GLUABILITY OF LOBLOLLY PINE EARLYWOOD AND LATEWOOD[1]

Evangelos J. Biblis and Yau-Sen Chiu

Department of Forestry, Auburn University, Auburn, Alabama 36830

ABSTRACT

Adhesive-bond quality of the following growth zone combinations of loblolly pine was evaluated with an epoxy, a resorcinol-formaldehyde, and a phenolic adhesive: latewood to latewood, earlywood to earlywood, and latewood to earlywood. For latewood-to-latewood bonds, the influence of each of two surface treatments—(a) alcohol-benzene solution and (b) sodium hydroxide solution with each of the three adhesives—was also evaluated. Bonds of latewood-to-latewood zones were poor with all adhesives; surface treatments did not improve bond quality. In assemblies of latewood to latewood, the epoxy developed significantly stronger bonds than the resorcinol-formaldehyde. In turn, the resorcinol-formaldehyde developed stronger bonds than the phenolic adhesive. In assemblies of earlywood-to-earlywood zones, all three adhesives developed excellent bonds.

Adhesion between latewood zones of southern yellow pine is poor with most wood adhesives, while bonds of earlywood to earlywood may be as strong as earlywood itself. This distinct difference in gluability probably is caused by differences in anatomical characteristics and chemical compositions between earlywood and latewood. Although several workers have investigated the quality of adhesive bonds in southern yellow pine plywood, (Blomquist and Olson 1964; Koch 1965a, 1965b; Koch and Jenkinson 1965; Suchsland and Stevens 1968), there is very little information available concerning the gluability of different combinations of earlywood and latewood zones (Hse 1968).

Bonded surfaces of southern yellow pine in plywood and laminated products include bonds of the following combinations: (1) earlywood to earlywood, (2) latewood to latewood, and (3) earlywood to latewood. The distinct difference in gluability between the two growth zones creates difficulty in controlling quality of adhesive bonds, especially in bonding surfaces where individual areas of each growth zone are relatively large (as in veneer and flat-grained lumber).

Evaluation of earlywood and latewood zone gluability presents special problems in specimen design although the effect of specimen geometry on bond strength is always of concern to investigators. Williamson and Nearn (1958), during testing of adhesive bonds in tension perpendicular to grain, showed that bending moment effect of cross-laminated specimens may induce differential stress and cause a considerable variability in results. Bending moment and stress concentration effects that cause plywood shear specimens to fail first in tension followed by cleavage were studied by Northcott (1952), and Yavorsky, Cunningham and Hundley (1955). To overcome these effects, Baur (1960) fabricated a double-lap plywood shear specimen. If the double-lap specimen is properly aligned in the testing grips, splitting of cores is eliminated and bending effects are reduced. Because of a reduction in cleavage stress, this double-lap plywood shear specimen gave higher shear strength values than did the ASTM plywood shear specimen. Biblis and Fitzgerald (1970) fabricated solid double-lap shear specimens that are similar in configuration to double-lap plywood shear specimens to test shear properties of earlywood, latewood, and solidwood[2] of southern pine. They found that double-lap shear specimens gave better esti-

---

[2] Solidwood is defined as normal piece of pine wood which combines naturally earlywood and latewood growth zones.

mates of shear parallel-to-grain properties than block-shear specimens.

Hse (1968) investigated gluability of earlywood and latewood of southern pine veneer using only a phenol-formaldehyde resin and reported that the adhesive-bond quality, as tested wet and dry in tension perpendicular to grain and expressed as glue-line tensile strength, was best in earlywood to earlywood bonds and poorest in latewood to latewood bonds; adhesive-bond quality of earlywood to latewood bonds was intermediate. Hse also found that earlywood bonds required a longer closed assembly time than latewood bonds for an optimum bond.

Since phenolic adhesives are unsatisfactory for bonding latewood to latewood, perhaps other types of adhesives (i.e. epoxy and resorcinol-formaldehyde) might develop better adhesive-bond quality. Resorcinol-formaldehyde adhesives have been used successfully in exterior laminations with both low and high density species even in species with a considerable amount of extractives (tropical species).

Epoxy adhesives are used primarily for bonding metal to metal, plastic to plastic, and metal to plastic. Epoxy adhesives also have been used for bonding wood to metal and wood to plastics. Adhesion of epoxy adhesives in bonding wood to wood has been reported by Clarke and Nearn (1957), Olson and Blomquist (1962), and Williamson and Nearn (1958). Epoxy adhesives were reported by Eley (1961) to have the following advantages compared to other synthetic-resin adhesives: (1) they develop higher shear strength, (2) they develop low polymerization shrinkage, (3) they produce no volatile by-products during curing, such as water or formaldehyde, and (4) they ensure desired physical and mechanical properties when mixed with "plasticizers."

Chemical treatments of latewood surfaces might improve the quality of bond. Truax (1929) indicated that treatment with 10% solution of caustic soda before gluing with casein or animal glue improves the joint strength effectively in certain species. Rapp (1948), and Troop and Wangaard (1950)

reported beneficial effects of caustic soda surface treatment in *Lignum vitae* bonded with resorcinol-type adhesives. Chen (1970) investigated the possible effect of extractives on strength of glue bonds in eight tropical species. The strength of adhesion joints bonded with urea-formaldehyde and with resorcinol-formaldehyde was improved by the following treatments: (a) 10% solution of sodium hydroxide, (b) acetone, and (c) alcohol-benzene solutions with all species studied except Primavera (*Tabebuia* Spp. donnell-Smithii). It is evident that quality and quantity of extractives in different species cause considerable variation in the improvement obtained from these chemical treatments.

EXPERIMENTAL PROCEDURE

Adhesive-bond quality of the following wood growth zone combinations was evaluated: latewood to latewood, earlywood to earlywood, and latewood to earlywood. In addition, solidwood to solidwood bond quality was evaluated for comparison with both double-lap shear specimens and standard ASTM block-shear specimens. For evaluation of bond quality of individual growth zones, glue-line shear strength and percentage of wood failure of only double-lap shear specimens were used.

A completely random design with a modified factorial arrangement of treatments was used. For latewood to latewood bonds, influence of three adhesives and three surface treatments on the adhesive-bond quality were evaluated. Only the influence of three adhesives on the adhesive-bond quality was evaluated for each of the other three types of bond.

Material

Wood: Several air-dried loblolly pine (*Pinus taeda* L.) planks 2 inches in thickness and 10 inches in width were used for this study. From vertical-grained planks, sections with relatively wide growth zones of either earlywood or latewood were selected for cutting specimens. A few flat-grained planks also were selected for preparing solidwood specimens.

Adhesives[3]: Adhesives used in this study were: (1) a two-component resorcinol-formaldehyde adhesive (Koppers Penacolite G-1131); (2) a two-component epoxy adhesive (Armstrong A-12T); and (3) a liquid phenol formaldehyde adhesive (Reichhold; Plyophen 22–398). The three adhesives were mixed and spread in accordance with manufacturers' recommendations.

Preparation of double-lap shear specimens

1. *Latewood-to-latewood double-lap shear specimens*

Planks were cross-cut into blocks at lengths of 6 and 7 inches. From tangential surfaces of these blocks, longitudinal sections were cut approximately ¼ inch in thickness in such a way that one surface exhibited an entire latewood zone while the other surface exposed a mixture of both zones. All sections were cut from blocks with a carbide-tipped saw blade that produced a smooth, even surface. Sections cut from 7-inch blocks were laminated in pairs with resorcinol-formaldehyde adhesive at room temperature in such a way that the latewood zone was exposed on the outer sides of each laminated section. All laminated sections were machined to specimen components 4¼ inches in length, 1¼ inches in width, and ¼ inch in thickness. These components (a) were used centrally in latewood-to-latewood double-lap shear specimen (A) as shown in Figs. 1 and 2. The filler (c), of 2-inch length, was cut from one end of the original 7-inch section. Sections cut from 6-inch blocks were laminated to a solidwood section of the same size with resorcinol-formaldehyde at room temperature. These laminated sections were machined to 5¼ inches in length, 1¼ inches in width, and ¼ inch in thickness and were used as side components (b) of latewood-to-latewood double-lap shear specimens (A) as shown in Fig. 1.
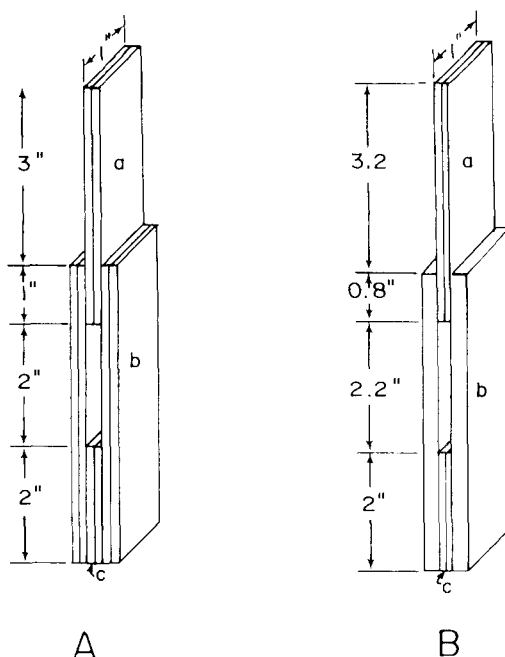

Fig. 1. Latewood-to-latewood double-lap shear specimen (A) and earlywood-to-earlywood double-lap shear specimen (B).

Seventy-two latewood-to-latewood double-lap shear specimens were prepared. For every middle component (a, Fig. 1-A) two side components (b, Fig. 1-A) were selected at random. Each specimen was assembled in such a way that the latewood zone of side components was faced to the latewood zone of middle components. To ensure that middle components would not fail in tension during tests, a bonding area of 1 × 1 inch was used on each lap surface (a total of 2 square inches bonded shear area). This critical total bonding area of 2 square inches was determined from preliminary tests.

All components for latewood-to-latewood double-lap shear specimens were assigned randomly to three adhesive groups with twenty-four specimens for each group. Each of these three groups again was assigned randomly to three surface treatment subgroups of eight specimens each. These subgroups were treated as follows: (1) no treatment (control), (2) mixture of 1:2 alcohol-benzene solution applied to bond-

---

[3] The use of particular brands of adhesive types in this experiment does not constitute an endorsement for these adhesive brands.

ing surface, and (3) 10% sodium hydroxide solution applied to bonding surface. For both chemical treatments, bonding surfaces were treated by being wiped for 1 min with a clean cloth saturated with chemical solution. After treatment, surfaces dried for ½ hr in the assigned conditioned atmosphere. The group of specimens bonded with resorcinol-formaldehyde was conditioned to equilibrium at 73 F and 50% relative humidity before bonding. The other two groups bonded with epoxy and phenolic adhesives were conditioned to equilibrium at 110 F and 17% relative humidity before bonding.

All three adhesives were used with 100 lbs spread per MDGL (1000 square feet of double glue line). For bonding specimens with resorcinol-formaldehyde adhesive, a 10-min open assembly time was used. For bonding specimens with epoxy and phenolic adhesives, a 5-min closed assembly time was used. A special clamp fixture was designed and used to keep specimens in alignment during application of pressure. Bonding pressure of approximately 120 psi was applied with "C" clamps and an accurate torque wrench. With this method, a glue line thickness of 0.006 inch was obtained with resorcinol-formaldehyde adhesive, and 0.008 inch with epoxy and phenolic adhesives. Specimens bonded with resorcinol-formaldehyde adhesive were cured at 73 F and 50% relative humidity for 12 hr before release of pressure. Specimens bonded with epoxy adhesive were cured in an oven at 165 F for 2 hr. Specimens bonded with phenolic adhesive were cured in an oven at 285 F for 1 hr.

After curing, all specimens were machined to the dimensions as shown in Fig. 1-A. Bonded shear area of a finished latewood-to-latewood double-lap shear specimen is shown in Fig. 2-A. All specimens after final machining were stored in a controlled atmosphere of 50% RH and 73 F until testing.

2. Earlywood-to-earlywood double-lap shear specimens

Planks with relatively wide earlywood zones were used for preparing thin sections

exposing an earlywood zone on one side. Specimen preparation was similar to that for latewood to latewood except that preparation of components and their assembly was such to test the bond between earlywood zones as shown in Fig. 1-B.

Twenty-four earlywood-to-earlywood double-lap shear specimens were prepared. For each middle component (a, Fig. 1-B) two side components (b, Fig. 1-B) were selected at random. Each specimen was assembled in such a way that the earlywood zone of side components (b) was faced to the earlywood zone of a middle component (a). To ensure that the middle component (a) would not fail in tension during tests, a bonding area of 0.8 × 1.0 inch was used on each lap surface (a total of 1.6 square inches bonded shear area). This critical total bonding area of 1.6 square inches was determined from preliminary tests.

All specimen components for earlywood-to-earlywood double-lap shear specimens were assigned randomly to three adhesive groups with eight specimens for each group. Except for assembly time and bonding pressure, specimens were bonded and cured with each of three adhesives in the same way as latewood-to-latewood double-lap shear specimens. For bonding specimens with epoxy and phenolic adhesives, 3 min of closed assembly time was used. For bonding specimens with resorcinol-formaldehyde adhesive, 5 min open assembly time was used. Bonding pressure of approximately 150 psi was applied through "C" clamps by a torque wrench equipped with an automatic torque control dial.

All cured specimens were machined to final dimensions as shown in Fig. 1-B.

3. Composite (latewood-to-earlywood) double-lap shear specimens

This type of specimen was constructed by bonding a middle component (a) exposing latewood zones (similar to that of a latewood-to-latewood double-lap shear specimen) to two side components (b) exposing one earlywood zone (similar to that of an
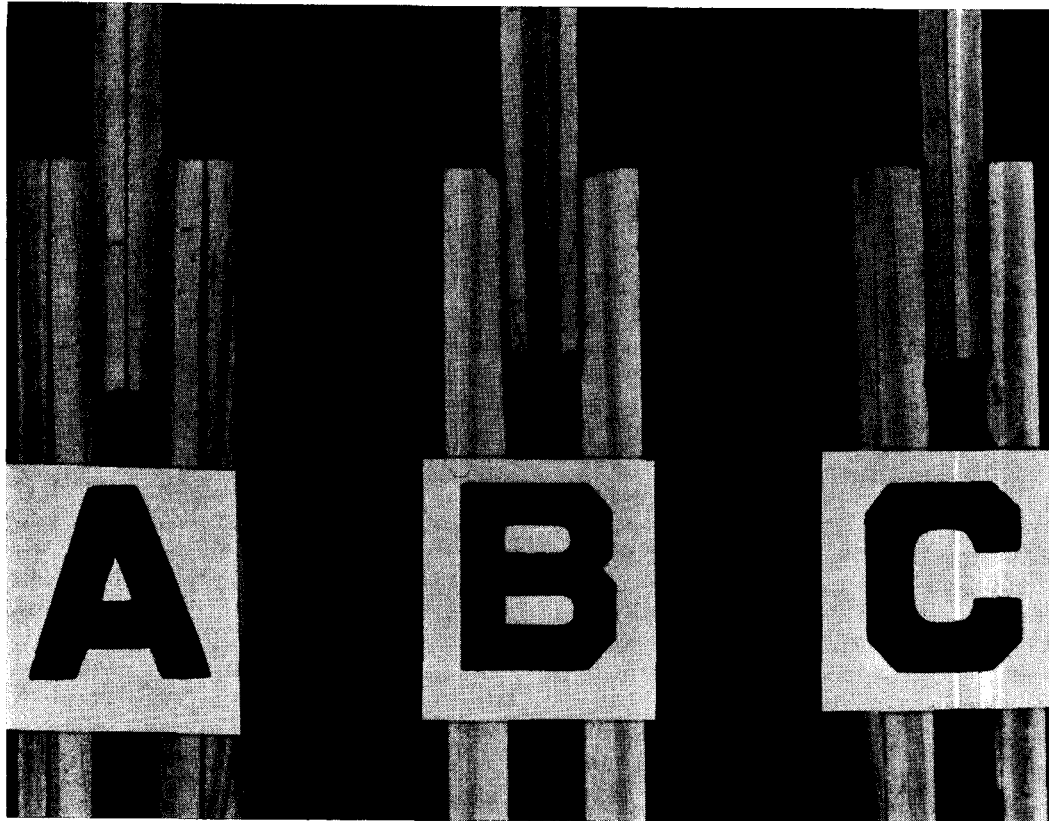
Fig. 2. Growth zone arrangement of double-lap shear specimens. (A) latewood to latewood, (B) earlywood to earlywood, and (C) latewood to earlywood.

earlywood-to-earlywood double-lap shear specimen). Eighteen composite double-lap shear specimens were prepared. Each specimen was assembled in such a way that the earlywood zone of side component (b) was faced to the latewood zone of middle component (a). Bonding area of 0.8 × 1.0 inch was used on each lap surface (a total of 1.6 square inches of bonded shear area).

All components of composite double-lap shear specimens were assigned randomly to three adhesive groups with six specimens for each group. Specimens were bonded and cured with each of three adhesives in the same way as earlywood-to-earlywood double-lap shear specimens.

All cured specimens were machined to the same dimensions as earlywood-to-early-wood double-lap shear specimens and stored in a controlled atmosphere of 50% RH and 73 F until testing. Bonding shear area of a finished specimen is shown in Fig. 2-C.

4. Solidwood-to-solidwood double-lap shear specimens

Planks were cross cut into blocks at length of 6 and 7 inches. From radial surfaces of these blocks, sections were cut ¼ inch in thickness for assembling the specimens as shown in Fig. 3. Twenty-four solidwood-to-solidwood double-lap shear specimens were prepared. Bonding area of 1.0 × 1.0 inch was used on each lap surface (a total of 2.0 square inches of bonded shear area).

All components of these specimens were assigned randomly to three adhesive groups with eight specimens for each group. Specimens were bonded with each of three adhesives and cured in the same way as early-
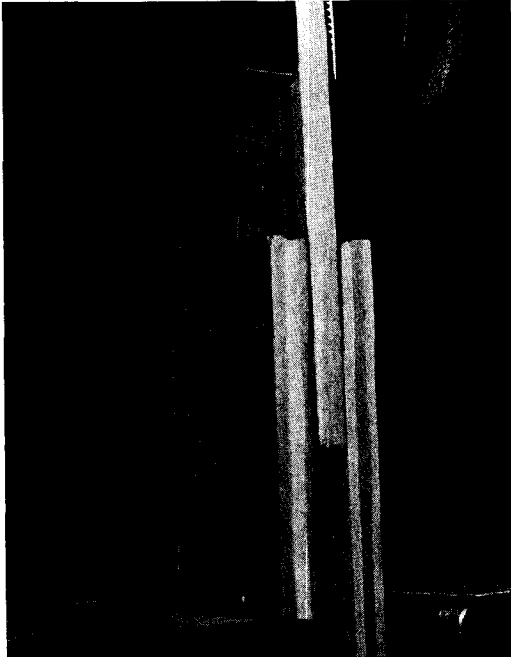
FIG. 3. Oblique view of solidwood double-lap shear specimen.

wood-to-earlywood double-lap shear specimens.

All cured specimens were machined to the same dimensions as latewood-to-latewood specimens and stored in a controlled atmosphere at 50% RH and 73 F until testing.

Testing of double-lap shear specimens

Before testing, the bonded shear area of each specimen was measured, and the sum of both bonded lap shear areas (formed by components a and b) was calculated and expressed in square inches for each double-lap shear specimen.

An Instron (model TT-D-L) testing machine was used for testing double-lap shear specimens. Each specimen was tested to failure in shear with a loading speed of 0.030 inch/min.

Preparation and testing of standard block-shear specimens

Eight strips of edge-grained wood, 1 × 3 inches in cross section and 13 inches in length, and consisting approximately of equal percentages of earlywood and latewood, were used. These strips were surfaced to 1½-inch thickness, and laminated in pairs (radial surface lamination). Two pairs were laminated with resorcinol-formaldehyde adhesive and cured at 73 F and 50% RH for 24 hr. An additional two pairs were laminated with epoxy adhesive and cured in an oven at 165 F for 2 hr. Bonding pressure of approximately 120 psi was applied to all specimens with both adhesives.

A total of 11 block-shear specimens bonded with resorcinol-formaldehyde adhesive and 12 specimens bonded with epoxy adhesive were machined and tested according to ASTM standards D905–49 (1961).

RESULTS AND DISCUSSION

Glue-line shear strength of each double-lap shear specimen was calculated as the ratio of maximum shear load to the total shear area (sum of both lap areas).

Variability in glue-line shear strength values among the same type specimens was caused partly by a small difference in length of the two lap shear areas (approximately 0.005 to 0.008 inches) that developed during bonding. This difference in length might have caused initiation of shear failure on the shorter lap area. However, since both bond areas were equally resisting the shear load prior to total failure, the total shear area was calculated on the basis of both bonding areas. In the case where failure took place only on one side, the percentage of wood failure on the fail side was considered as percentage of wood failure for the specimen. All types of specimens bonded with phenolic adhesive, except those of solidwood, developed failure primarily on one side.

Latewood-to-latewood bond

The average glue-line shear strength values and percentages of wood failure of latewood specimens (surface treated and bonded with three adhesives) are shown in Table 1. The quality of adhesive bonds of both treated and untreated specimens,

TABLE 1. *Average values[1] of glue-line shear strength and percentages of wood failure of bonded late-wood-to-latewood double-lap specimens with three adhesives and two surface treatments.*

| | Resorcinol—formaldehyde adhesive | | | | | |
| | Control[3] | | Treatment 1[4] | | Treatment 2[5] | |
Range[2]	Shear strength (psi)	Wood[6] failure (%)	Shear strength (psi)	Wood failure (%)	Shear strength (psi)	Wood failure (%)
Max	757	70	860	70	1229	80
Min	603	15	508	15	589	20
Mean	681	53	654	46	699	47
Sd	53	18	110	19	200	22

| | Epoxy Adhesive | | | | | |
| | Control | | Treatment 1 | | Treatment 2 | |
	Shear strength (psi)	Wood failure (%)	Shear strength (psi)	Wood failure (%)	Shear strength (psi)	Wood failure (%)
Max	1229	95	1173	100	821	80
Min	589	30	647	35	588	25
Mean	867	71	857	70	699	45
Sd	200	22	184	25	75	19

| | Phenolic Adhesive | | | | | |
| | Control | | Treatment 1 | | Treatment 2 | |
	Shear strength (psi)	Wood failure (%)	Shear strength (psi)	Wood failure (%)	Shear strength (psi)	Wood failure (%)
Max	538	8	531	10	626	15
Min	257	2	151	2	267	2
Mean	325	5	340	6	385	6
Sd	93	2	119	3	118	5

[1] Each mean value represents an average of eight specimens.
[2] Sd designates sample standard deviation.
[3] Nontreated specimen used as control.
[4] Wiped for one minute with cloth saturated with a 1:2 alcohol-benzene solution.
[5] Wiped for one minute with cloth saturated with a 10% sodium hydroxide solution.
[6] Maximum and minimum percentages of wood failure do not correspond to maximum and minimum values of glue-line shear strength.

as evaluated by bond shear strength and percentage of wood failure, was the best with epoxy adhesive and the poorest with phenolic adhesive; the resorcinol-formaldehyde adhesive produced an intermediate quality bond.

An analysis of variance of glue-line shear strength among the three adhesives indicates a significant difference in shear strength among the tested adhesives at 99.5% probability level (an F value of 84.46 with 2 and 63 degrees of freedom.) The same analysis of variance and F-test shows no significant differences in shear strength among treated and untreated surfaces. Interactions between adhesive types and sur-

face treatments had no significant effect on shear strength.

A separate analysis of variance of the percentages of wood failure among the three adhesives, and between treated and untreated surfaces, shows identical results obtained in the analysis of variance of glue-line shear strength.

Although the epoxy adhesive gave higher glue-line shear strength and higher percentage of wood failure in both treated and untreated latewood to latewood bonds, the shear strength values are considerably lower than corresponding values of this species latewood zone as reported by Biblis and Fitzgerald (1970).

TABLE 2. *Average values[1] of glue-line shear strength and percentages of wood failure of bonded late-wood-to-latewood, latewood-to-earlywood, earlywood-to-earlywood, and solidwood-to-solidwood double-lap shear specimens with three adhesives*

| | | ADHESIVES | | | | | |
| | | Epoxy | | Resorcinol | | Phenolic | |
Group	Range	Shear strength (psi)	Wood failure (%)[2]	Shear strength (psi)	Wood failure (%)	Shear strength (psi)	Wood failure (%)
A. Latewood to Latewood	Max	1229	95	757	70	538	8
	Min	589	30	603	15	257	2
	Mean	867	71	681	53	325	5
	Sd	200	22	53	18	93	2
B. Latewood to Earlywood	Max	1107	98	891	85	388	50
	Min	709	90	411	55	239	10
	Mean	914	95	649	73	331	30
	Sd	113	3	169	12	52	5
C. Earlywood to Earlywood	Max	918	100	827	100	784	90
	Min	598	100	550	100	639	75
	Mean	734	100	731	100	692	83
	Sd	103	0	90	0	59	6
Average Mean[3]		838	89	687	75	454	38
D. Solidwood to Solidwood	Max	919	90	708	90	564	60
	Min	660	45	560	45	418	20
	Mean	807	81	651	69	505	34
	Sd	80	15	35	19	53	15

[1] Mean value of each group is an average of eight specimens with the exception of that of latewood to earlywood, which is the average of six specimens.

[2] Maximum and minimum percentages of wood failure do not correspond to maximum and minimum values of shear strength.

[3] Calculated from means of latewood-to-latewood, latewood-to-earlywood, and earlywood-to-earlywood specimens.

Earlywood-to-earlywood bond

The average glue-line shear strength values and percentages of wood failure of earlywood specimens bonded with three adhesives are shown in Table 2. Average values of glue-line shear strength developed by the three tested adhesives are in the same range of approximately 700 psi.

An analysis of variance and F-test of glue-line shear strength among the three adhesives indicates a nonsignificant difference among them at 99.5% probability level.

Actually, average glue-line shear strengths developed by the epoxy and resorcinol-formaldehyde adhesives with 100% of wood failure are almost equal (734 and 731 psi, respectively). These two values of glue-line shear strength also are almost equal to the average shear strength for earlywood (736 psi) reported by Biblis and Fitzgerald (1970). This agreement is to be expected

since the adhesive bonds developed 100% of wood failure.

Latewood-to-earlywood bond

Average glue-line shear strength values and percentages of wood failure of composite specimens (latewood to earlywood) bonded with three adhesives are shown in Table 2. Wood failures developed almost exclusively in the earlywood with all three adhesives. The epoxy adhesive developed the maximum average bond shear strength and the maximum percentages of wood failure, followed by resorcinol-formaldehyde. The phenolic adhesive, as in the bond between latewood to latewood, developed the minimum bond shear strength and percentage of wood failure.

An analysis of variance of glue-line shear strength among the three adhesives indicates a significant difference in shear

TABLE 3. *Average values[1] of glue-line shear strength and percentages of wood failure of bonded solidwood-to-solidwood standard block-shear specimens with epoxy and resorcinol formaldehyde adhesives*

	ADHESIVES			
	Epoxy		Resorcinol	
Range	Shear strength (psi)	Wood failure (%)[2]	Shear strength (psi)	Wood failure (%)
Max	2,178	100	2,116	90
Min	1,817	90	1,419	75
Mean	1,946	96	1,752	84
Sd	122	4	188	4

[1] Mean values presented are averages of twelve and eleven specimens, respectively, for epoxy and resorcinol adhesives.

[2] Maximum and minimum percentages of wood failure do not correspond to maximum and minimum values of shear strength.

strength among adhesives at 99.5% probability level (an *F* value of 31.2 with 2 and 17 df). The Duncan's multiple range test shows that shear strength obtained by each adhesive is significantly different from each of the other two adhesives.

A separate analysis of variance of the percentages of wood failure among the three adhesives shows identical results obtained from the analysis of variance of glue-line shear strength.

Solidwood-to-solidwood bond

Average glue-line shear strength values and percentages of wood failure of solidwood specimens, bonded with three adhesives, are shown in Table 2. Again, highest values of bond shear strength and highest percentages of wood failure developed in the epoxy adhesive specimens, followed by resorcinol-formaldehyde specimens. The phenolic adhesive developed the lowest shear strengths and lowest percentages of wood failure.

An analysis of variance of glue-line shear strength among the three adhesives indicates a significant difference in shear strength among adhesives at 99.5% probability level (an *F* value of 45.2 with 2 and 23 df). The Duncan's multiple range test of means shows that shear strength obtained by each adhesive is significantly different from each of the other two adhesives.

A separate analysis of variance of percentages of wood failure among adhesive group specimens indicates a significant difference in percentages of wood failure among adhesives at 99.5% probability level. The Duncan's multiple range test shows that the percentage of wood failure obtained by phenolic adhesive (the lowest) is significantly different from the others.

Although the epoxy adhesive gave higher shear strength and percentage of wood failure, glue-line shear strength values obtained by this adhesive are lower than shear strength values of solidwood (1,326 psi) reported by Biblis and Fitzgerald (1970).

Average glue-line shear strength values and percentages of wood failure of solidwood ASTM standard block-shear specimens, bonded with epoxy and resorcinol-formaldehyde adhesives, are shown in Table 3. Average glue-line shear strength values are compared with those obtained from solidwood double-lap specimens. The average glue-line shear strength of block-shear specimens bonded with epoxy (1,946 psi) was 141% higher than that of double-lap specimens (807 psi). Block-shear strength (1,752 psi) was 169% higher than that of double-lap specimens (651 psi). This indicates that size and shape of specimens have a significant influence on glue-line shear strength.

The average glue-line shear strength of standard block-shear specimens bonded with epoxy adhesive (1,946 psi) is approximately equal to the shear strength for solidwood (1,965 psi) reported by Biblis and Fitzgerald (1970). This agreement was expected since the adhesive bond developed 96% of wood failure.

Comparison of glue-bond quality among four types of specimens

1. *Latewood to latewood vs. earlywood to earlywood*

Specimens, representing bonds of earlywood to earlywood that were bonded with either resorcinol-formaldehyde or phenolic adhesives, developed higher glue-line shear strength than specimens representing bonds

of latewood to latewood (Table 2). Percentages of wood failure that developed in earlywood specimens with these two adhesives (100 and 83%, respectively) are also higher than those in latewood specimens (53 and 5%, respectively). This indicates that the bond quality in latewood specimens with these two adhesives is poor since glue-line shear strength did not exceed that of earlywood specimens with full percentage of wood failure.

Specimens representing bonds of latewood to latewood that were bonded with epoxy adhesive developed higher glue-line shear strength (867 psi) than similarly bonded earlywood-to-earlywood specimens (734 psi), although percentage of wood failure (71%) is lower than for earlywood specimens (100%). This indicates again that epoxy adhesive performs better in bonding latewood than the other two adhesives.

2. Composite vs. latewood and earlywood

As shown in Table 2, the percentage of wood failure that developed in composite specimens (latewood to earlywood) with either of the three adhesives is higher than that of latewood specimens but lower than that of earlywood specimens. Bonding strength, as compared with that of earlywood and latewood specimens, does not follow this relationship. In these three types of specimens bonded with epoxy adhesive, the composite specimens developed highest glue-line shear strength average value (914 psi) than either earlywood specimens (734 psi) or latewood specimens (867 psi). Composite specimens bonded with resorcinol-formaldehyde adhesive developed a glue-line shear strength average value (649 psi) that is lower than either earlywood specimens (731 psi) or latewood specimens (681 psi). Composite specimens bonded with phenolic adhesive developed a glue-line shear strength average value (331 psi) that is approximately equal to that of latewood specimens (325 psi), but is considerably lower than that of earlywood specimens (692 psi).

3. Solidwood vs. other three types

In a solidwood specimen, the bonded radial surface area involves the following combinations of growth zones: earlywood to earlywood, latewood to latewood, and latewood to earlywood. Values of glue-line shear strength and percentage of wood failure of these three combinations, each bonded with three adhesives, are shown in Table 2. The phenolic adhesive that developed poor bonds in assemblies of latewood to latewood and in latewood to earlywood developed relatively stronger bonds in solidwood to solidwood.

SUMMARY AND CONCLUSIONS

(1) Effect of adhesive type in bond quality between latewood-to-latewood zones is significant. In both treated and untreated specimens representing bonds between latewood to latewood, adhesive-bond quality (evaluated separately by shear strength and percentage of wood failure) was best with epoxy adhesive and poorest with phenolic adhesive; resorcinol-formaldehyde adhesive developed an intermediate quality bond. Effect of surface treatment with alcohol-benzene solution, or 10% sodium hydroxide solution on adhesive-bond quality was not significant.

(2) Effect of adhesive type on glue-line shear strength of specimens representing bonds of earlywood to earlywood is not significant. Specimens representing bonds of earlywood-to-earlywood zones that were bonded with epoxy, resorcinol-formaldehyde, and phenolic adhesives developed equal glue-line shear strengths of approximately 700 psi. Epoxy and resorcinol-formaldehyde adhesives developed 100% wood failure, while phenolic adhesive developed 80% wood failure.

(3) In bonds between latewood to earlywood, epoxy adhesive developed the highest averages in shear strength and wood failure, followed by resorcinol-formaldehyde; the phenolic adhesive

developed the lowest shear strength and percentage of wood failure. Wood failure developed almost exclusively within the earlywood zone by all three adhesives.

(4) Effect of adhesive type on glue-line shear strength of specimens representing bonds of solidwood (radial surfaces) is significant. The best bond (higher shear strength and larger percentage of wood failure) was obtained with the epoxy adhesive and the poorest with phenolic adhesive.

(5) Average glue-line shear strengths of solidwood standard block-shear specimens, bonded with epoxy and resorcinol-formaldehyde adhesives, are 141 and 169% higher, respectively, than corresponding values of solidwood double-lap specimens. This indicates that size and shape of specimens have a significant influence on glue-line shear strength.

(6) Quality of latewood-to-latewood bonds (bonded with resorcinol-formaldehyde and phenolic adhesives) is poor since glue-line shear strength did not exceed that of earlywood to earlywood. Epoxy adhesive performs better in bonding latewood to latewood than the other two adhesives by exceeding shear strength of earlywood.

(7) Percentages of wood failures that developed in composite specimens (latewood to earlywood) with either of the three adhesives are higher than those of latewood-to-latewood specimens but lower than for earlywood-to-earlywood specimens. Composite specimens bonded with epoxy adhesive developed higher glue-line shear strength than earlywood-to-earlywood specimens and those of latewood-to-latewood specimens. Composite specimens bonded with resorcinol-formaldehyde adhesive developed an average shear strength that is lower than either earlywood-to-earlywood specimens or latewood-to-latewood specimens. Composite specimens bonded with phe-

nolic adhesive developed an average glue-line shear strength that is approximately equal to that of latewood-to-latewood specimens but is considerably lower than that of earlywood-to-earlywood specimens.

REFERENCES

AMERICAN SOCIETY FOR TESTING AND MATERIALS. 1961. Tests for veneer, plywood, and other glued constructions. ASTM D805–52. Philadelphia.

BAUR, E. 1960. Bemerkungen uber Zugpscherprufungen an dreifach verleimten Sperholzplatten nach DIN 532255. Holz Roh- Werkst. 18(6): 219–222.

BIBLIS, E. J., AND J. D. FITZGERALD, JR. 1970. Shear properties of loblolly pine growth zones. Wood Sci. 2(4): 193–202.

BLOMQUIST, R. F., AND W. Z. OLSON. 1964. Experiments in gluing southern pine. USDA Forest Prod. Lab. Res. Note FPL-032. Madison, Wisconsin.

CHEN, CHIA-MING. 1970. Effect of extractive removal on adhesion and wettability of some tropical woods. Forest Prod. J. 20 (1): 36–41.

CLARKE, J. T., AND W. T. NEARN. 1957. Factors affecting the quality of an epoxy resin wood-wood bond. Forest Prod. J. 7(1):20–27.

ELEY, D. D. 1961. Adhesion. Oxford University Press, London.

HSE, C. Y. 1968. Gluability of southern pine earlywood and latewood. Forest Prod. J. 18 (12):32–36.

KOCH, P. 1965a. Maximizing wood failure. Forest Prod. J. 15(9): 355–361.

———. 1965b. Maximizing wet shear strength. Forest Prod. J. 15(11): 463–465.

———, AND JENKINSON, P. 1965. Maximizing dry strength. Forest Prod. J. 15(12): 488–494.

NORTHCOTT, P. L. 1952. The development of glue line cleavage test. Forest Prod. J. 2(5): 216–224.

OLSON, W. Z., AND R. F. BLOMQUIST. 1962. Epoxy resin adhesives for gluing wood. Forest Prod. J. 12(2): 74–80.

RAPP, E. 1948. The gluing of lignum vitae. Unpublished thesis. Yale School of Forestry, New Haven, Conn.

SUCHSLAND, O., AND R. R. STEVENS. 1968. Gluability of southern pine veneers dried at high temperature. Forest Prod. J. 18(1): 38–42.

TRUAX, T. R. 1929. The gluing of wood. USDA Bull. No. 1500.

TROOP, B. S., AND F. F. WANGAARD. 1950. The gluing properties of certain tropical American woods. Tech. Rept. No. 4. Yale School of Forestry, New Haven, Conn.

WILLIAMSON, F. L., AND W. T. NEARN. 1958. Wood to wood bonds with epoxide resins— species effect. Forest Prod. J. **8**(6): 182–188.

YAVORSKY, J. M., J. H. CUNNINGHAM, AND N. G. HUNDLEY. 1955. Survey of factors affecting strength tests of glue joints. Forest Prod. J. **5**(10): 306–311.

TAGE L. ELERS

Friends and former associates will be saddened to learn of the sudden and unexpected death of Dr. Tage L. Elers on February 16 in Sweden.

Dr. Elers received his Ph.D. from North Carolina State University in 1963 following his undergraduate engineering education in Sweden and his bachelor's and master's degrees from the University of Washington College of Forest Resources. He was president of the Elers' Wood Consulting AB in Stockholm and had previously been a member of the Wood Science and Technology faculty at the Pennsylvania State University and a senior engineer with the Wood Products Research Department of Potlatch Forests, Inc.

During the time that he was a resident of the United States, Dr. Elers undertook a number of consulting assignments for the Swedish forest products manufacturing industry. In 1969, he returned to Sweden to engage in the consulting business but remained in contact with his many friends here.

Mrs. Elers (Ulla) and the two children live at Skolgvagen 4, S-170, 24 Skalbey, Sweden.