problems in this instance, of course, are the time-rate of load function, as well as the possible loss of strength resulting from plastic yield: however, if the visco-elastic material reaches shear equilibrium or has a yield limit, it could be used.

Using the calibration curve from figure 6 and strain data from figures 14, 16, 16, and 20, the average maximum stresses at the extremities of each of the four uncalibrated specimens are obtained. The results of the strain variation data for all six panels are shown in figure 21.

The average maximum stress would imply a severe increase with specific gravity, relatively no change with lumber size, and a large decrease with an increase in glueline thickness, as shown in figure 21.

Since there is a major decrease in stress with increase in glueline thickness, the shear stress cannot be constant from infinite to zero-edge restraint, but has to be some decreasing function,

On this basis, it can be concluded that a lower modulus of rigidity would decrease the stress in a thin glueline. The first analysis of the 2 by 6 replication having a 0.58 specific gravity and a 0.0625 glueline seemed to contradict this hypothesis since there was a 21 ratio of the measured strains. A recheck was made of the modulus of rigidity of the adhesive in these specimens and it was found to be different by almost a 2:1 ratio.

When this recalibration was taken into account the stress intensity and distribution was found to be approximately the same for both specimens.

It is difficult to say what actually did happen in these specimens since both the rate of load (swelling rate) and the material response (mechanical behavior) are time dependent. The final average shear stresses measured represent some equilibrium value after a given period of exposure time. It could be that the stress was actually higher at some time than that observed at equilibrium. This could have occurred if the adhesive exhibited a type of yield behavior shown in figure 22.

The important fact is that even if the calibration curves are in error, the resultant measured stress distribution is an indication of the true stress situation and the true stress will be in direct proportion to that shown in figures 9 and 12. These figures show a maximum stress of 200 pounds per square inch resulting from a 3-1/2 percent change in moisture content. The true maximum stress would be in direct proportion to this value.

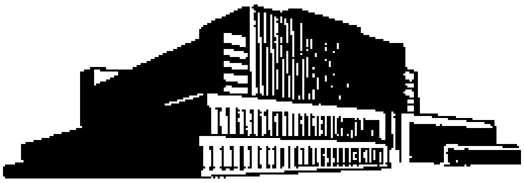
The strain distributions presented show almost a linear increase with respect to horizontal position. This would be characteristic of an adhesive with a very low shear modulus, such that the elastic properties of the adherends are high compared to the adhesive. For a more rigid adhesive system, it would be expected that the stresses would be concentrated more at the transverse extremities.

The data do not provide quantitative results on the variation of stress with moisture content, but from the strain diagrams it would he reasonable to expect a nearly linear increase in stress as the moisture content increases.

In summary the technique of determining stress variations and intensities in a gluejoint by means of a calibrated adhesive, used as a strain recording tool, can be extremely useful.

The method is relatively rapid, with precision increasing with increases in adhesive thickness and with decreasing modulus of rigidity because of the magnitudes of the relative deformations. The adhesive used in this study has obvious disadvantages in its calibration, but an adhesive with nearly 100 percent elasticity in the working range of the stress induced in wood bonding would make the technique simple.

This type of information, regarding both the mechanical behavior of the adhesive and the forces induced into the joint, is fundamental to the proper use and design of an adhesive for a particular application.



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