THE EFFECT OF CLAMPING PRESSURE AND ORTHOTROPIC WOOD STRUCTURE ON STRENGTH OF GLUED BONDS[1]

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ABSTRACT

Reference values for compression strength perpendicular to the grain were determined for radial and tangential sections of samples of sugar maple and ponderosa pine. Samples to be glued were matched according to specific gravity and orthotropic structure and bonded along the grain in tangential or radial sections. Magnitude of clamp pressure was controlled throughout a range of pressures commonly applied in industry, up to about 80% of the compression strength of the wood sample. Tests were conducted on the bonded samples to determine glueline shear strength and percent of wood failure at the bonded surfaces. Results were subjected to regression analysis to ascertain relationships. It was determined that clamping pressure had a different effect on both shear strength and percent of wood failure depending on species and orthotropic section. It is possible to maximize joint strength by applying proper clamping pressure. Results similar in direction but differing in magnitude were obtained with both PVAc and U-F adhesives. A generalized measure of clamping pressure was defined as the ratio of applied clamping pressure to the compression strength (CP/CS) of the wood section to be glued. Using this concept, the optimum clamping pressure for sugar maple was found to be 0.3 times compression strength using U-F glue and 0.5 times using PVAc glue. This approach to determining reliable clamping pressure data can lead to improved gluing practice and more precise testing procedures.

Keywords: Clamping pressure, glueline strength, glueline testing, optimum clamp pressure, orthotropic wood structure, percentage of wood failure, wood bonding.

INTRODUCTION

In theory, wood members having perfectly plane, smooth surfaces can be satisfactorily fastened together with little or no pressure (Baumann and Marian 1961; Kollmann et al. 1975; Zenkteler 1968) when using an adhesive that emits no volatile substances and causes no wood swelling during the curing or setting process. In practice, however, this ideal situation never occurs. The interrelationships among factors involved in the gluing process and the resulting effects on strength of glued joints are complex and may not yet be fully understood.

This study grew out of a desire to identify improved wood gluing techniques. The magnitude of clamp pressure applied in the gluing process is one of the factors that significantly

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influence glueline strength and percentage of wood failure in tested joints. It was determined that reliable data on optimum clamp pressure can lead to better wood gluing practice.

BACKGROUND

Several authors have shown that clamp pressure serves a number of purposes in the creation of strong glued joints:

1. It forces the adhesive into a thin film and brings it into contact with the surfaces to be bonded (Cagle 1968; Selbo 1975).
2. It overcomes viscous resistance to spreading of the adhesive film at curing or setting temperature (Baumann and Marian 1961; Forest Products Lab 1974).
3. It overcomes internal pressure exerted by the release of adhesive solvents and water vapor (Kollmann et al. 1975; Zenkteler 1968).
4. It overcomes internal pressure exerted by the swelling substrates (Perkitny and Kingston 1972).
5. It overcomes surface imperfections and dimensional mismatch between the mating surfaces during curing or setting time (Cagle 1968).
6. Finally, clamp pressure serves to hold the assembly parts in position until the adhesive sets or cures (Brown et al. 1952).

Clamp pressure has been treated in various ways in the literature, including relationship to special types of glues and physical condition of the surface prior to gluing. In basic handbooks on wood and wood adhesives (Forest Products Lab 1974; Kollmann et al. 1975) suggestions about the magnitude of clamp pressure are very general without pointing to any optimum level.

Research dealing directly with clamp pressure problems in relation to the mechanical properties of wood has been limited. Truax (1929) reported satisfactory glueline results with clamp pressures ranging from 0.7 MPa to 4.4 MPa and emphasized that the wood being glued had to be strong enough to withstand crushing at the higher pressures. It has also been reported (Stasiak 1963) that the necessary glueline clamping pressure can be related to the elastic properties of wood, the surface texture, and the hardness of the wood species to be glued. Marra (1980) recognized that one of the penalties of excessively high pressure is compression of the wood beyond its proportional limit.

The Wood Handbook (Forest Products Lab 1974) describes wood as being an orthotropic material that possesses unique and independent mechanical properties in the three mutually perpendicular axes, i.e., longitudinal, tangential, and radial direction. But this knowledge of unique wood properties has not been effectively utilized in the gluing process. There are no reports in the literature linking the magnitude of clamp pressure with orthotropic mechanical properties of wood.

Recent research (Rabiej and Behm 1989) has verified that orientation of the orthotropic structure has a systematic and significant effect on the tested compression strength of wood. It follows that the compression strength and thus the grain orientation of stock to be bonded is a fundamental factor that limits the magnitude of effective clamp pressure. Experimental glueline data (Rabiej and Brown 1986) have shown that orthotropic wood structure and magnitude of clamp pressure are among the factors that affect the setting rate of adhesives. Resin penetration during gluing is also significantly influenced by wood structure (Brady and Kamke 1989). It has also been observed that the magnitude of clamp pressure required in a gluing operation is somewhat contingent on the moisture content and condition of the wood surfaces, as well as the physical properties of the wood, which vary with orientation of the bonding surfaces.

Some recognition of these principles has been demonstrated by furniture craftsmen who have traditionally applied greater pressure to bond hardwoods than softwoods. For example, oak (*Quercus* sp.) is usually glued at a clamp pressure of 0.7 MPa to 1.2 MPa, whereas a softwood such as pine (*Pinus silvestris* L.) is normally glued at a pressure of 0.4 MPa to 0.8 MPa (Metrak 1975; Zenkteler 1968).

Baumann and Marian (1961) summarized the difficulty in defining an optimum clamping pressure in the following statement: "... optimum pressure may assume very different values in the various gluing processes. ... the optimum pressure cannot be uniformly defined for all glues and gluing conditions ... as is shown by various examples cited in literature, the pressure depends on the type of glue used, viscosity, pressing temperature, type and surface of wood, moisture content, etc. ..."

SCOPE

The purpose of this paper is to report the results of a study undertaken to determine optimum clamping pressure for gluing selected wood species. The importance of orthotropic wood structure, along with other variables inherent in the gluing process were prime considerations in assessing resultant mechanical properties of glued wood joints.

The independent factors studied were organized into three main categories: wood properties, bonding conditions, and types of adhesives. Orthotropic section (radial or tangential) and specific gravity were controlled for each species.

Applied clamp pressure during gluing was varied from 0.01 MPa (hand rubbing) to about 80% of the compression strength of the wood sample. For much of the experimentation, 0.7 MPa (100 psi) and 2.8 MP (400 psi) were arbitrarily selected since they are commonly applied in the furniture industry.

Adhesives used in the study were a polyvinyl alcohol blend with polyvinyl acetate (PVAc adhesive), and a urea-formaldehyde resin with 100 parts resin to 10 parts of catalyst by weight (U-F adhesive). The adhesives were donated by Franklin International and Perkins Co., respectively. Since these two glues were the only ones used, variables such as viscosity, molecular weight distribution, solids content, and fillers were held constant.

Gluing parameters that were controlled included: adhesive spread rate, open assembly time, closed assembly time, wood moisture content, surface preparation, ambient relative humidity and temperature, and conditioning time. In each series of experiments, only one factor was varied; all others were kept constant. Regression analysis of the experimental data was used to determine correlation between tested properties and independent variables.

Materials and preparation of specimens

Two anatomically different woods were selected for the study: ponderosa pine (*Pinus ponderosa*) and sugar maple (*Acer saccharum*).

Wood samples of each species were prepared from 19-mm-thick stock that had been brought to equilibrium moisture content at relative humidity of 50% ± 5% and temperature of 20 C ± 2. Pieces of stock 127 mm long were selected for straightness of grain and freedom from defects. They were sanded along the grain with a 60 grit belt. These represented, as nearly as possible, ideally quartersawn (radial section) or flatsawn (tangential section) pieces. The pieces were matched according to specific gravity and orthotropic structure and were bonded along the grain in tangential or radial sections (Figs. 1A and 1B). During the gluing procedure, grain orientation and magnitude of clamp pressure were closely controlled. The other bonding conditions were as follows:

glue spread rate: 250 g/m^2
open assembly time: 15 seconds
closed assembly time: 2 minutes
cure temperature: 20 C ± 2 (68 F ± 3.6)
clamp pressure duration for PVAc adhesive: 2 hours
clamp pressure duration for U-F adhesive: 3 hours
post-clamp cure and seasoning time: seven days

Matched pieces were glued into test bars measuring 38 × 38 × 127 mm. Specimens of 38 × 38 × 51 mm (1.5 × 1.5 × 2.0 in.) were cut from the glued bars (see Fig. 1A, B). All specimens were marked with respect to specific gravity, grain orientation, type of adhesive applied, and magnitude of applied clamp pres-

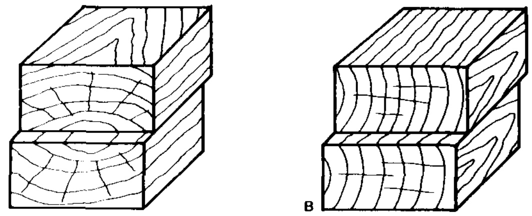

FIG. 1. Grain orientation of bonded specimens for testing. A. Tangential sections. B. Radial sections.

sure. Specimens with the same specific gravity were used during the study, except when the effect of specific gravity on shear strength (SH) and percent of wood failure (WF) of the glueline was studied.

Test methods

Selected physical and mechanical properties were determined using the recognized ASTM (1983, 1989) test method.

For each species, a reference value for compression strength perpendicular to the grain was determined for both radial and tangential sections of each sample. The compression strength of wood perpendicular to the grain is affected by the way load is distributed across the sample surface (Kollmann and Côté 1968). Therefore, specimen sizes were selected to match available equipment so that the total area of the sample was covered by the load footprint. Compression strength tests were conducted on specimens measuring 25 × 25 × 25 mm.

Tests of glueline shear strength were performed with load applied in a continuous motion at a rate of 2.5 mm per minute. The glueline shear specimens were 12.7 mm narrower than recommended by ASTM D 905-89 to reduce the maximum loads required.

In all tests, specific gravity of the wood sample was recorded. While it differed from the 0.65 value recommended by ASTM D 905-89, subsequent testing required using samples with specific gravity as found under the prescribed conditions.

RESULTS AND DISCUSSION

Data summarizing the physical and related structural and mechanical properties of each of the selected wood species are found in Table 1. The other tested relationships are illustrated with regression lines graphed in Figs. 2 through 10 (correlation coefficients are in parentheses behind each legend). A summary of test parameters and statistical data for each test may be found in Table 2. In all cases, the reported test results were significant at the 95% level of confidence unless specifically stated otherwise in discussion of the data.

Compression strength of a wood sample measured with load applied to the longitudinal-radial surface is significantly different than compression strength measured with load applied to the longitudinal-tangential surface. Therefore, all references to compression strength in this paper are in respect to specific orientation of the wood during a particular test and should not be confused with "average" values derived from random samples. Similarly, when the term "glueline shear strength" is used, it will always refer to a particular orthotropic orientation, i.e., matched radially bonded sections or tangentially bonded sections. This is an important distinction because

TABLE 1. *Average physical and mechanical properties of tested species.**

Species	Property						
	EMC	SG	CSR⊥	CST⊥	CSE‖	SHR‖	SHT‖
Sugar Maple	6.9	0.68	17.2	30.5	90.5	30.3	38.3
	(1.1)	(9.4)	(18.5)	(14.0)	(11.0)	(9.3)	(7.1)
Ponderosa Pine	7.1	0.47	9.8	7.3	62.3	16.4	17.3
	(3.5)	(12.2)	(20.1)	(11.7)	(18.9)	(17.3)	(17.1)

* Numbers in parentheses are coefficients of variation in percent.
EMC = equilibrium moisture content in %; SG = specific gravity; CSR⊥ = compression strength on longitudinal-radial surface, MPa; CST⊥ = compression strength on longitudinal-tangential surface, MPa; CSE‖ = compression strength on transverse surface, MPa; SHR‖ = shear strength on longitudinal-radial surface, MPa; SHT‖ = shear strength on longitudinal-radial surface, MPa.

TABLE 2. *Experiment parameters and regression equation coefficients.*

Fig. No.	Species of wood kind of adhesive	Orthotropic wood sections bonded	*N*	Specific gravity	Gluing parameters: Pressure	Gluing parameters: Clamp time (min)	Tested property: SH[7]	Tested property: WF[8]	Independent variable	Regression coefficients[1]: A	Regression coefficients[1]: B	Regression coefficients[1]: C	Correlation coefficient *R*
2	Sugar Maple	TT[2]	12	0.65–0.81	2.8 MPa	120	×	—	SG[4]	−4.63	554.691	—	0.836
	PVAc	TT	12	0.65–0.81	2.8 MPa	120	—	×	SG	449.874	−537.024	—	0.890
		RR[3]	12	0.67–0.80	2.8 MPa	120	×	—	SG	−31.921	79.109	—	0.856
		RR	12	0.67–0.80	2.8 MPa	120	—	×	SG	90.641	10.866	—	0.122
3	Ponderosa	TT	12	0.44–0.54	0.7 MPa	120	×	—	SG	4.080	12.574	—	0.443
	Pine	TT	12	0.44–0.54	0.7 MPa	120	—	×	SG	124.724	−58.351	—	0.342
	PVAc	RR	12	0.44–0.55	0.7 MPa	120	×	—	SG	1.788	21.114	—	0.876
		RR	12	0.44–0.55	0.7 MPa	120	—	×	SG	100.000	—	—	0.000
4	Sugar Maple	TT	22	0.68	0.01–22.4 MPa	120	×	—	CP[5]	25.406	1.467	−0.044	0.799
	PVAc	TT	22	0.68	0.01–22.4 MPa	120	—	×	CP	55.713	7.025	−0.274	0.588
		RR	22	0.68	0.01–12.6 MPa	120	×	—	CP	20.767	1.778	−0.101	0.807
		RR	22	0.68	0.01–12.6 MPa	120	—	×	CP	77.025	7.089	−0.449	0.609
5	Sugar Maple	TT	12	0.65–0.81	2.8 MPa	120	CP/CS[6]	—	SG	0.214	−0.173	—	0.998
	PVAc	RR	12	0.67–0.80	2.8 MPa	120	CP/CS	—	SG	0.477	−0.438	—	0.994
6	Sugar Maple	TT	22	0.68	0.1–0.78	120	×	—	CP/CS	25.409	42.496	−36.828	0.798
	PVAc	TT	22	0.68	0.1–0.78	120	—	×	CP/CS	55.735	203.344	−229.850	0.587
		RR	22	0.68	0.1–0.74	120	×	—	CP/CS	20.767	30.399	−29.438	0.807
		RR	22	0.68	0.1–0.74	120	—	×	CP/CS	77.022	121.239	−131.323	0.698
7	Sugar Maple	TT	22	0.79–0.85	0.1–0.64	120	×	—	CP/CS	22.073	38.401	−21.754	0.874
	PVAc	TT	22	0.79–0.85	0.1–0.64	120	—	×	CP/CS	10.859	67.841	−55.092	0.336
		RR	22	0.80	0.1–0.78	120	×	—	CP/CS	20.250	33.083	−32.052	0.773
		RR	22	0.80	0.1–0.78	120	—	×	CP/CS	16.842	343.556	−326.001	0.851
8	Ponderosa	TT	22	0.46	0.001–0.85	120	×	—	CP/CS	7.092	6.462	−12.001	0.491
	Pine	TT	22	0.46	0.001–0.85	120	—	×	CP/CS	89.143	53.157	−51.718	0.600
	PVAc	RR	22	0.46	0.001–0.71	120	×	—	CP/CS	9.186	6.363	−6.734	0.496
		RR	22	0.46	0.001–0.71	120	—	×	CP/CS	100.000	−2.5E−12	3.3E−12	0.000
9	Sugar	TT	22	0.69	0.001–0.78	180	×	—	CP/CS	28.204	13.567	−27.406	0.747
	Maple	TT	22	0.69	0.001–0.78	180	—	×	CP/CS	6.508	144.597	−153.872	0.699
	U-F	RR	22	0.69	0.001–0.74	180	×	—	CP/CS	19.982	20.860	−31.793	0.594
		RR	22	0.69	0.001–0.74	180	—	×	CP/CS	34.132	247.84	−229.387	0.925

TABLE 2. *Continued.*

Fig. No.	Species of wood kind of adhesive	Orthotropic wood sections bonded	*N*	Specific gravity	Gluing parameters: Pressure	Gluing parameters: Clamp time (min)	Tested property: SH[7]	Tested property: WF[8]	Independent variable	Regression coefficients[1]: A	Regression coefficients[1]: B	Regression coefficients[1]: C	Correlation coefficient *R*
10	Ponderosa	TT	22	0.49	0.001–0.74	180	×	—	CP/CS	7.999	0.827	6.490	0.404
	Pine	TT	22	0.49	0.001–0.74	180	—	×	CP/CS	48.584	191.621	−240.317	0.417
	U-F	RR	22	0.49	0.001–0.77	180	×	—	CP/CS	12.236	−7.802	11.604	0.264
		RR	22	0.49	0.001–0.77	180	—	×	CP/CS	81.686	56.467	−54.120	0.530

[1] Type of equations: $Y = A + BX + CX^2$; $Y = A + BX$.
[2] TT = tangential section.
[3] RR = radial section.
[4] SG = specific gravity.
[5] CP = clamp pressure.
[6] CP/CS = ratio of clamp pressure to compression strength of wood sample.
[7] SH = shear strength.
[8] WF = wood failure.

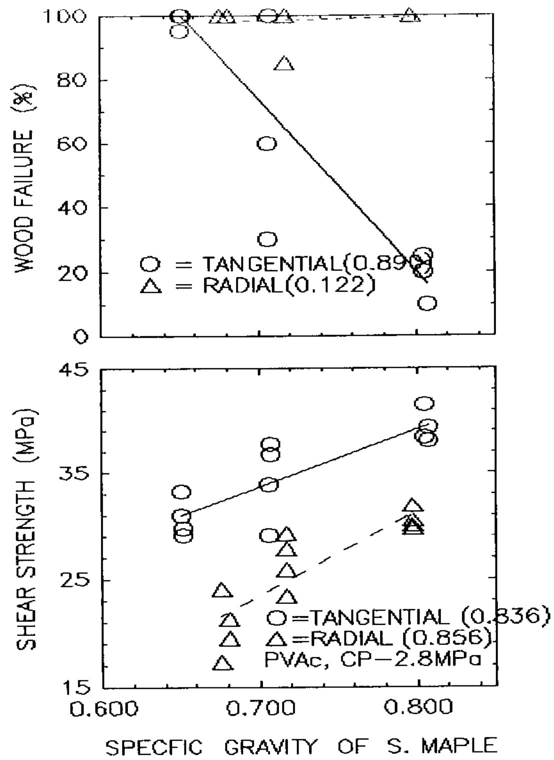

FIG. 2. Effect of specific gravity on shear strength and percentage of wood failure in glued joints of sugar maple.

these matched sections with controlled specific gravity produce somewhat higher test values than are generally reported in the literature where glued halves may not be matched in either grain orientation or specific gravity.

Orthotropic wood properties and glueline strength

Since every piece of wood is unique, many variables are introduced into any study of wood or its applications. In this study, selected properties deriving from the orthotropic structure of wood were treated as primary and systematic variables. Mechanical and physical properties of wood vary in relation to three mutually perpendicular axes due to the orthotropic structure of wood. For example, using solid wood samples, the tangential compression strength of sugar maple is higher than the radial compression strength. The reverse is true for ponderosa pine, where radial compression

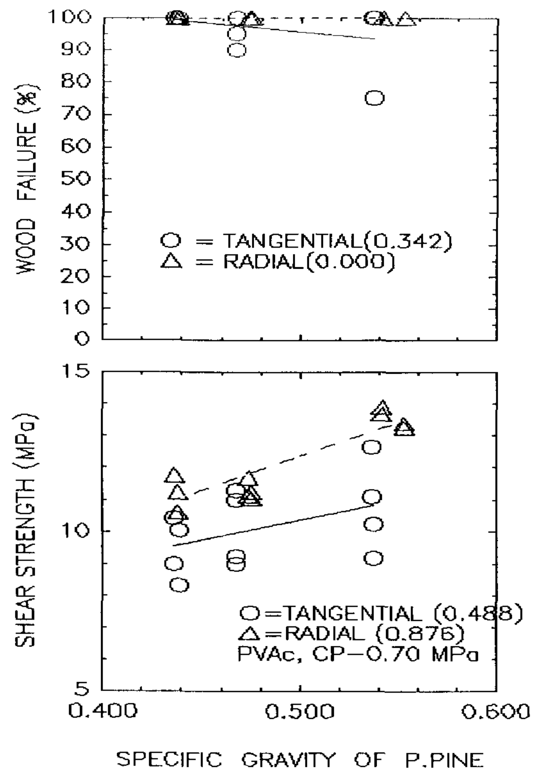

FIG. 3. Effect of specific gravity on shear strength and percentage of wood failure in glued joints of ponderosa pine.

strength is higher than tangential compression strength. These species also exhibit variations in shear strength similar to their relative compression strength characteristics. Summary data (Table 1) on compression strength and shear strength of the two studied species bear out the variation in mechanical properties that result from structural differences.

The effects of the wood structure and specific gravity on glueline shear strength and percentage of wood failure are illustrated in Figs. 2 and 3. PVAc adhesive was used in both cases and the applied clamp pressure was constant at 2.8 MPa (400 psi) for maple and 0.7 MPa (100 psi) for pine. Studying the percentage of wood failure in a tested joint provides information about the mode of failure as well as joint strength and leads to a better understanding of the behavior of the adhesive. In this test, as in all others throughout the study, there was no glue starvation observed in the tested joints.

As can be seen from Fig. 2, tested glueline strength of tangential sections of maple is significantly higher than for radial sections. Increasing specific gravity of the samples also had a positive effect on the glueline strength for both orthotropic sections. These results parallel those obtained with solid wood samples. Note, however, that the percentage of wood failure results varied according to section (upper part of Fig. 2). The radially bonded specimens produced 98% wood failure, with results unaffected by increasing specific gravity from 0.68 to 0.80. On the other hand, wood failure of tangentially bonded specimens varied inversely with specific gravity with 100% wood failure produced at 0.65 specific gravity but only 25% at 0.81 specific gravity.

A strong relationship was observed (Fig. 2) between glueline shear strength and specific gravity of maple, as indicated by correlation coefficients greater than 0.8 for both tangentially and radially bonded specimens. It was noted, however, that when the data were lumped together so as to ignore the grain orientation, the coefficient dropped to $R_W = 0.52$.

The observed relationships between specific gravity of pine, glueline shear strength, and percentage of wood failure achieved with PVAc adhesive are illustrated in Fig. 3. It should be noted that strength tests with pine produced results opposite those observed with maple. Highest glueline shear strength for pine was produced with radially bonded samples and lowest by tangentially bonded samples. Radially bonded pine specimens showed a direct relationship between shear strength and specific gravity with a correlation coefficient of 0.88. However, the relationship for tangentially bonded specimens was less clear with a correlation coefficient of only 0.49.

All radially bonded specimens produced 100% wood failure, while tangentially bonded specimens averaged 97%. Specific gravity played no significant role in percent of wood failure.

For both sugar maple and pine, the orien-

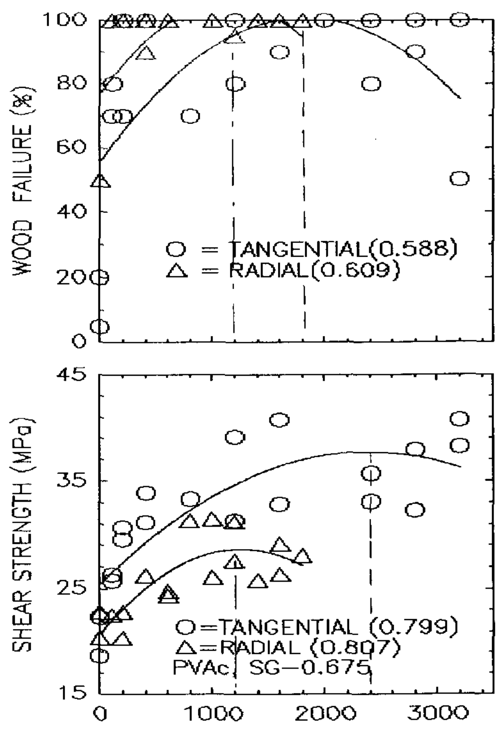

FIG. 4. Effect of clamp pressure on shear strength and percentage of wood failure in glued joints of sugar maple.

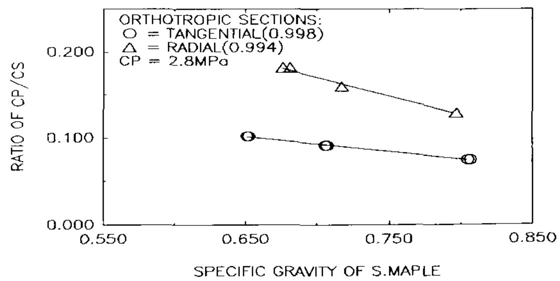

FIG. 5. Relationship between specific gravity and relative clamp pressure (expressed as a proportion of compression strength) for glued joints of sugar maple.

tation of specimens relative to orthotropic structure has a direct influence on the results of glueline tests and should not be ignored.

Effect of the magnitude of clamp pressure on glueline strength of maple

In tests to determine the effect of the magnitude of clamp pressure, specific gravity of specimens was kept constant to eliminate any effect on glueline strength and percent of wood failure. Then the separation of radially cut specimens from tangentially cut specimens allowed a means of concentrating on only the relationships between clamp pressure and structural orientation as they affect the results of glueline tests. Results of tests on sugar maple are shown in Fig. 4. For both radial and tangential sections, hand-rubbing clamp pressure led to the lowest glueline shear strength values and lowest percentage of wood failure. Increasing the clamp pressure produced increased values of both shear strength and wood failure at the glue line.

The vertical, dashed lines show the optimum clamp pressure for maximum shear strength (lower part of Fig. 4) and maximum wood failure (upper part of Fig. 4) for both radially bonded and tangentially bonded specimens. When clamp pressures were increased beyond these lines, the test values started to decrease. Maximum effective (optimum) clamp pressure for radially bonded specimens with SG = 0.68 was approximately 8.4 MPa, while for tangentially bonded specimens it was approximately 16.8 MPa.

Note that for radially bonded specimens, the optimum clamp pressure for maximum percentage of wood failure (94%) was about the same as for shear strength. However, for tangentially bonded specimens, the optimum clamp pressure to achieve maximum percentage of wood failure (80%) was somewhat lower than that required for maximum shear strength. Correlation coefficients obtained ($R_{SH}t = 0.80$, $R_{SH}r = 0.81$, $R_{WF}r = 0.61$, $R_{WF}t = 0.59$) justify a high degree of confidence in these data.

Since compression strength of the sample limits the maximum clamp pressure that can be applied without destruction, it was desired to express optimum clamp pressure for any sample as a coefficient of compression strength. Figure 5 shows a general relationship between clamp pressure and compression strength, and specifically illustrates the effect of the structural orientation of the bonded pieces. Using

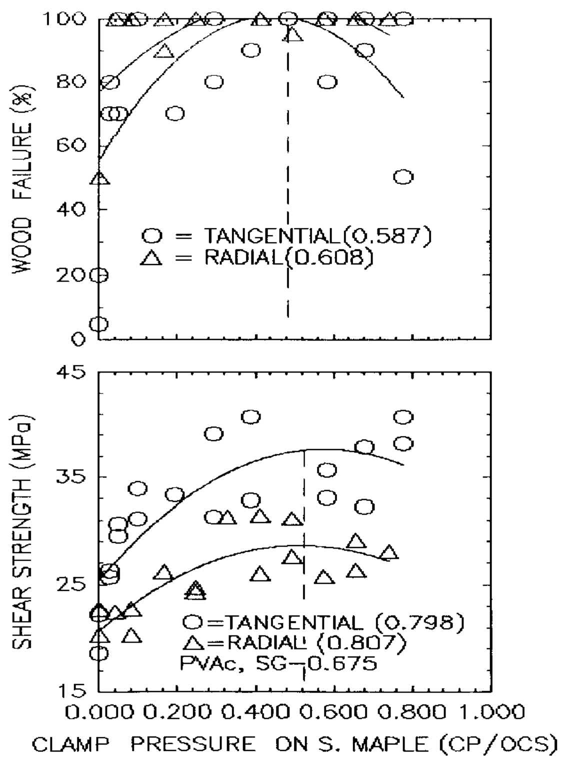

FIG. 6. Effect of relative clamp pressure on shear strength and percentage of wood failure in glued joints of medium density sugar maple.

bonded maple samples that had been clamped with a pressure of 2.8 MPa, the constant clamp pressure (CP) was divided by the tested compression strength at the proportional limit (CS) of the respective sample. This ratio, CP/CS, was then plotted against the specific gravity of the samples (individual data points were plotted). Ratios were higher for radial than for tangential sections because the compression strength of radial sections of maple is lower. It is apparent that the application of load caused radial sections to be stressed nearer to their elastic limit than were tangential sections subjected to the same load.

Using the idea of a coefficient to aid in the study of general relationships, the data represented in Fig. 4 were transformed into the graph presented in Fig. 6, where the value of clamp pressure in MPa has been replaced by the calculated values of the CP/CS ratio. Using this ratio, the variation in compression strength of the individual bonded specimens due to orientation of the orthotropic wood structure was recognized as a basic factor in determining optimum clamp pressure.

As can be seen from the lower graph in Fig. 6, optimum clamp pressure for shear strength is in the range of 0.5 to 0.6 CP/CS for both radial and tangential sections of maple. The optimum clamp pressure for maximum wood failure as read from the upper graph is slightly below 0.5 CP/CS.

Closer inspection of the lower graph in Fig. 6 shows that curves expressing the relationship between glueline shear strength and the CP/CS ratio in the range from 0.0 to 0.3 are steeper than from 0.3 and above for both radial and tangential sections. In other words, for radial sections, the greatest gain in glueline strength attributable to increases in clamp pressure (21 to 27 MPa) occurs by the time CP/CS reaches 0.3. With further increases in CP/CS, glueline shear strength only increases to about 29 MPa. With tangential sections, glueline shear strength quickly rises from 25 MPa to 35 MPa and peaks slightly above 37 MPa. Thus, it appears that for most practical applications, clamping pressures for sugar maple where the CP/CS ratio equals 0.3 will be optimum in terms of economy of effort and soundness of joints.

All data show decreasing values of shear strength when the clamping pressure is increased above the apparent optimum CP/CS ratio. This supports the notion that excessively high pressure results in compression of the wood beyond its proportional limit (Marra 1980; Truax 1929).

Results of tests on sugar maple of higher specific gravity (0.80) are illustrated in Fig. 7. Both glueline shear strength and percentage of wood failure of radially bonded specimens are positively affected by increasing clamp pressure and again reach maximum value when the CP/CS ratio reaches about 0.5. Tests on tangentially bonded specimens of higher specific gravity maple (staggered values of 0.79, 0.81, 0.83, 0.85) yielded somewhat different results. Note that since specific gravity was not held constant, an optimum value of clamp pressure could not be identified. The mean value for percent of wood failure was only 23%. There is clearly a difference between orthotropic sections at higher specific gravity, while both of the low specific gravity sections produced 100% wood failure at the optimum clamp pressure (Fig. 6).

Conclusions drawn from data presented suggest that the ultimate glueline strength of sugar maple may be increased by:

bonding structurally stronger wood sections (tangential),
using specimens of higher specific gravity, and
applying optimum clamp pressure.

The mechanism involved in the first two actions is well understood. The improvement of glueline shear strength by optimizing clamp pressure is presumably due to closer contact of wood surfaces that have been plasticized by water contained in the adhesive, and increased glue penetration into the substrates. Increased adhesive penetration involves a larger volume of substrate in the carrying of shear stresses during testing or service (Suchsland 1958). The matching of orthotropic orientation in bonded joints may also reduce internal stresses in the glue line that are caused by differential swelling and shrinking pressures (Perkitny and Kingston 1972) between radial and tangential sections. Because of these factors, it is suspected that glueline durability may also be much improved when grain orientation is among the parameters that are optimized in the gluing process.

The observed test results may be largely explained by fundamental adhesive and adhesion phenomena related to the structure of wood. Panshin and de Zeeuw (1970) proved that vessel elements in the earlywood of diffuse porous species are shorter than those found in the latewood of the annual growth ring. Thus, the vessel elements may be more easily pulled out of earlywood resulting in a greater percentage of wood failure than occurs in latewood.

In tangential sections, the structure of sugar maple is reinforced with about 18% of the wood being rays that act like ties anchoring adjacent annual rings (Brown et al. 1952). In order to get deep wood failure on these sections, an adhesive must possess very high adhesion properties and a substantial depth of penetration.

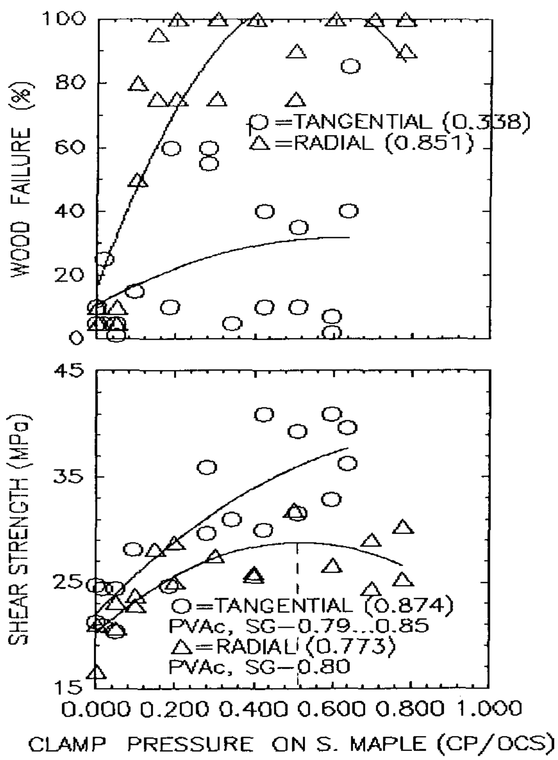

FIG. 7. Effect of relative clamp pressure on shear strength and percentage of wood failure in glued joints of high density sugar maple.

Another factor that seems to affect the percentage of wood failure is overall specific gravity of tested specimens and variation in specific gravity in the annual growth ring. Figure 2 shows clearly that for tangential sections of sugar maple, increasing specific gravity exerts a strong negative influence on the percentage of wood failure. However, the intensity of the relationship presented for tangentially bonded specimens was not apparent for the radially bonded specimens.

Structural variations that are manifest in variations in specific gravity reveal many rea-

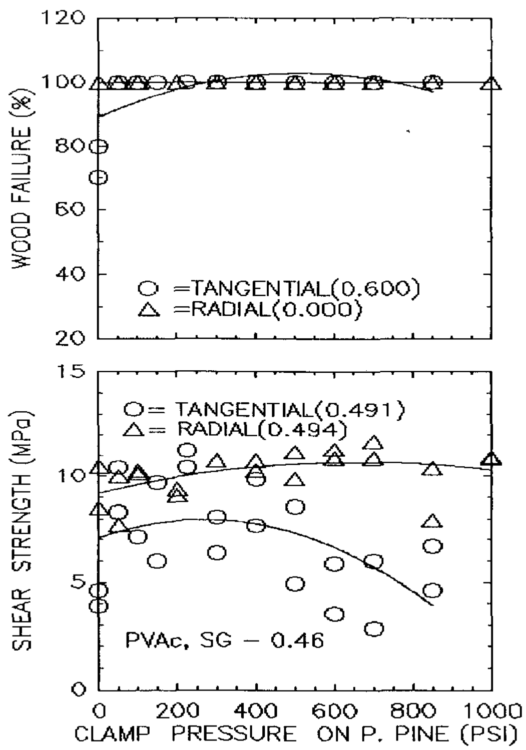

FIG. 8. Effect of relative clamp pressure on shear strength and percentage of wood failure in glued joints of ponderosa pine.

sons for wood failure variability. Diffuse porous hardwoods such as maple have mean values of specific gravity of from 0.50 to 0.53 for earlywood and from 0.67 to 0.75 for latewood (Kollmann and Côté 1968). Porosity of wood is inversely related to its specific gravity. It follows that a wood of higher specific gravity offers a less porous structure, and hence reduced capillary absorption and glue penetration. Variation of chemical composition of earlywood to latewood also plays a role in percentage of wood failure at the glue line. Fragmentary work with a few species indicates that not only is there more cellulose in latewood but it also has a greater degree of polymerization, higher specific gravity, and more crystallinity (Panshin and de Zeeuw 1970). All of these factors reduce the number of unbonded hydroxyl groups, thus adhesion of glue and its penetration. Porous earlywood has more amorphous areas that offer more unbonded hydroxyl groups and thus more bonding opportunity for the absorbed adhesive.

Strength of the glue line is usually greater as thickness of the adhesive film decreases, which in turn tends to be accompanied by a higher percentage of wood failure of the substrates. It seems obvious that the thickness of the glue line is reduced as clamping pressure is increased. It is generally recognized that glue penetration plays a substantial role in glueline development and its failure. Glue that has penetrated the substrate improves the mechanical strength properties of wood layers that were saturated by the glue. One effect is that specimens with proper glue penetration will show deeper wood failure than those with less penetration. The observed differences of the percentage of glue joint wood failure between radial and tangential sections of maple support a hypothesis that the radial orientation allows for deeper adhesive penetration than does the tangential orientation. Electron microscopy is needed for further verification of this phenomenon.

Effect of the magnitude of clamp pressure on glueline strength of pine

As with solid wood, test specimens of orthotropically matched and glued pine exhibited different relationships than maple among clamp pressure, glueline shear strength, and percentage of wood failure.

These relationships for pine wood of a constant specific gravity of 0.46 are depicted in Fig. 8. For radial specimens, the mean glueline shear strength was 10.1 MPa, and for tangential specimens it was 7.0 MPa. It should be noted that this property of pine (higher glueline shear strength for radially bonded specimens than for tangentially bonded specimens) is the opposite of the results observed for maple. The percentage of wood failure was 100% for radial sections and 98% for tangential sections.

These experiments verified that orthotropic characteristics are unique to each species of wood and should therefore be recognized in tests of wood properties and applications in order to reduce the effects of interaction of independent variables.

Test results on maple also suggest that as specific gravity of wood increases, especially on tangential sections, either the holding power of fibers in the wood structure exceeds the cohesive forces of an adhesive or, decreasing porosity of wood significantly reduces glue penetration. As a result, percentage of wood failure during glueline tests decreased as the specific gravity of the sample increased.

Effect of type of adhesive on glueline strength

Test results using urea-formaldehyde (U-F) adhesive are illustrated in Figs. 9–10. For the maple samples, with all other factors held constant, the glueline shear strength achieved with U-F adhesive was somewhat lower than with the PVAc formulation. This relationship was true for both orthotropic sections. The nature of the curves obtained with U-F adhesives was also quite different, with the peak strength values being reached at much lower clamp pressures and falling off rapidly as pressure was increased. Percentage of wood failure was also lower with U-F adhesives on maple, particularly on the tangential sections. There were slight variations in specific gravity between samples tested with the different glue formulations, but this was probably not a significant factor. The relative shear strength between radial and tangential sections was maintained with the tangentially bonded specimens exhibiting higher values than the radially bonded specimens. Note in Fig. 9 that the maximum amount of clamp pressure applied on the tangentially bonded specimens of maple was almost twice as large as that for the radially bonded specimens. This again shows that radially cut specimens are fundamentally different from tangentially cut specimens in terms of compression and shear strength. The data also suggest that relative units (the ratio of clamp pressure to compressioin strength) will be useful in determining optimum clamping pressure.

The observed relationships for pine bonded

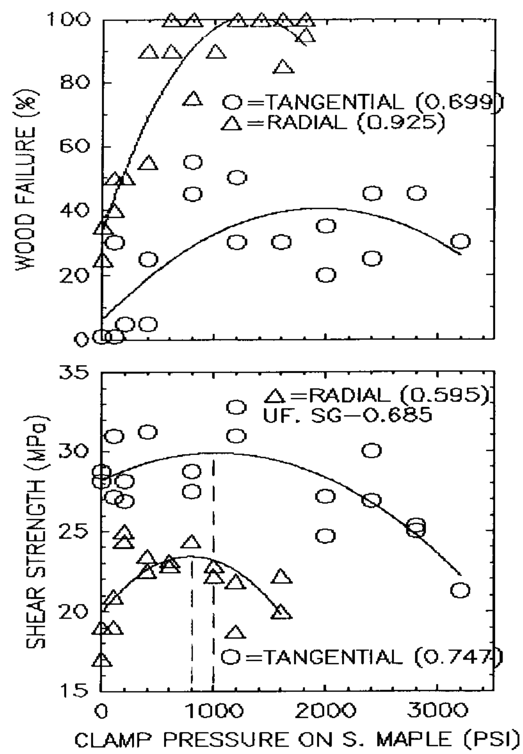

FIG. 9. Effect of relative clamp pressure on shear strength and percentage of wood failure in sugar maple joints using U-F glue.

with U-F glue are presented in Fig. 10. It is noteworthy that tests on pine did not produce high correlation among glueline shear strength, wood failure and the CP/CS ratio (Table 2). However, the different performance of pine wood with respect to orthotropic orientation should be emphasized. The radially bonded specimens produced higher glueline shear strength than the tangentially bonded specimens. This relationship is opposite that for maple and is consistent with other data (Okkonen and River 1989).

Effect of the wood species on the glueline shear strength and percentage of wood failure

A number of practical observations may be made based on data presented in Figs. 2–10. Differences in glueline shear strength and percentage of wood failure vary by wood species

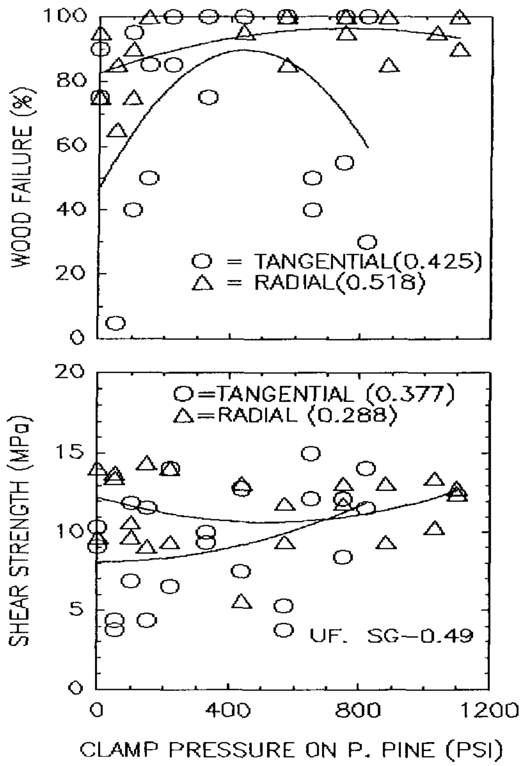

FIG. 10. Effect of relative clamp pressure on shear strength and percentage of wood failure in ponderosa pine joints using U-F glue.

and by orthotropic section. This can be explained by structural differences affecting glue penetration into the substrate and the uniformity and thickness of the glue line. The basic morphology of wood is important in understanding the effect of orthotropic wood structure on glueline development and its mechanical properties.

It may be assumed that glueline shear strength tests results were higher for maple than for pine due to:

generally higher density maple wood,
more homogeneous wood structure due to more even specific gravity distribution in the annual growth ring of maple (Kollmann and Côté 1968),
about 18% of the structural elements (wood rays) are placed in the radial direction in maple vs. only 5% in pine (Brown et al. 1952).

The highest percentage of wood failure was recorded on radially bonded specimens regardless of the tested wood species, probably because glue has easy access to the earlywood in the annual growth ring. The tangentially bonded specimens of pine produced a greater percentage of wood failure than similar specimens of maple, probably due to greater porosity.

The distinct inverse relationship between specific gravity and the percentage of wood failure was especially apparent when tangentially matched specimens of maple were bonded with either adhesive.

CONCLUSIONS

1. The strength of glue lines using the adhesives employed in this study is closely related to the orthotropic structure and specific gravity of the wood species. Highest shear strengths were found in tangentially bonded specimens of sugar maple, while lowest were produced by tangentially bonded specimens of ponderosa pine.
2. Tangentially bonded specimens of sugar maple exhibited significantly higher glueline shear strength and lower percentage of wood failure than did radially bonded specimens. In contrast, radially bonded pine specimens exhibited both higher shear strength and percentage of wood failure than did tangentially bonded specimens. The exact reasons for this phenomenon require further study.
3. Optimum clamp pressure for sugar maple was determined to be a ratio of 0.3 times the compression strength using U-F glue and 0.5 times using PVAc.
4. Increasing clamp pressure did not develop a substantially stronger glue line on either orthotropic section of pine.
5. Regardless of the magnitude of applied clamp pressure, a higher percentage of wood failure was observed for radially bonded specimens of both tested species than for tangentially bonded specimens.
6. Tangentially bonded specimens showed a significant decrease in wood failure values when the specific gravity of the specimen in-

creased. The radially bonded specimens did not follow this pattern closely. More studies are required to explore that phenomenon.

7. Both types of adhesives used in the study performed similarly on the tested wood species in terms of relative clamp pressure needed and results relative to orthotropic section.

8. The same clamp pressure produces different results in the two tested species because of the difference in compression strength with respect to orthotropic orientation as well as variations in specific gravity.

9. Optimum clamp pressure can be expressed as a coefficient of compression strength for the specific sections being glued.

10. The criteria for optimum clamp pressure to be applied during the process of gluing solid wood seem to be correlated to:

differences in orthotropic wood structure;
compression strength at the proportional limit, which differs for radial and tangential sections of the same species;
specific gravity of the glued wood;
physical and mechanical properties of the adhesive.

11. In order to develop a better understanding of how clamp pressure and other parameters affect the physical and mechanical properties of a glue line, further investigation is needed in the following areas:

examination of the glue line and its adjacent layers through microscopic and ultramicroscopic tests;
exploring why the radially bonded specimens produced significantly higher wood failure results;
testing durability and quality of physical and mechanical properties of the glue line through the accelerated aging method, cycle loading method, long-term loading method;
testing how orthotropic wood structure affects water resistance of glue lines.

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