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PERFORMANCE OF A RIGID AND A FLEXIBLE ADHESIVE IN LUMBER JOINTS SUBJECTED TO MOISTURE CONTENT CHANGES

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PERFORMANCE OF A RIGID AND A FLEXIBLE ADHESIVE IN LUMBER JOINTS SUBJECTED TO MOISTURE CONTENT CHANGES

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Summary

Experimental work was undertaken to investigate the extent and magnitude of deterioration that can occur in typical plywood-to-lumber glue joints subjected to stresses resulting from changes in the moisture content of the wood, and to compare the performance of a somewhat flexible or deformable adhesive to that of a rigid adhesive in these joints.

Results showed that the degradation of lumber-to-plywood joints can be very severe as a result of one cycle from 80° F. and 30 percent relative humidity, to 80° F. and 97 percent relative humidity, returning to a low moisture condition. Failure included physical destruction of the lumber, glue, or plywood, or only a weakening of the joint, depending on the orientation of the plywood face grain to the grain of the lumber. Losses in shear strength of exposed joints exceeded 30 percent in some cases when compared to control joints.

In joints where conditions of specific gravity and wood quality permitted direct comparison of the rigid resorcinol-resin glue and the somewhat deformable modified epoxy-resin adhesive, the deformable adhesive showed distinct superiority.

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

Introduction

One of the major concerns of the timber fabrication industry is the possibility of glue joints being weakened or destroyed by internal stresses without the glue–line being degraded. These internal stresses are induced by swelling and shrinking of one or more structural joint components as the moisture content changes in the wood due to atmospheric moisture changes. Effects of such induced stresses are most severe in constructions where the grain of adjacent plies is at angles as compared to parallel grain, and in constructions utilizing higher density woods.

This particular plywood-to-lumber construction is of concern to plywood component fabricators, and manufacturers of prefabricated houses, roof trusses, furniture, and other wood products. In principle, the concern of stresses in joints at considerable grain angles is industry–wide.

This study was designed to explore induced stresses in typical plywood–to–lumber joints and to investigate a means of stress alleviation, particularly the possible advantages of a glueline that has some controlled degree of deformability when compared to conventional rigid woodworking glues.

The study of moisture–induced stresses on plywood–to–lumber glued joints requires a consideration of the following questions:

(1) Does a critical situation actually exist? Can such glued–wood joints be weakened or destroyed by swelling and shrinking? In such adverse changes, is the wood or the glueline most damaged?

(2) What is the extent or severity of the physical joint deterioration if it exists?

(3) What are the probable consequences of joint deterioration due to such stresses in practical applications?

(4) What variables or factors influence joint damage in addition to the moisture content change?

In anticipation of some degree of joint deterioration with standard, rigid adhesive joints, a partially deformable experimental adhesive with relatively low shear modulus was included for comparison with the rigid joint specimens.

The reason for using a deformable adhesive was the expectation that it would absorb some of the strain. This characteristic would, in theory, relieve the internal stresses to some extent; however, the other variables involved in such a joint study were not well established and were to be determined as adequately3 as possible with the experimental techniques used,

Experimental Conditions

Selection of Specimen Joint

After a detailed examination of the type of joints used in plywood-lumber component construction, the specimen was chosen to represent or typify some of the most common types and sizes of joints, using 3/4-inch plywood panels bonded to both sides of nominal 2-inch lumber boards (fig. 1).

Typical plywood-to-lumber joint construction might occur in such structural units as rigid frames, light wood trusses (1,8),[2] flat stressed-skin panels (7), arched stressed-skin panels (5), plywood box beams (4), and other types of plate (6) or shell combinations.

Load Conditions

The type of stress induced in these joints from externally applied loads was recognized as a factor which would influence performance.

To avoid the complexity of externally induced joint stresses, if superimposed on the internal stresses due to moisture content changes, all evaluation of specimens conditioned to specified moisture contents was therefore done without applied external loads.

Generally, the methods of joint fabrication and material preparation were governed by accepted good practice (10). For special variables, such as range of moisture content considered typical for external or interior conditions, the Douglas Fir Plywood Association's General Design Specification No. 1 (3) was used as a guide.

Materials

Lumber

Commercial flat-sawn Coast-type Douglas-fir lumber, C and Better grade, was used for the evaluation. This lumber was purchased as kiln dried and was supplied in the range of 6 and 12 percent moisture content, and surfaced four sides. The sizes used were nominal 2 by 2, 2 by 4, 2 by 6, 2 by 8, 2 by 10, and 2 by 12 inches, all 12 feet in length.

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

Plywood

The plywood was commercial 5–ply 3/4–inch exterior–type Douglas–fir, with A–C faces. This plywood was used exclusively throughout the work.

Adhesives

Two different adhesives were used to bond plywood to lumber in the study. They differ in the chemical type as well as in the elastic behavior.

The conventional adhesive was a standard commercial phenol–resorcinol resin glue with a paraformaldehyde hardener (room temperature setting). This adhesive had been studied previously (11) and the elastic modulus of rigidity[3] determined to be approximately 135,000 pounds per square inch after a 7–day cure at room temperature.

The flexible adhesive was an experimental modified epoxy–resin formulation previously used at the U.S. Forest Products Laboratory. This was composed of 100 parts by weight of a commercial bisphenol-A-epichlorohydrin epoxy resin, 10 parts by weight of diethylenetriamine curing agent, and 70 parts by weight of a commercial polysulfide rubber. The apparent modulus of rigidity of this adhesive had previously been determined as approximately 12,000 pounds per square inch after 8 days' cure at room temperature and 15,000 pounds per square inch after 28 days' cure at room temperature (11). Block shear tests from previous data[4] indicate that the epoxy adhesive would develop adequate shear strength in Douglas–fir parallel to the grain, resulting in 100 percent wood failure when tested dry after a 24–hour cure at room temperature. Such joint strengths were therefore comparable in this respect to those of the phenol–resorcinol resin glue.

It is important to note that the modulus of rigidity of Coast–type Douglas–fir has been reported as approximately 13,000 pounds per square inch in the radial–tangential plane at 11.2 percent moisture content (9). The adhesives used then have elastic properties approximately equal to (epoxy–polysulfide), and 10 times (resorcinol formaldehyde) the modulus of rigidity of the wood in the plane of maximum swelling strain.

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[3] "Modulus of rigidity" is defined as the elastic property computed by dividing shear stress by the corresponding shear strain.

$$G = \frac{\tau}{\delta}$$

G = Modulus of rigidity
τ = Shear stress = pounds per square inch
δ = Shear strain = inches per inch

[4] Krueger, G. P. Techniques for determining the modulus of rigidity of an adhesive in a timber joint and some applications of engineered adhesives, M.S. Thesis, University of Wisconsin, 1961.

Experimental Procedure

Moisture Content Change Cycle

The range of moisture content in use that is specified for "exterior use" according to Douglas Fir Plywood Association (3) is 3 to 21 percent. This would be a moisture content change of 18 percent. The cycle chosen for the present study was from approximately 7 to 24 percent moisture content, a change of 17 percent. The test consisted of one cycle, This cycle started at 7 percent (in approximate equilibrium at 80° F. and 30 percent relative humidity), increased to 24 percent (approximate equilibrium at 80° F. and 97 percent relative humidity), then dropped again to 7 percent moisture content (80° F. and 30 percent relative humidity). The cycle was begun at the low moisture content level which was the condition when joints were glued.

Lumber and Plywood Orientation

In typical plywood-to-lumber joint designs, the restraint imposed by plywood glued to the lumber can take three possible forms: (1) restraint on the outer tangential face of the lumber with respect to the annual rings (bark side), (2) restraint on the inner face of the lumber with respect to the annual rings (pith side), and (3) restraint on both sides of the lumber. The third type was employed in this evaluation. This discussion presumes that the lumber will be flat-sawn with the tangential plane approximately parallel to the wide face of the board, giving a maximum swelling stress parallel to the glueline (fig. 2). In this study, two plywood grain orientations were used: The face grain of the plywood was arranged either perpendicular (90° orientation) or parallel (0° orientation) to the lumber longitudinal grain, to represent the two most extreme swelling conditions (fig. 2).

Adhesive Thickness

Normally, adhesive thickness is not a consideration in an evaluation of bonded joints, since typical wood glues are normally used with thin gluelines of 5 mils or less. In this study it was significant. The epoxy resin has good dimensional-stability and gap-filling properties and can be spread or even cast to any reasonable thickness without encountering bonding problems. The adhesive will bond satisfactorily without any appreciable external gluing pressure and, because of the high solids content and complete reactivity, will not shrink and crack during the cure stage. Because the purpose of the flexible epoxy-resin formulation was to absorb energy or swelling deformations, it is apparent that a thicker than normal adhesive film would absorb more swelling. The optimum thickness of the epoxy resin for this purpose was unknown, so the gluelines were arbitrarily made three times the thickness of the phenol-resorcinol film. The resorcinol film normally will cure to approximately 0.005 inch under apressure of 150 pounds per square inch. The epoxy film then was made approximately 0.015 inch thick. No spacers were required in this case because 0.015 inch was a normal thickness with the particular epoxy resin formulation when a minimum pressure is applied.

Initial Test Conditions

All lumber, plywood, adhesives, and containers were conditioned at 80° F. and 30 percent relative humidity prior to gluing and testing to conform to initial test conditions. Wood components were at approximately 7 percent moisture content when in equilibrium with these conditions.

Lumber Preparation and Conditioning

Twenty-four pieces of each of the sixlumber sizes (2 by 2 to 2 by 12) were cut from the Douglas-fir lumber into 30-inch lengths. Prior to cutting the 30-inch lengths, these sections had been selected to be free of skip or wane and so that all knots were small, tight, and sound. The material was all essentially flat grain with relatively uniform annual ring curvatures.

Fifteen days after conditioning at 80° F. and 30 percent relative humidity and just prior to gluing the lumber, the moisture content was determined by oven-drying. Moisture contents were found to vary between 8 and 9 percent, with an average of 8.5 percent.

The Douglas-fir plywood was cut from nine 4- by 8-foot panels and marked so that the positions of individual pieces could be identified for correlation later in the test.

After cutting 30-inch lengths into adequate widths to cover the various lumber sizes, the plywood was also conditioned at 80° F. and 30 percent relative humidity.

Gluing Procedure and Specimens

Epoxy-resin panels.--The epoxy panels (fig. 1) were bonded first. Twelve 30-inch panels were glued, two for each of the six lumber sizes. Of the two panels for each lumber size, one had the face grain of the plywood oriented parallel and one had the plywood face grain oriented perpendicular to the longitudinal grain of the lumber. The A-grade face of the plywood was always bonded to the lumber.

The short pot life of the epoxy-resin adhesive made it impossible to glue all specimens with one batch of mixed adhesives. Therefore, four batches of 540 grams each were used, but all gluing was done on the same day.

Twenty to 24 hours before gluing, the lumber was surfaced by running one face over a jointer and the other through a single-head planer.

The gluing operation consisted of spreading both faces of the glue joint (four surfaces per panel). The adhesive was spread with a brush in the longitudinal grain direction of the lumber. After 5 to 10 minutes of open assembly, the assembled components were set into an 18- by 60-inch screw press bed, but no pressure was exerted by the screw press until the entire 12-panel layup was complete. When the layup was complete, a slight, unmeasured pressure was exerted by jackscrews to maintain the assemblies in position during cure at 80° F. and 30 percent relative humidity.

The total amount of adhesive (double spread) averaged130 pounds per thousand square feet of glue joint area. Twenty-four hours after gluing, the panels were removed from the press and placed in a 80° F. and 30 percent relative humidity conditioning room to cure and condition for 8 days.

On the ninth day after gluing, the panels were cut into 12 cross sections, each 2-3/8 inches along the grain of the lumber. The joints were then weighed at 80° F. and 30 percent relative humidity, and the control specimens were kept at these conditions while exposure specimens were stored at 80° F. and 97 percent relative humidity. Figure 3 illustrates a typical 30-inch bonded panel cut into 2-3/8-inch joints. The exposure and control joints are shown in their relative positions as they were taken from the panel.

Resorcinol-resin panels.--Equipment capacity limited the number of resorcinol panels that could be bonded in one day, and, therefore, gluing was done on three consecutive days. The lumber and plywood were prepared and conditioned in the same manner described for the epoxy-bonded panels. The only exception to this procedure was an additional day of conditioning at 80° F. and 30 percent relative humidity.

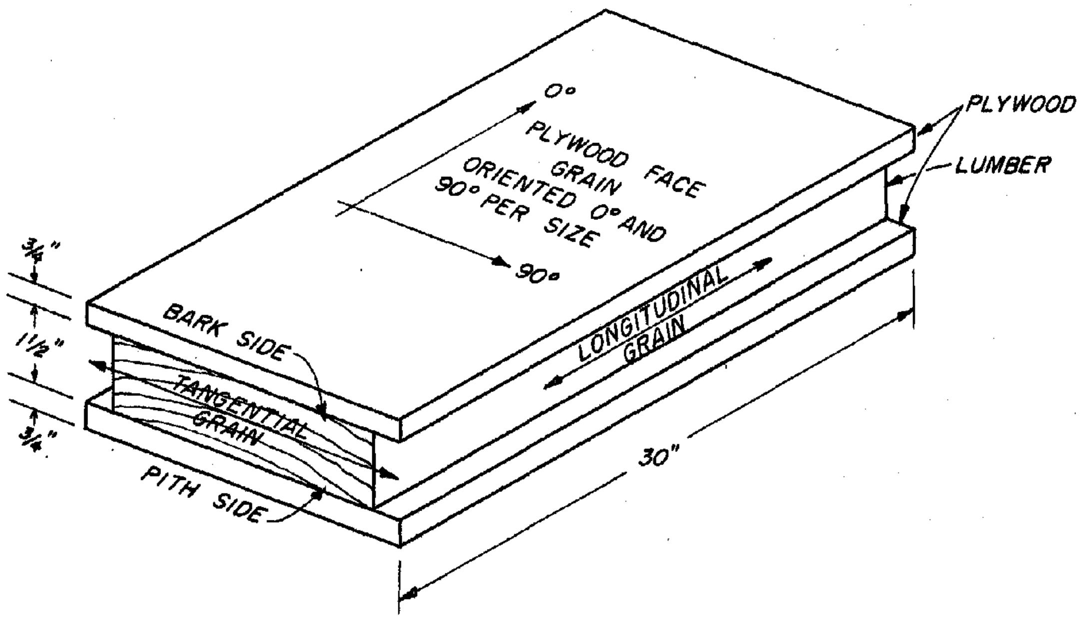

Figure 1.--Plywood panels were bonded to both sides of nominal 2-inch boards to form bonded panel from which specimens were cut. Lumber sizes used were nominal 2 by 2, 2 by 4, 2 by 6, 2 by 8, 2 by 10, and 2 by 12 inches.

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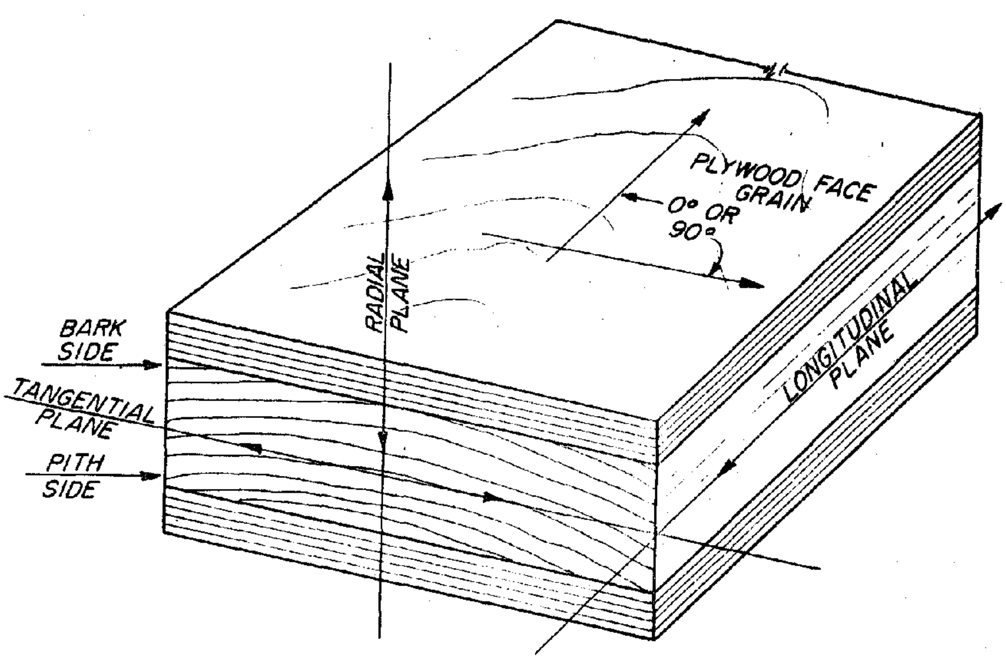

Figure 2.--Orientation of plywood to lumber in bonded panel from which specimens were cut.

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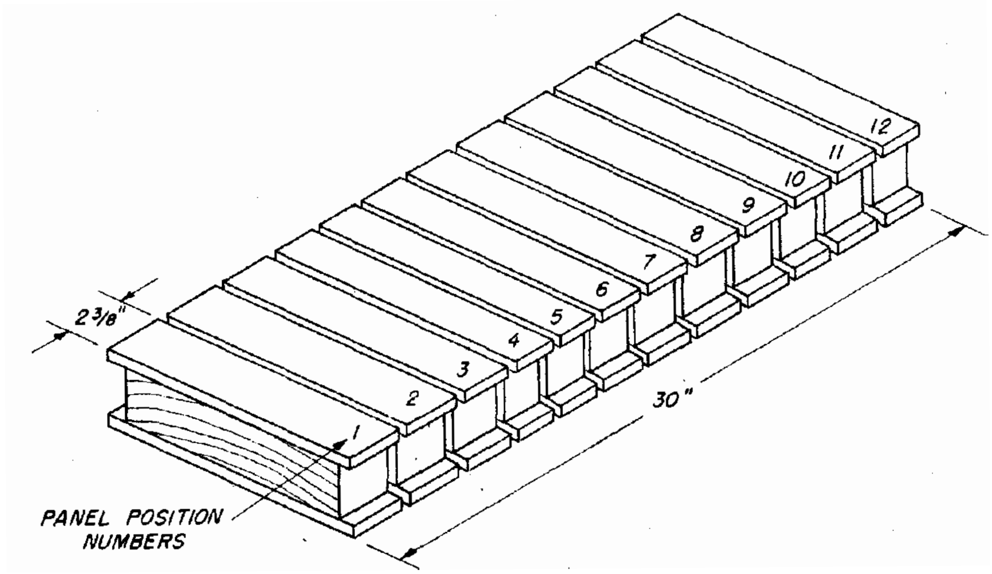

Figure 3.--Method of cutting test and control joints from bonded panel. Even numbers refer to control joints; odd numbers refer to exposed joints.

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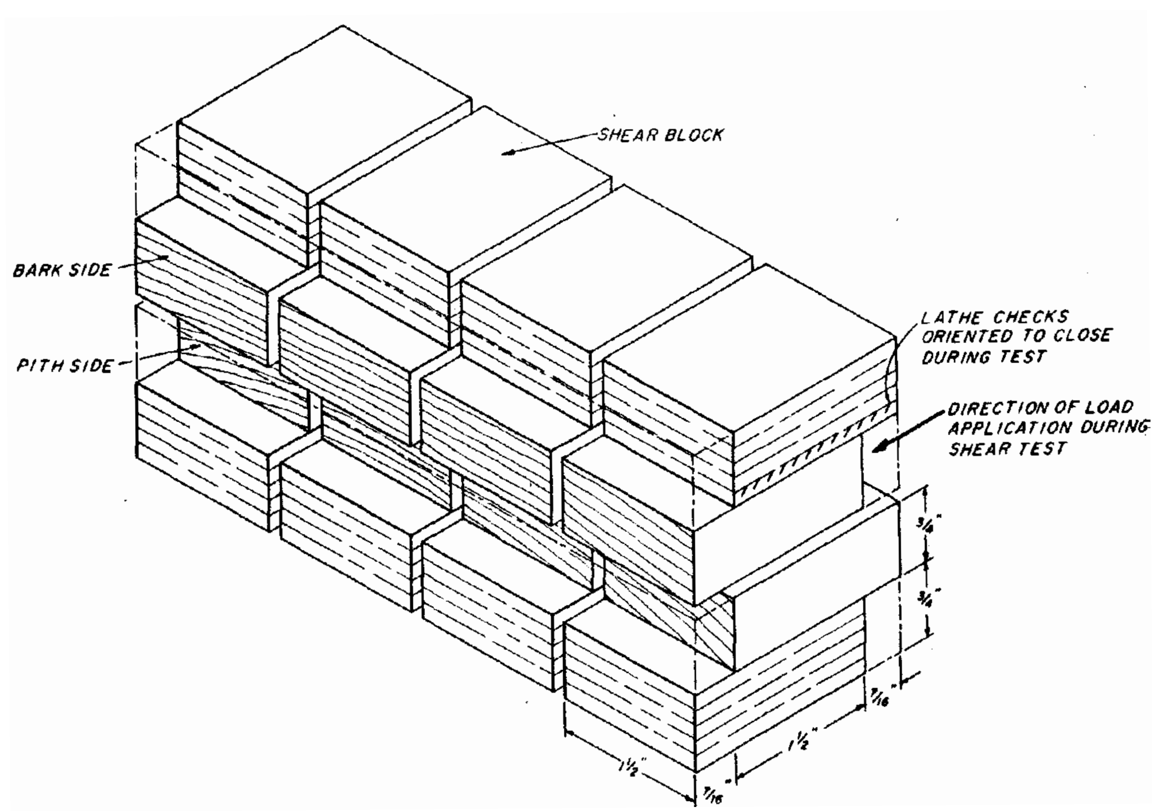

Figure 4.--Method of cutting joints into shear blocks for evaluation.

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On each day of gluing, the resorcinol–resin adhesive was mixed in one batch and applied with brushes to both bonding surfaces in a direction parallel to the longitudinal grain of the lumber. The average total amount of adhesive spread for each of the three batches was 100 pounds per thousand square feet of joint area. In each layup, the open assembly time varied from 5 to 10 minutes, and the subsequent closed assembly time varied from 15 to 20 minutes. In no instance was a batch of mixed adhesive used after 60 minutes from the time of mixing.

In each layup of the resorcinol–resin panels, pressure was applied by jackscrews and measured with a compressometer. The average pressure applied to each layup was 150 pounds per square inch, and it was maintained for 20 hours at 80 ° F. and 30 percent relative humidity,

Each resorcinol–resin panel was removed from the clamps 20 to 22 hours after gluing and remained at 80° F. and 30 percent relative humidity until the last assembly had been removed on the fourth day from the start of gluing. All the resorcinol panels were stored and conditioned at 80° F. and 30 percent relative humidity for 7 days after the last assembly was removed from the press. On the eighth day, the panels were each cut into six test and six control joints in the method shown in figures 3 and 4, After cutting, loose fragments were brushed from the joints and the specimens were weighed. The joints for the controls were stored at 80° F. and 30 percent relative humidity, while the exposure joints were stored at 80° F. and 97 percent relative humidity.

As the specimens were weighed for each adhesive at the time the 2–3/8–inch joints were cut, it was noted that there was no consistent weight gradient or increase from the ends to the center of the 30–inch panels. The gradient, had it existed, might have implied nonuniform moisture content and inadequate conditioning.

Exposure Procedure

The specimens for each adhesive type were started on an exposure cycle at 80° F. and 97 percent relative humidity at different times; consequently, the cycling records are independent. The average rate of moisture increase for each adhesive type is given in table 1.

On the 14th day after exposure at 80° F. and 30 percent relative humidity samples were cut from representative joints from each resorcinol panel for a moisture content determination by ovendrying and a specific gravity determination on each panel. The same procedure was used for the epoxy–resin panels, except the determination was made after 11 days of exposure at 80° F. and 30 percent relative humidity (table 2).

The data presented are not meant to imply that equilibrium had been reached in all the specimens, but after approximately 26 days the weights were changing at a very slow rate and it was considered unnecessary to continue the exposure cycle.

Shear Specimen Preparation and Evaluation Procedure

One of the primary objectives of this study was to determine the amount of degradation of the joints that had gone through the humidity exposure cycle.

For this evaluation, several methods were considered. These included a tension test (12) and use of a penetrating dye to reveal separations in the joints. Many of the joints did not have separations, and the swelling stress creating joint degradation was considered to be only a function of the transverse dimension rather than both the transverse and longitudinal dimensions; therefore, neither of these methods were considered applicable, and it was decided to use a modified block shear test. This block shear test was performed on the standard block shear testing equipment (2). This test seemed most applicable to reveal variations in joint strength in the transverse direction.

Figure 4 illustrates how atypical joint was cut into shear blocks for evaluation. The evaluation of a joint in this manner permitted the study of strength losses with respect to the transverse position across the joint, as well as with respect to joint orientation to the annual rings of the lumber, Both exposed joints and the control joints that had been stored at 80° F. and 30 percent relative humidity for about 30 days were cut by the method shown in figure 4. The modification of the standard shear test was to use a 1–1/2–inch width instead of 2 inches, thus producing a shear area of 2.25 square inches instead of the usual 3 square inches. The plywood adjacent to the lumber was examined and the blocks cut in a manner so that the shear load would close the lathe checks in the veneers during testing. This orientation was governed by the face ply for 90° orientation joints and by the second ply for 0° orientation joints. All shear tests were made in the dry condition.

The 2– by 2–inch sections were cut into two exposure specimens (one from each lumber face), 2– by 4–inch sections were cut into four specimens; 2– by 6–inch, cut into six specimens; 2– by 8-inch, cut into eight specimens; 2– by 10–inch, cut into 10 specimens; and the 2– by 12–inch, cut into 14 specimens per joint. All shear specimens were stored at 80° F. and30 percent relative humidity until the time of evaluation.

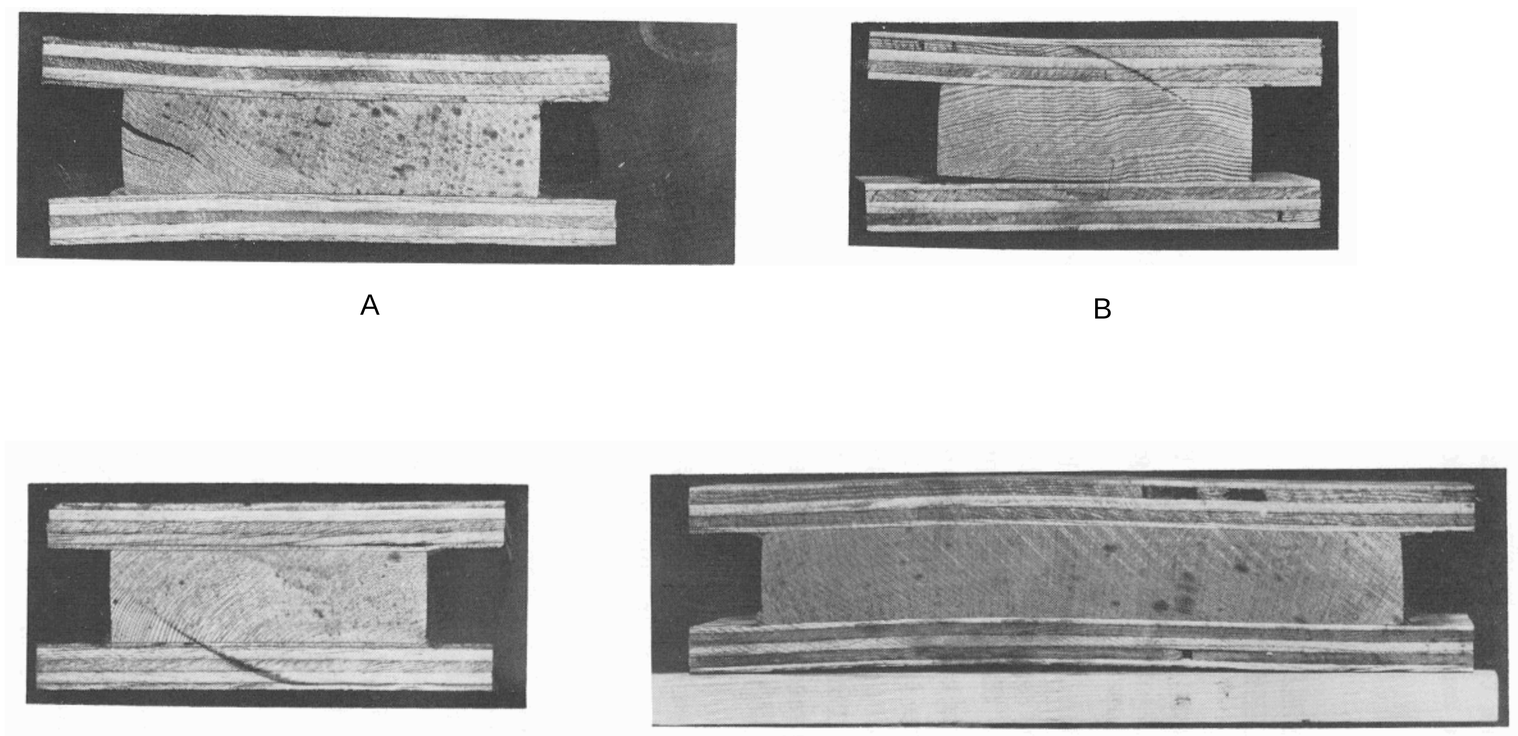

Figure 5.--Examples of typical joint failures during the exposure cycle: A is a type I failure on a 2 by 8 joint; B is a type II failure on a 2 by 6 joint; C is a type III failure on a 2 by 6 joint; and D is an example of warping of a joint.

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Results and Observations

Exposure Cycle

An important part of the experimental results was the observation and measurements of joint degradation that occurred during the exposure period. These observations were made during the increasing moisture content phase as well as during the decreasing moisture content phase of the cycle.

There were three general types of failure in the exposed specimens during the increasing moisture content phase of the cycle. These types of failures, designated as I, II, and III, are illustrated in figure 5.

Failure type I was a tangential check in the lumber caused by tension on the exposed fibers of the wood.

Failure type II was a joint separation that could occur at the lumber–glue interface, or entirely within the adhesive layer as a result of primary shear stress and some tension on the glue joints.

Failure type III was entirely plywood destruction occurring only in the specimens with 0° plywood orientation. This type of failure was most pronounced in the joints that had a rough cut plywood face ply so that the lathe checks were deep and slanted in opposition to the direction of shear force.

All specimens exhibited some degree of warp as illustrated by the 2 by 12 in figure 5. The direction of the warp varied with the individual grain and annual ring orientations.

Epoxy-Bonded Specimens

During the increase in moisture content from approximately 7 to 23 percent of the epoxy joints, 3 out of a total of 72 exposed joints showed some minor destruction to the joints. All three were 2 by 8 specimens with 0'' grain orientation. One had a type II and two had type III failures.

During the drying phase of the cycle, which decreased the moisture content from approximately 23 to 7 percent, no additional destruction of the joints was noted. Large radial drying checks appeared in almost every specimen and it was noted that, for the most part, all specimen warping was removed

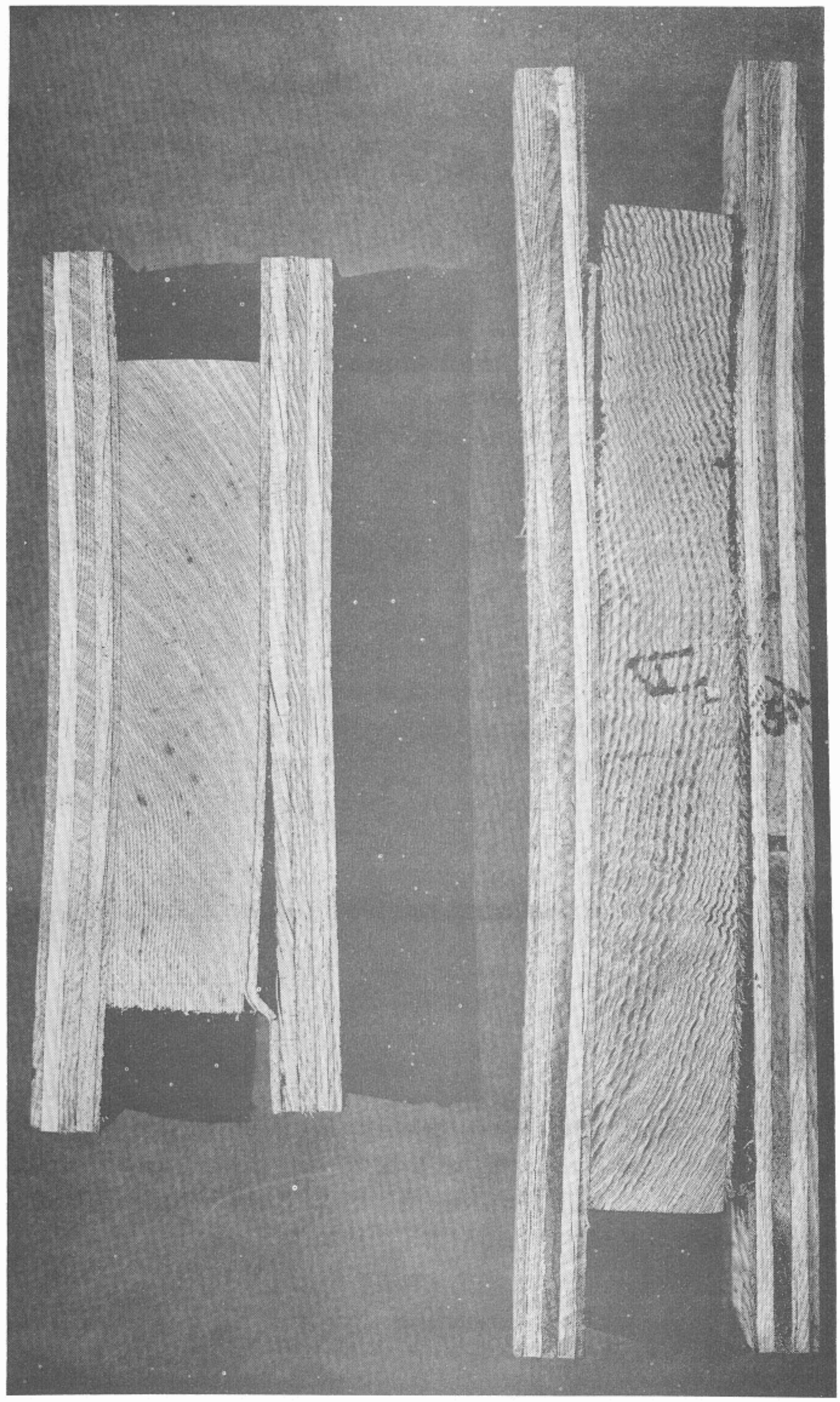

Figure 6.--Examples of typical type III failures in the exposed resorcinol-resin glued joints.

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Resorcinol-Bonded Specimens

During the increase in moisture content from approximately 7 to 25 percent, 15 out of 72 specimens exhibited major destruction to the first plywood ply. (Type III failure in the plywood with 0° orientation was noted in 6 of the 2 by 8, 3 of the 2 by 10, and 6 of the 2 by 12 size.) In some instances, the separation amounted to two-thirds of the length of the glue joint.

The drying phase of the cycle, which decreased the moisture content from approximately 25 to 6 percent, produced no additional visible degradation except in one 2- by 8-inch, 0° orientation specimen where a 1-inch separation occurred at one end. In addition, there were scattered radial drying checks and slight lathe check openings in the face ply of the plywood where the slope of the checks was in opposition to the direction of drying shear stresses.

Figure 6 illustrates some of the typical type III failures in the resorcinol joints.

Types of Shear Failures Resulting From Block Shear Tests

After the shear test specimens were cut from the large assemblies following exposure, the specimens were evaluated in the dry condition. It was necessary to examine and classify the broken specimens on the basis of the failure, so that accurate comparisons could be made between exposed and control specimens as well as between adhesives. Valid comparisons could be made only if the type of failure was essentially the same in all cases.

Four zones of failure were considered for characterizing the types of joint failure (figs. 7A and 7B). Zone 1 is failure primarily in the lumber, zone 2 is failure primarily in the face ply of the plywood, and zone 3 is shear failure at the interface between the first and second plywood plies. Zone 4 is a rolling shear failure in the second core ply for joints with 0° grain orientation. Since the swelling and shrinking stresses could have an effect on the strength of the lumber or of the face ply of the plywood, failures in zones 1, 2, and 3 were considered as being a general critical zone. All failures, however, were wood failures at one of the designated positions.

Inspection of the 0° orientation specimens showed that generally the percentage of the specimens that failed in the strong critical zone (zones 1, 2, and 3 of fig. 7A) was not substantially different between test specimens after exposure and unexposed controls. Where there were differences, as a result of exposure, the

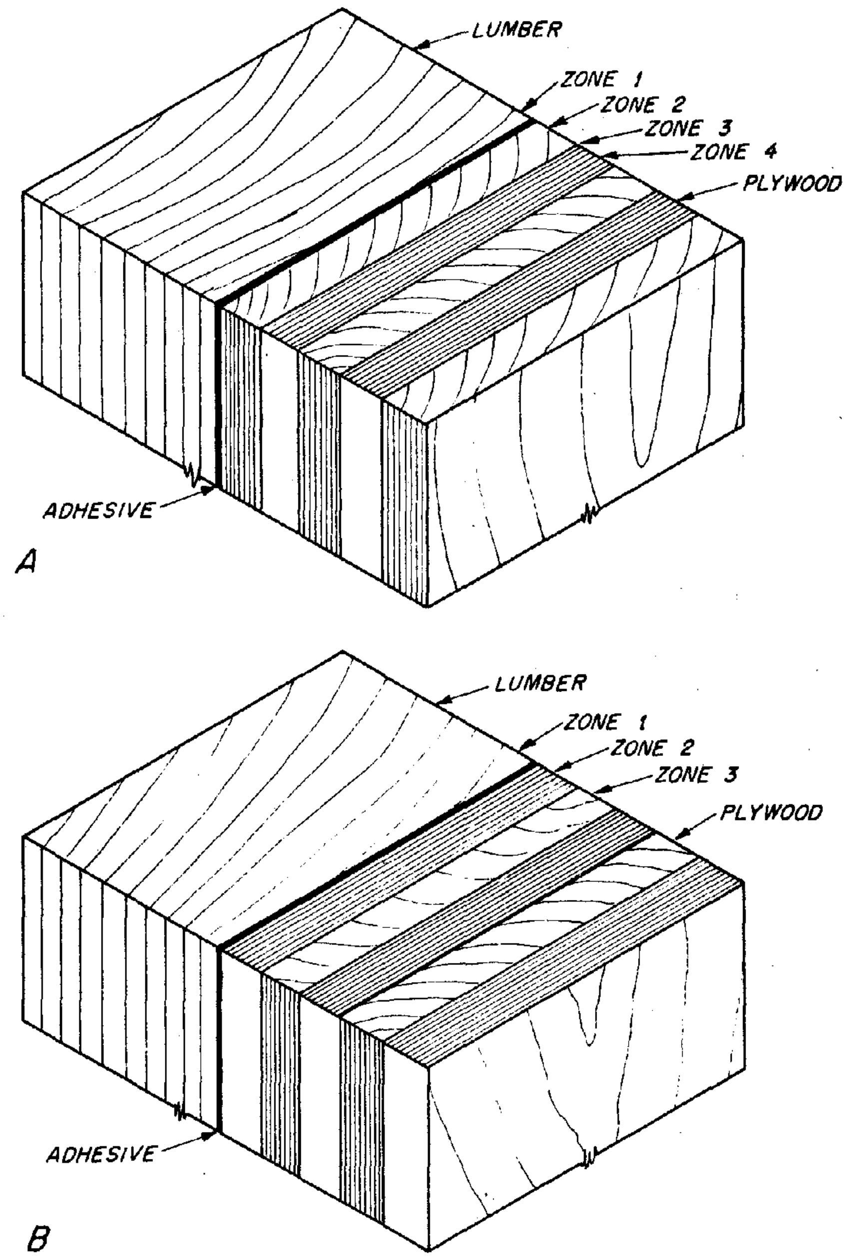

Figure 7.--A, zones of failure with plywood at 0° orientation to the lumber; B, zones of failure with plywood at 90° orientation to the lumber. Zone 1 is a failure primarily in the lumber, zone 2 is a failure primarily in the face ply of the plywood, zone 3 is shear failure at the interface between the first and second plywood plies, and zone 4 is a rolling shear failure in the second core ply.

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rolling shear failures in the second core ply did not lower the average strength values. The differences between the resorcinol and epoxy adhesives were noticeable because the epoxy blocks had about 50 percent of the failure in the critical zone and 50 percent rolling shear in the second core ply, whereas the resorcinol blocks had 94 percent in the critical zone. The epoxy joint loads, however, were of the same order of magnitude as the resorcinol joints.

For the 90° grain orientation (fig. 7B) specimens, there were no major differences between the exposed blocks and the controls with respect to the nature of shear failure for either adhesive. The difference between the resorcinol and the epoxy blocks, however, was noticeable. The epoxy blocks had 100 percent rolling shear failure in the plywood face ply, but the resorcinol blocks had 82 percent in rolling shear and 18 percent in the lumber.

In all cases where the joints had not separated during the exposure cycle, there was 100 percent wood or plywood failure in the shear blocks as a result of the shear tests. Where separations had occurred during the exposure cycle, the block could not be evaluated and zero load was recorded.

Shear Test Results

The ultimate failing load was recorded in pounds for each shear specimen.

Each block had an area of 2.25 square inches so that the conversion to average block stress in pounds per square inch is linear. The average stress per 2-3/8-inch-wide joint (fig. 3) was computed by averaging the pounds per square inch values for the individual shear specimens (fig. 4).

The joint loads, which are the sum of the individual shear specimen, loads in pounds are tabulated in tables 3 to 10. These tables are separated according to size, panel position (fig. 3), plywood orientation, and bark side or pith side, respectively, with respect to the annual rings.

Figures 8 and 9 summarize the average stress values (in pounds per square inch) at failure for all specimens per panel with the two adhesives. This summary is also divided according to size and orientation. The percent reduction in strength of the cycled joints is indicated for each size and was computed by the following formula:

$$\frac{\text{Average control load} - \text{average test load}}{\text{Average control load}} \times 100 = \text{percent reduction}$$

(Average test load was the value after the exposure cycle.)

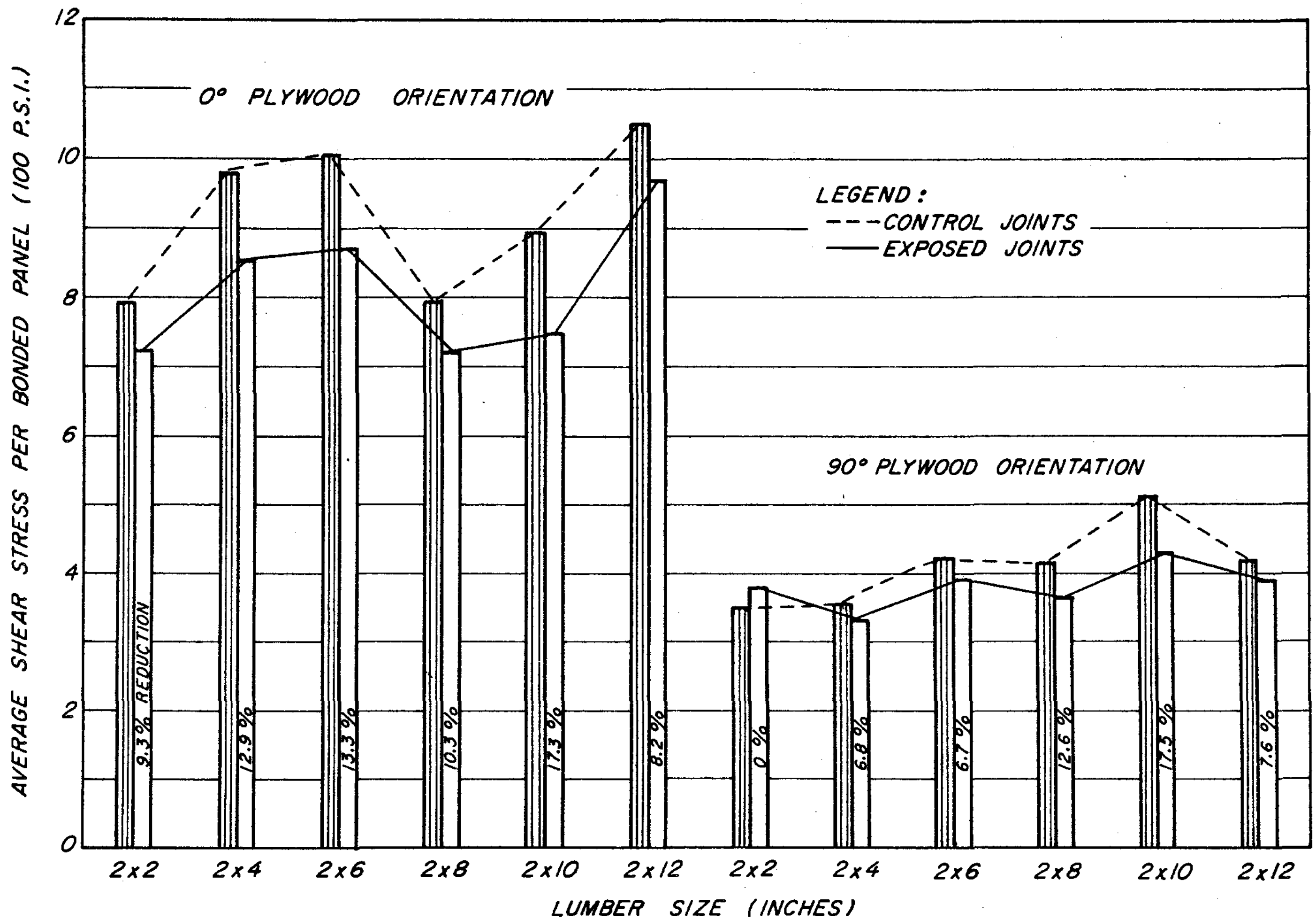

Figure 8--Comparison of average stress values for the control joints and the exposed joints made with epoxy-resin adhesive. Percent reduction is the percentage difference between the values for the control joints and the exposed joints for each size. Control joints are designated by lined bars, and exposed joints by clear bars.

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The average stress values in pounds per square inch shown were computed by averaging the ultimate loads for all shear specimens cut from each of the six joints for each joint size of each adhesive and then reducing the load to a common denominator by dividing by the total shear area of these joints.

Table 11 summarizes the percentages of reduction of strength as computed and lists the corresponding average lumber specific gravities for the particular panel size and the number of the plywood panel that was bonded on the bark and pith sides of the boards.

In the process of analyzing the block shear data, graphical profiles of block shear loads were plotted with respect to their transverse positions across the joint. It was anticipated that there would be noticeable decreases in block loads at the transverse extremities of the joints. This characteristic was expected especially in the larger joint sizes where there were 8 shear specimens per joint for the 2- by 8- size, 10 for the 2- by 10-size, and 14 for the 2- by 12-inch size. All of the data were plotted in the manner described, but in 0° or 90° orientation there was no consistent indication of any lower strengths for specimens cut from the edges of the wider panels in instances where there was an actual joint separation.

When the average exposed joint stress showed a decrease compared to the control joints, the weakening or decrease was generally constant throughout the joint.

Statistical Analysis of Test Data

A statistical analysis was made to determine whether the loss of strengths of the cycled joints, as compared to the control joints, was significant or within the range of the variability of the material. Table 12 lists the mean square values for each adhesive, separated by size and orientation. The differences, as well as the least significant differences at various confidence levels, based on the mean square of error, are also tabulated. The last column indicates whether the difference between exposed joints and control joints was significant and at what confidence level, if there was a difference. The mean square terms are based on 12 values (using bark and pith sides) per size, per orientation, and per adhesive. These 12 values are tabulated in tables 3 to 10.

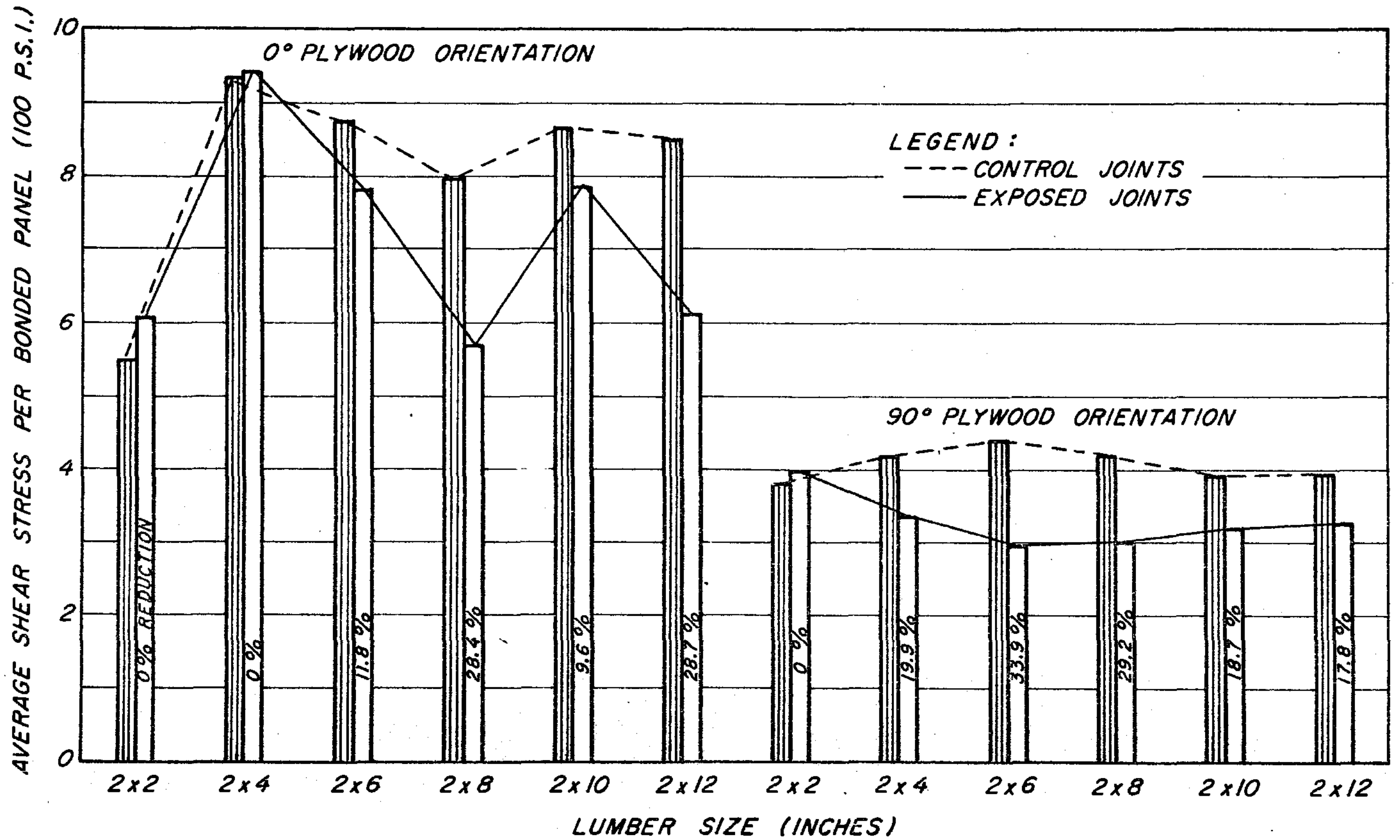

Figure 9--Comparison of average stress values for control joints and exposed joints made with resorcinol-resin adhesive. Percent reduction is the percentage difference between the values for the control joints and the exposed joints for each size. Control joints are designated by lined bars, and exposed joints by clear bars.

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Discussion of Results

Comparison of Specimens With 0° Plywood Orientation

A comparison was first made of the results for cycled joints and the control joints that had the plywood face grain oriented 0° to the lumber longitudinal grain.

From tables 11 and 12, the 2- by 2- and 2- by 4-inch sizes of the resorcinol joints showed no significant changes of strength after cycling. There were significant strength differences between cycled and control resorcinol-glued joints: The strength reductions were 11.8 percent for the 2 by 6 joint size, 28.4 for 2 by 8, 9.6 for 2 by 10, and 28.7 for the 2 by 12.

Correlating the strength reductions for joints that had a significant difference with delamination observations during the humidity cycle, it was noted that the large reductions in strength in the 2- by 8- and 2- by 12-inch sizes were directly attributable to actual joint separations during cycling. In the sizes from 2 by 6 through 2 by 12 inches, 62-1/2 percent of the joints made with the resorcinol-resin glue exhibited some degree of the type of plywood destruction shown in figure 6.

The epoxy-resin joints that were cycled, which had reductions of 9.3 percent for the 2- by 2-inch joint size, 10.3 for 2 by 8, and 8.2 for the 2 by 12, were not significantly different from the controls for those sizes. However, the reductions of 12.9 percent for the 2- by 4-inch joint size, 13.3 for 2 by 6, and 17.3 for the 2 by 10, were significantly different from the controls. The observations during the humidity cycle showed that, of the sizes that had significant differences, none had visible physical destruction occurring during cycling. Only the 2- by 8-inch joint sizes had three joints with minor degradation.

In all instances for any adhesive, the amount of joint destruction must be a function of the intensity of shear stress induced at the glueline as a result of the swelling strain. For the 0° orientation specimens, two factors appeared to have a marked effect on the magnitude of the results reported previously on the basis of the observed specimen warp and physical destruction. One factor was the specific gravity of the lumber and the other was the quality of the face ply of the plywood. The width of the lumber appeared to have no consistent influence on the average percent reduction of strength or on the joints which showed significant differences between cycled and control specimens.

In view of the conditions stated previously, a valid comparison of adhesive performances can only be made where there is a direct correlation of lumber specific gravity and plywood panel number. In this correlation, on the basis of percent reduction of strength, it would seem reasonable to disregard the size effect and compare all sizes of 2 by 6 through 2 by 12 as a group. In a comparison of specific gravities between adhesives, there are no joints that have a direct correlation for the same plywood panel numbers. There are two points to be considered, however. It was possible to check for consistency of results for certain resorcinol-glued joint specimens with the same plywood panel numbers and very similar specific gravity of the lumber. The percentage of reduction in strength at 0.65 to 0.70 specific gravity, was 2-1/2 to 3 times the reduction compared to 0.50 to 0.55 specific gravity, with at least one side of the joints having the same plywood panel (table 11). In joint specimens with the epoxy adhesive and the same plywood panels, the effect of specific gravity variation in lumber from 0.50 to 0.70 had no noticeable effect on the degree of strength reduction as a result of the cyclic exposure.

This information, along with the observations that the resorcinol joints had a higher percent of failures in the critical zone (previously defined) compared to the epoxy joints, indicates a better performance with the flexible glue; however, generally speaking, the weak plywood face ply of the plywood and its effects on results obscured any positive correlation of data for this plywood orientation.

One of the objectives of the study, however, was confirmed When glued plywood-to-lumber assemblies of significant size are made with conventional rigid wood glues and are subjected to cycles of high and low humidity, the internal stresses on the joints are severe and may severely destroy the joint by damage to the wood even if the glue joints retain a high degree of their actual integrity. Where loss of strength reaches 25 percent or more, the consequences can be severe, but this danger does not appear to exist in 2 by 2 sizes, with the 0° grain orientation, but only in sizes from 2 by 4 through 2 by 12 as evaluated.

Comparison of Specimens With 90° Plywood Orientation

The performance of the joints oriented so that the face of the plywood is 90° to the longitudinal grain of the lumber was entirely different from the 0° orientation. Here the plywood has a strong tension element parallel to the direction of the swelling shear stress, and the weak and more vulnerable elements are the adhesive bond and the lumber in the radial-tangential plane. Where the 0° orientation established data on overall joint performance and was essentially a test of the plywood, the 90° orientation condition is a more proper adhesive joint performance test.

As in the 0° orientation, the specific gravity of the lumber was the primary variable to be considered in comparisons because of its effect on shear stress intensity.

From tables 11 and 12, the exposed resorcinol joints showed significant strength differences from the controls for all sizes except the 2- by 2-inch joint size. The observations during the humidity cycle showed no visible physical destruction during exposure.

The epoxy-resin joints that were cycled showed a significant difference from the controls only in the 2 by 10 size, and the observations during the exposure period indicated no visible physical damage to the joints. Figures 8 and 9 show that the average pounds per square inch values per joint size were in the same high ranges (8,000 pounds per square inch or higher) for the controls for both resorcinol and the epoxy adhesives so that here there was a direct correlation. The only variation was the control for the epoxy 2- by 10-inch joints, which was noticeably higher. The nature of failure of the shear blocks was different because the resorcinol joints had 18 percent failures in the lumber and 82 percent in rolling shear in the weak plywood face ply, whereas the epoxy had 100 percent failure in rolling shear.

A close correlation of specific gravities on a size-for-size basis is possible from these data. Table 13 gives the comparable specimen values for the various panels with plywood and lumber at 90°.

The percentages of strength reduction (table 13) may have been influenced by plywood variability, even over the face of one of the 4- by 8-foot panels, as well as by variability in the fir lumber even though it was in the same specific gravity range. However, considering the gross effects, the resorcinol joints, 2 by 6 to2 by 12, had an average specific gravity of 0.52 and an average reduction in strength of 24.9 percent. The epoxy joints had an average specific gravity of 0.52 and an average percent reduction in strength of 11.1 percent. It can be concluded from these data that in this case the flexible epoxy adhesive exhibited an improvement over the rigid adhesive. In the resorcinol joints again there was an increase in the percentages of reduction in strength with increases in specific gravity for the 2 by 6 to 2 by 12 sizes.

Further limited observations of the epoxy adhesive joints indicated that this adhesive is viscoelastic in nature and will strain up to 1/2 inch per inch in shear. This behavior, apparently, can relieve stress in the joint and could account for the observed performance.

Conclusions

This study has illustrated some of the major factors to be considered in the design of plywood–to–wood joints that will be subjected to rather severe moisture content changes in service, and particularly the effects of 0° and 90° grain orientations of the two wood surfaces. Two important experimental factors influencing such joint performance are lumber density, which affects the magnitude of the internal stresses due to swelling and shrinking, and plywood quality, particularly veneer quality, which determines whether the veneers fail prematurely under these internal stresses. The large reductions in joint strengths clearly emphasize the problem proposed in the introduction.

The variable that appeared to contribute the most to the magnitude of strength losses in joints was the specific gravity of the lumber. Another major variable was the quality of the plywood face ply, but its influence depends on the orientation of the plywood face grain to the longitudinal grain of the lumber. Since the effects of these and other variables were not previously well defined and controlled, the present experiment did not provide for perfect matching and correlation of all conditions and must, therefore, be considered only as exploratory in scope.

The beneficial effects of a somewhat flexible, strain–absorbing adhesive have been illustrated, particularly in joints where the face ply of the plywood was at 90" to the grain of the lumber. However, use of a deformable adhesive of a finite thickness is simply employing a basic engineering principle of modifying boundary conditions to reduce stress concentrations. This general principle has widespread potential applications in many applied areas of wood bonding.

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Table 1.--Averagerate of moisture content increase for resorcinol and epoxy-resin adhesives

Adhesive type	Total days of exposure	Atmospheric conditions: Temperature	Atmospheric conditions: Relative humidity	Average moisture content[1]
		°F.	Percent	Percent
Resorcinol	0	80	30	7
	8	80	97	18
	13	80	97	21
	29	80	97	25
	3	80	30	10
	13	80	30	7
Epoxy-resin	0	80	30	7
	9	80	97	18
	14	80	97	21
	26	80	97	23
	6	80	30	7.4
	10	80	30	7

[1]Moisture contents were determined by weighing test joints and comparing these with original weights at 80° F. and 30 percent relative humidity at which an actual moisture content was determined by ovendrying.

Table 2.--Average results €or the resorcinol- and epoxy-resin bonded panels at the final 80° F. and 30 percent relative humidity condition

Joint size	Adhesive	Plywood orientation	Average moisture content[1]	Average specific gravity[2]
Inches		°F.	Percent	
2 by 2	Resorcinol	0	6.8	0.50
2 by 2	Epoxy	0	6.9	.53
2 by 2	Resorcinol	90	6.7	.48
2 by 2	Epoxy	90	7.3	.47
2 by 4	Resorcinol	0	6.6	.61
2 by 4	Epoxy	0	7.8	.43
2 by 4	Resorcinol	90	6.2	.60
2 by 4	Epoxy	90	7.7	.43
2 by 6	Resorcinol	0	6.5	.49
2 by 6	Epoxy	0	6.9	.47
2 by 6	Resorcinol	90	6.8	.55
2 by 6	Epoxy	90	6.9	.52
2 by 8	Resorcinol	0	6.3	.69
2 by 8	Epoxy	0	6.3	.65
2 by 8	Resorcinol	90	6.5	.55
2 by 8	Epoxy	90	7.2	.63
2 by 10	Resorcinol	0	6.5	.57
2 by 10	Epoxy	0	6.4	.49
2 by 10	Resorcinol	90	6.6	.52
2 by 10	Epoxy	90	6.4	.52
2 by 12	Resorcinol	0	6.7	.66
2 by 12	Epoxy	0	6.0	.41
2 by 12	Resorcinol	90	6.3	.45
2 by 12	Epoxy	90	6.2	.38

[1] Moisture content specimens were cut from exposed surfaces of test joints and are probably slightly lower than the average for the whole joint.

[2] Specific gravities of the entire specimens are computed on a basis of ovendry weight and ovendry volume.

Table 3.--Total joint strengths[1] before cyclic exposure (control joints) of block shear specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 0° grain orientation with a modified epoxy-resin adhesive

Joint size	Annual ring position	Joint number[2] 2	4	6	8	10	12
2 by 2	Outside[3]	1,840	1,880	1,740	1,560	1,720	1,120
2 by 2	Inside[4]	1,860	1,580	2,340	2,420	1,860	1,580
2 by 4	Outside	4,720	4,200	4,980	4,720	4,480	4,500
2 by 4	Inside	3,840	3,880	4,880	4,320	4,580	3,780
2 by 6	Outside	7,040	6,420	6,100	7,500	7,640	7,520
2 by 6	Inside	5,980	6,340	5,980	6,980	7,220	6,620
2 by 8	Outside	6,560	7,000	8,940	7,840	6,780	7,020
2 by 8	Inside	6,780	6,700	6,480	6,860	7,040	7,940
2 by 10	Outside	10,280	10,320	11,740	10,800	9,840	8,600
2 by 10	Inside	9,940	10,240	10,060	11,120	9,380	9,140
2 by 12	Outside	15,040	15,680	19,220	18,820	18,300	15,720
2 by 12	Inside	18,200	17,300	16,320	16,460	15,700	13,580

[1]Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2]Even numbers refer to control joints; odd numbers refer to exposed joints.

[3]Glueline is on bark side of lumber.

[4]Glueline is on pith side of lumber.

Table 4.--Total joint strengths[1] after cyclic exposure to relative humidity changes (exposed joints) of block shear test specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 0° grain orientation with a modified epoxy-resin adhesive

Joint size	Annual ring position	Joint number[2] 1	3	5	7	9	11
2 by 2	Outside[3]	1,540	1,660	1,560	1,400	1,780	1,540
2 by 2	Inside[4]	1,300	1,400	1,900	2,360	1,820	1,300
2 by 4	Outside	3,900	3,920	3,460	4,100	4,550	4,000
2 by 4	Inside	2,320	3,340	3,920	4,100	3,800	4,500
2 by 6	Outside	5,340	5,520	5,430	5,040	6,100	6,100
2 by 6	Inside	6,760	5,460	6,180	6,420	6,140	5,980
2 by 8	Outside	6,100	7,820	6,040	6,780	6,500	6,140
2 by 8	Inside	5,540	5,340	5,740	6,660	5,600	6,960
2 by 10	Outside	8,360	8,180	7,440	9,400	8,900	9,160
2 by 10	Inside	7,800	8,800	7,700	7,940	8,700	7,880
2 by 12	Outside	12,440	13,100	13,440	15,980	17,120	18,440
2 by 12	Inside	17,100	15,130	16,980	16,320	13,400	14,200

[1]Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2]Even numbers refer to control joints; odd numbers refer to exposed joints.

[3]Glueline is on bark side of lumber.

[4]Glueline is on pith side of lumber.

Table 5.--Total joint strengths[1] before cyclic exposure (control joints) of block shear test specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 90° grain orientation with a modified epoxy-resin adhesive

Joint size	Annual ring position	Joint number[2]					
		2	4	6	8	10	12
2 by 2	Outside[3]	880	780	900	740	720	560
2 by 2	Inside[4]	1,200	820	920	680	640	640
2 by 4	Outside	1,420	1,440	1,700	1,320	1,780	1,560
2 by 4	Inside	1,460	1,620	1,420	2,240	1,600	1,480
2 by 6	Outside	3,320	2,520	2,360	3,340	2,460	3,180
2 by 6	Inside	3,440	2,310	2,340	2,500	2,880	3,300
2 by 8	Outside	3,140	3,580	3,920	5,240	3,860	4,060
2 by 8	Inside	2,420	1,860	4,540	4,380	3,940	3,660
2 by 10	Outside	5,760	7,720	7,180	4,680	4,040	4,200
2 by 10	Inside	5,180	5,180	5,440	8,820	6,300	4,960
2 by 12	Outside	5,460	5,860	5,900	6,860	9,300	7,000
2 by 12	Inside	8,120	8,040	6,840	5,820	4,900	5,060

[1] Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2] Even numbers refer to control joints; odd numbers refer to exposed joints.

[3] Glueline is on bark side of lumber.

[4] Glueline is on pith side of lumber.

Table 6.--Total joint strengths[1] after cyclic exposure to relative humidity changes (exposed joints) of block shear test specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 90° grain orientation with a modified epoxy-resin adhesive

Joint size	Annual ring position	Joint number[2]					
		1	3	5	7	9	11
2 by 2	Outside[3]	860	800	840	940	1,040	1,120
2 by 2	Inside[4]	720	820	740	860	680	860
2 by 4	Outside	1,500	1,390	1,440	1,460	1,420	1,580
2 by 4	Inside	1,360	1,400	1,220	1,560	2,100	1,280
2 by 6	Outside	2,980	2,540	1,800	2,060	1,760	3,240
2 by 6	Inside	3,700	2,720	2,280	2,880	2,880	2,880
2 by 8	Outside	2,900	3,160	2,880	3,100	3,660	3,240
2 by 8	Inside	2,920	2,880	3,300	3,260	3,360	4,220
2 by 10	Outside	3,980	7,240	4,740	4,460	3,920	4,780
2 by 10	Inside	3,980	2,880	4,620	6,560	5,500	4,500
2 by 12	Outside	4,680	5,200	6,060	6,100	6,180	5,020
2 by 12	Inside	6,600	8,420	5,620	6,940	5,060	7,260

[1] Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2] Even numbers refer to control joints; odd numbers refer to exposed joints.

[3] Glueline is on bark side of lumber.

[4] Glueline is on pith side of lumber.

Table 7,--Total joint strengths[1] before cyclic exposure (control joints) of block shear test specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 0° grain orientation with a resorcinol-resin glue

Joint size	Annual ring position	Joint number[2]					
		2	4	6	8	10	12
2 by 2	Outside[3]	1,640	1,260	1,940	1,820	1,780	1,580
2 by 2	Inside[4]	580	840	920	760	1,160	560
2 by 4	Outside	4,740	5,000	4,700	3,620	4,160	4,000
2 by 4	Inside	3,660	4,440	3,860	4,380	3,380	4,560
2 by 6	Outside	7,020	6,040	6,280	6,360	5,680	6,640
2 by 6	Inside	5,420	6,340	6,080	5,040	4,820	5,540
2 by 8	Outside	7,240	8,220	8,240	7,720	7,780	7,480
2 by 8	Inside	5,920	4,940	4,600	7,560	8,320	7,580
2 by 10	Outside	8,660	9,460	12,300	11,840	11,800	10,360
2 by 10	Inside	7,360	9,580	8,920	9,440	9,020	8,160
2 by 12	Outside	16,120	14,460	14,940	14,620	14,240	14,820
2 by 12	Inside	11,800	10,720	11,920	13,960	11,960	11,320

[1] Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2] Even numbers refer to control joints; odd numbers refer to exposed joints.

[3] Glueline is on bark side of lumber.

[4] Glueline is on pith side of lumber.

Table 8.--Total joint strengths[1] after cyclic exposure to relative humidity changes (exposed joints) of block shear test specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 0° grain orientation with a resorcinol-resin glue

Joint size	Annual ring position	Joint number[2] 1	3	5	7	9	11
2 by 2	Outside[3]	1,540	720	1,640	1,840	2,000	1,900
2 by 2	Inside[4]	680	940	1,180	1,200	1,400	1,360
2 by 4	Outside	3,860	5,320	5,300	4,620	4,880	4,280
2 by 4	Inside	3,740	3,920	3,580	4,280	3,120	3,880
2 by 6	Outside	5,340	5,860	5,500	6,980	5,080	5,120
2 by 6	Inside	4,560	5,360	5,880	4,720	4,580	3,760
2 by 8	Outside	7,220	7,060	3,920	3,100	2,480	5,520
2 by 8	Inside	3,080	5,540	4,240	6,400	6,360	6,260
2 by 10	Outside	8,300	8,180	7,600	10,340	10,080	11,760
2 by 10	Inside	7,860	8,720	8,520	9,440	6,420	7,820
2 by 12	Outside	7,380	14,240	14,300	14,600	12,320	12,020
2 by 12	Inside	7,500	5,940	8,160	8,200	6,160	3,520

[1] Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2] Even numbers refer to control joints; odd numbers refer to exposed joints.

[3] Glueline is on bark side of lumber.

[4] Glueline is on pith side of lumber.

Table 9.--Total joint strengths[1] before cyclic exposure (control joints) of block shear test specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 90° grain orientation with a resorcinol-resin glue

Joint size	Annual ring position	Joint number[2] 2	4	6	8	10	12
2 by 2	Outside[3]	1,120	1,060	880	920	1,100	960
2 by 2	Inside[4]	900	540	100	1,060	880	760
2 by 4	Outside	2,200	1,900	1,960	1,940	1,720	1,920
2 by 4	Inside	2,160	1,940	1,920	1,620	1,720	1,560
2 by 6	Outside	2,220	2,400	3,340	2,840	2,700	2,600
2 by 6	Inside	3,980	3,680	2,720	3,240	2,740	3,200
2 by 8	Outside	3,080	5,400	4,780	5,040	4,840	3,260
2 by 8	Inside	1,940	2,720	3,140	3,900	3,440	3,880
2 by 10	Outside	5,300	4,040	4,620	4,400	4,100	4,280
2 by 10	Inside	4,180	4,100	4,080	4,520	4,400	4,660
2 by 12	Outside	6,320	6,440	6,220	6,460	5,700	6,060
2 by 12	Inside	7,260	6,720	5,560	6,070	6,200	5,400

[1] Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2] Even numbers refer to control joints; odd numbers refer to exposed joints.

[3] Glueline is on bark side of lumber.

[4] Glueline is on pith side of lumber.

Table 10.--Total joint strengths[1] after cyclic exposure to relative humidity changes (exposed joints) of block shear test specimens cut from assemblies of Douglas-fir plywood glued to Douglas-fir lumber at 90° grain orientation with resorcinol-resin glue

Joint size	Annual ring position	Joint number[2]					
		1	3	5	7	9	11
2 by 2	Outside[3]	1,040	840	760	880	820	780
2 by 2	Inside[4]	820	1,040	980	1,140	920	760
2 by 4	Outside	1,600	1,780	1,440	1,420	1,500	1,320
2 by 4	Inside	1,300	1,520	1,680	1,700	1,320	1,500
2 by 6	Outside	1,660	1,900	1,880	1,720	2,300	1,440
2 by 6	Inside	2,800	2,260	1,960	1,860	1,840	1,920
2 by 8	Outside	2,000	3,180	3,160	3,500	3,660	4,420
2 by 8	Inside	1,560	1,860	1,840	2,240	2,760	2,020
2 by 10	Outside	4,020	3,760	3,780	3,440	2,680	3,620
2 by 10	Inside	3,040	3,960	3,760	3,500	3,320	3,860
2 by 12	Outside	5,720	5,400	4,520	5,300	5,080	5,060
2 by 12	Inside	3,660	6,200	5,200	5,640	4,820	4,620

[1] Sum of all individual block shear test values (in pounds) for specimens cut from each glueline of joint.

[2] Even numbers refer to control joints; odd numbers refer to exposed joints.

[3] Glueline is on bark side of lumber.

[4] Glueline is on pith side of lumber.

Table 11.--Summary of specific gravity of lumber and plywood panels used for the evaluations

Adhesive panel	Plywood face orientation	Lumber size	Percent reduction of test joint strength from control strength	Lumber specific gravity[1]	Panel number[2] Outside	Panel number[2] Inside
	Degrees					
Epoxy	0	2 by 2	9.3	0.53	2	2
		2 by 4	12.9	.43	2	2
		2 by 6	13.3	.47	2	2
		2 by 8	10.3	.65	1	1
		2 by 10	17.3	.49	1	1
		2 by 12	8.2	.41	3	3
	90	2 by 2	.0	.47	9	9
		2 by 4	6.8	.43	8	8
		2 by 6	6.7	.52	3	3
		2 by 8	12.6	.64	6	6
		2 by 10	17.5	.52	4	4
		2 by 12	7.6	.38	9	9
Resorcinol	0	2 by 2	.0	.50	8	7
		2 by 4	.0	.61	5	4
		2 by 6	11.8	.49	4	9
		2 by 8	28.4	.69	4	3
		2 by 10	9.6	.57	3	3
		2 by 12	28.7	.66	9	8
	90	2 by 2	.0	.48	2	4
		2 by 4	19.9	.60	9	9
		2 by 6	33.9	.55	8	1
		2 by 8	29.2	.55	4	9
		2 by 10	18.7	.52	1	9
		2 by 12	17.8	.45	7	9

[1] Based on ovendry weight and ovendry volume.

[2] Arbitrary numbers assigned to original 4- by 8-foot plywood panels.

Table 12.--Statistical analysis summary for epoxy-resin and resorcinol-resin adhesives

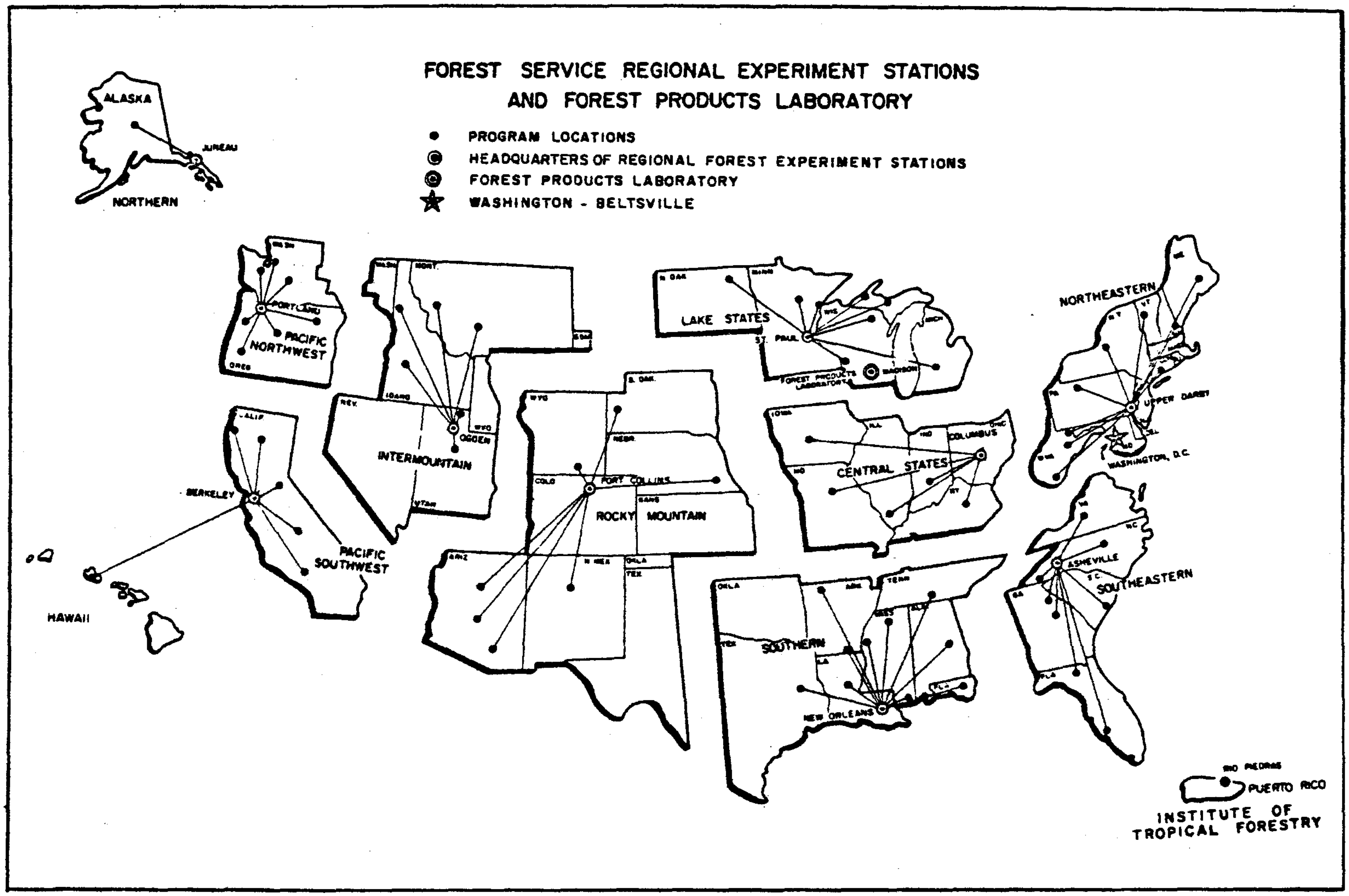
Joint size	Plywood face orientation	Adhesive panel	Mean square values: Control joints	Mean square values: Exposed joints	Mean square values: Difference	Least significant difference: 5 percent	Least significant difference: 1 percent	Least significant difference: 0.1 percent	Significant level
	Degrees								
2 by 2	0	Epoxy	1,792	1,630	162	306	407	529	Not significant
		Resorcinol	1,237	1,367	-130	306	407	529	Not significant
	90	Epoxy	790	857	-67	137	182	236	Not significant
		Resorcinol	857	898	-41	137	182	236	Not significant
2 by 4	0	Epoxy	4,407	3,828	579	422	561	728	1 percent
		Resorcinol	4,208	4,232	-24	422	561	728	Not significant
	90	Epoxy	1,587	1,476	111	182	242	315	Not significant
		Resorcinol	1,880	1,507	373	182	242	315	0.1 percent
2 by 6	0	Epoxy	6,778	5,872	906	626	832	1,081	1.0 percent
		Resorcinol	5,938	5,228	710	626	832	1,081	5 percent
	90	Epoxy	2,829	2,643	186	448	595	773	Not significant
		Resorcinol	2,972	1,962	1,010	448	595	773	0.1 percent
2 by 8	0	Epoxy	7,162	6,435	727	954	1,267	1,646	Not significant
		Resorcinol	7,133	5,098	2,035	954	1,267	1,646	0.1 percent
	90	Epoxy	3,717	3,240	477	617	820	1,065	Not significant
		Resorcinol	3,785	2,683	1,102	617	820	1,065	0.1 percent
2 by 10	0	Epoxy	10,122	8,355	1,767	871	1,157	1,502	0.1 percent
		Resorcinol	9,742	8,753	989	871	1,157	1,502	5 percent
	90	Epoxy	5,788	4,763	1,025	699	929	1,206	1.0 percent
		Resorcinol	4,390	3,562	828	699	929	1,206	5 percent
2 by 12	0	Epoxy	16,695	15,304	1,391	1,909	2,536	3,293	Not significant
		Resorcinol	13,407	9,528	3,879	1,909	2,536	3,293	0.1 percent
	90	Epoxy	6,597	6,095	502	985	1,309	1,699	Not significant
		Resorcinol	6,201	5,102	1,099	985	1,309	1,699	5 percent

Table 13.--Percentage shear strength reduction, after cyclic exposure to relative humidity changes, for plywood-to-lumber joints made with an epoxy- and a resorcinol-resin glue

Specimen size	Adhesive	Average strength reduction[1]	Joint composition		
			Specific gravity of lumber core	Panel numbers[2]	
				Bark side	Pith side
Inches		Percent			
2 by 6	Resorcinol	33.9	0.55	8	1
2 by 6	Epoxy	6.7	.52	3	3
2 by 8	Resorcinol	29.2	.55	4	9
2 by 8	Epoxy	12.6	.64	6	6
2 by 10	Resorcinol	18.7	.52	1	9
2 by 10	Epoxy	17.5	.52	4	4
2 by 12	Resorcinol	17.8	.45	7	9
2 by 12	Epoxy	7.6	.38	9	9

[1] Percentages of reduction of joint strength, after exposure, are based on control strengths.

[2] Panel numbers represent numbers given to original 4- by 8-foot plywood sheets from which the test panels were cut.



Forest Service regional experiment stations and Forest Products Laboratory