TENSION-PERPENDICULAR-TO-GLUELINE STRENGTH OF DOUGLAS-FIR LUMBER LAMINATED AT HIGH TEMPERATURES

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ABSTRACT

Preheated Douglas-fir was laminated with high-temperature phenol-resorcinol and urea-melamine adhesives employing the residual heat in the wood to accelerate the cure. Tension specimens were prepared from these laminations, as well as from conventionally glued-laminated wood and wood that was not glued. Prior to testing, one-half of the specimens were conditioned at room temperature and the other half received a 24-hr cold water soak.

All glued specimens were weaker than the solid-wood specimens. In the dry condition, the heat-treated material was comparable in strength to conventionally glued specimens. When tested wet (an estimate of durability), the strength reduction of the heat-treated wood glued with phenol-resorcinol ranged from 42% for treatments at 380 F (193 C) to 56% for treatments at 500 F (260 C). In contrast, the conventionally glued material was reduced in strength by only 8%, which compares with published values for solid wood. Thus, the heat-treated wood formed gluelines that are presumably less durable in tension than the conventionally glued-laminated wood.

Additional keywords: Pseudotsuga menziesii, glued-laminated beams, tensile strength, glueline durability, phenol resorcinol.

INTRODUCTION

In glued-laminated wood, as well as in solid wood, differential shrinkage arising from moisture gradients induces stresses that can result in checking and, in the case of glued wood, delamination at or adjacent to the glueline. Dietz et al. (1945) developed a mathematical model of the variation of the stresses across the glueline. By assuming a moisture gradient, the analysis indicated that maximum shear and tension-perpendicular-to-glueline stresses existed at the ends of the gluelines, and that the highest stresses occurred during the phase where the wood is drying out. They concluded with the statement that ". . . adhesives must be employed which have both high shearing strength and high tensile strength perpendicular to the glueline both when dry and when wet if laminated beams are to be dependable in service." According to Longworth (1971), it is common for the moisture gradient to be fairly steep, and it is estimated that tension-perpendicular-to-glueline stresses greater than 700 psi can be developed.

Glued-laminated beams using room-temperature-curing adhesives have been satisfactorily employed as structural load-bearing members in buildings for many years. During the past few years, processes that employ stored heat in the wood have been used to accelerate the cure of specially formulated high-temperature adhesives in fabricating structural glued-laminated beams, for the purpose of speeding up production.

Bohlen (1971) examined the shear strength of Douglas-fir lumber laminated at high temperatures with phenol-resorcinol-formaldehyde and urea-melamine-formaldehyde glues. This work provided evidence that when Douglas-fir at 9% moisture content was subjected to preheat temperatures in excess of 420 F (216 C) for one minute at 150 psi, although the gluelines per se remained intact, the wood adjacent to the gluelines was weakened. This weakness became evident when specimens laminated at preheat temperatures in the range from 420 to 500 F (216 to 260 C) fell apart during the second cycle of the 3-cycle moisture-drying tests specified in CSA-0177 (1965). Examination of these specimens indicated uniformly high wood failure, which led to the conclusion that the strength of the wood was degraded by the heat treatment.

The objectives of this experiment were to evaluate the tension-perpendicular-to-glueline strength of high-temperature laminated Douglas-fir over a wide range of wood-preheat temperatures, and to compare these results with closely matched conventionally laminated and solid wood specimens.

EXPERIMENTAL

Test method

Tensile testing of wood is a controversial subject that centers about what the shape of specimens should be so that stress concentrations will be minimized. Coker and Coleman (1930) studied the distribution of stresses within the specimen shape now described in ASTM-D-143 (1971) (Fig. 1). They found that stress concentrations occur because of the method of loading and that the principal stress is at an angle of about 50 degrees to the horizontal test plane. Marquardt and Youngquist (1956), in an analysis of tension test methods on wood, point out that the ideal tension specimen should be free from stress concentrations, should fail in the test section and not in or near the grips, and should be capable of being fabricated without injuring the specimen.

The ASTM specimen (Fig. 1) was selected for two reasons;

1. The specimen satisfies the above conditions relating to ease of fabrication and assurance of failure in the test section;

2. The basis for comparison of tension strength will be related to that of solid wood, as extensive data on hundreds of small clear specimens of solid wood were compiled by Kennedy (1965) from tests according to the ASTM specimen shape.

Specimen preparation

Specimens were selected from Douglas-fir wood (*Pseudotsuga menziesii* [Mirb.] Franco) that was free from strength-reducing characteristics such as pitchpockets, knots, grain deviations, etc. Although it is recognized that rather large strength differences occur between specimens tested radially and tangentially, the wood selected for laminating was random in grain orientation, since this simulates commercially produced material.

A quantity of 2 × 6-inch laminating-grade Douglas-fir lumber was planed, ripped to 2 × 3-inch size, and cut into 12-inch-long sections containing a minimum of defects. Two randomly selected sections were glued together to make one billet from which four tension-perpendicular-to-glueline specimens were cut according to ASTM standards (Fig. 1). Twenty billets were prepared using a high-temperature curing phenol-resorcinol-formaldehyde adhesive, 12 billets using high-temperature curing urea-melamine-formaldehyde adhesive. The wood was preheated for one minute at 150 psi in a press with electrically heated platens, spread with high-temperature curing adhesive, then clamped for one minute at 150 psi. Temperature levels evaluated were 380 F, 420 F, 460 F, and 500 F. The process and equipment for doing this hot-press laminating is described by Bohlen (1972). As this was a comparative experiment, five additional billets were prepared using material that was prepressed for one minute at 150 psi and room temperature. Conventional room-temperature curing phenol-resorcinol adhesive was spread on the wood and the billets were clamped for approximately 15 hr. Solid wood specimens were selected from the same laminating stock as well.

Tension specimens cut from each billet were selected to be matched with consideration of two test environments, dry and soak. Each test billet yielded four specimens (Fig. 1) and each alternate specimen was selected for one particular environment. Thus, from each billet, one specimen for

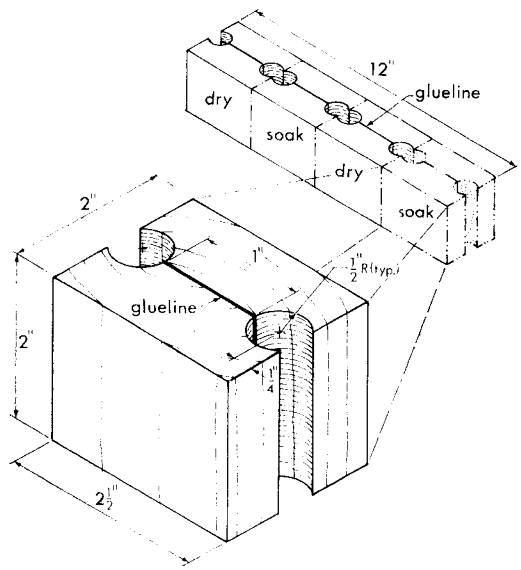

FIG. 1. Test billet and ASTM tension-perpendicular-to-glueline specimen.

TABLE 1. *Distribution of glued-laminated test specimens*

Adhesive and platen temp., F	No. of billets*	No. specimens in each treatment		Sub-totals (no. of specimens)
		Dry	Soak	
High-temperature phenol resorcinol				
380	5	10	10	20
420	5	10	10	20
460	5	10	10	20
500	5	10	10	20
High-temperature urea melamine				
380	3	6	6	12
420	3	6	6	12
460	3	6	6	12
500	3	6	6	12
Room-temperature phenol resorcinol controls				
70	4.5**	9	9	18
Totals	36.5	73	73	146

* Each billet yielded four specimens (Fig. 1).
** One half of one billet was retained and not tested.

each environment was obtained from an end and one specimen from the center portion. In all, 146 laminated specimens were prepared and distributed according to Table 1.

Environmental conditioning

The high-temperature laminated material that was tested in shear (Bohlen 1971) was conditioned in each of four environments: room temperature or "dry"; cold water "soak"; +130 F (54 C), and cyclic moisture per CSA-0177 (1965) for two of the three cycles specified. It was observed that the phenol-resorcinol shear specimens severely delaminated after the first cycle of the cyclic-delamination test. The specific urea-melamine glue used was not designed to be a waterproof adhesive and, consequently, these specimens could not endure one cycle of the moisture-cycling test. To give some estimate of durability in service, the glues should be evaluated in the high moisture-containing state per CSA-0112.5-(1960), as well as in the "dry" condition. Thus, for the present study it was decided to test only in the "dry" and "soak" conditions and to compare the results with the control specimens; i.e. solid wood and those glued with room-temperature curing phenol-resorcinol adhesives.

For the dry condition, the conditioning temperature and humidity environment was a constant 70 F (21 C) and 40% RH, which corresponds to an equilibrium moisture content in the wood of about 8%. Actual moisture contents by the oven-dry method indicated an average of 8.6%, ranging from 7.1 to 9.2%. The "soak" condition was achieved by immersing the specimens for 24 hr in cold tap water, which averaged 47 F (8 C). This treatment resulted in a specimen average moisture content of 35%, with a range from 24 to 45%. Moisture distribution across the test area of specimens was probably not uniform, so that some of them may have been somewhat less than at the fiber saturation point. These specimens were tested while wet.

Testing

The specimens were aligned in a fixture as shown in ASTM-D-143 (1971) and loaded in tension at the specified rate of 0.10 inches (2.5 mm) per minute. Ultimate load was recorded, cross-sectional dimensions were measured, specimens were weighed and the percentage wood failure was estimated. Strength per unit area (psi) was calculated and the results tabulated (Table 2).

TABLE 2. *Tension-perpendicular-to-glueline strength of Douglas-fir*

Specimen description	DRY							SOAK							Avg. dry/soak strength ratio (see note)
	No. of speci-mens	Ultimate tensile stress (psi)			Percent wood failure			No. of speci-mens	Ultimate tensile stress (psi)			Percent wood failure			
		Min.	Avg.	Max.	Min.	Avg.	Max.		Min.	Avg.	Max.	Min.	Avg.	Max.	
High-temperature phenol resorcinol at:															
380 F	10	231	335	470	85	97	100	10	116	195	245	95	98	100	1.72
420	10	170	303	422	90	98	100	10	73	132	249	95	98	100	2.30
460	10	75	240	415	80	95	100	10	58	103	151	95	97	100	2.33
500	10	0	213	331	90	97	100	10	59	94	132	90	98	100	2.27
High-temperature urea melamine at:															
380 F	6	224	255	291	95	99	100	6	133	163	204	75	94	100	1.57
420	6	216	262	425	100	100	100	6	87	235	346	10	40	100	1.11**
460	6	115	224	372	55	80	90	6	66	137	367	70	77	80	1.63
500	6	251	297	347	20	57	90	6	0	102	193	0	40	75	2.91
Room-temperature phenol-resorcinol controls	9	191	331	538	50	88	100	9	196	304	508	75	90	100	1.09
Solid-wood controls	8	255	412	535	-	-	-	8	334	500	665	-	-	-	0.825
Solid-clear wood per Kennedy (1965)*	374	158	444	1204	-	-	-	436	144	407	842	-	-	-	1.09

* Min. and max. values obtained from actual test data.
Note: Dry-soak strength differences for high-temperature specimens are significant at the 0.1% level except for item marked **. A Mann-Whitney distribution-free statistical analysis was used.

DISCUSSION

Solid wood tests

From Bulletin 1104 (Kennedy 1965), the average dry/green ratio of tension strength perpendicular to the grain is 1.09 (Table 2). The solid wood controls in this experiment were of average published dry strength (Table 2) and demonstrated a dry/soak ratio of 0.825 or an increase of average strength in the soak condition. Accepting the premise that the soak condition corresponds to the green condition in Bulletin 1104, the difference in ratios is probably explained by the small number of samples tested in this study.

Room-temperature phenol-resorcinol tests

The dry and soak average strengths of the conventionally glued specimens were 331 psi and 304 psi, respectively. The dry/soak average strength ratio of 1.09 is the same ratio as the published values for solid wood (Kennedy 1965).

High-temperature phenol-resorcinol tests

Over the range of temperatures studied, there was a gradual decrease in average strengths in the dry condition as the temperature was increased, with all of the specimens exhibiting quite high percentage wood failure (85 to 100%). This strength decrease suggests that the temperature history of the wood surface was critical to the development of the ultimate tensile stress and was primarily responsible for the reduction in strength perpendicular to the glueline. The effect was the more striking when examining minimum values, which were 231 psi at 380 F (193 C) and 0 psi at 500 F (260 C). The zero-strength specimen actually fell apart prior to loading after being placed in the text fixture, yet exhibited 90% wood failure.

Percentage wood failure, which is customarily employed as a means for estimating glue-bond strength, evidently does not apply in the case of heated wood. Table 2, which lists the strength and percentage wood failure after various heat treatments, clearly demonstrates in both dry and soak conditions that strength is completely independent of percentage wood failure. This same phenomenon was observed in high-temperature laminated shear specimens and is discussed at some length by Bohlen (1972).

In the soak condition, the average strength dropped considerably at all temperatures of heat treatment, which resulted in dry/soak average strength ratios ranging from 1.72 to 2.33. The large dry/soak ratio at all temperatures is an indication of a fundamental difference between the high-temperature laminated products and room-temperature laminated material.

High-temperature urea-melamine tests

The average strengths and the minimum strengths of specimens remained almost constant throughout the entire temperature range of heat treatments in the dry condition. This was unpredicted in view of the high-temperature phenol-resorcinol test results. However, the dry/soak strength ratio ranged from 1.11 to 2.91, substantiating the results obtained for high-temperature phenol-resorcinol specimens. It is worth noting that at the 500 F (260 C) heat-treatment temperature, two of the six soaked specimens fell apart while being placed in the test fixture. The dry specimens taken adjacent to these two specimens were of average strength for that heat treatment.

CONCLUSIONS

The conventional room-temperature phenol-resorcinol-glued Douglas-fir performed similarly to solid wood when comparing the dry and the wet conditions, although the average strength was lower for the glued wood.

The average strength in the dry condition of high-temperature phenol-resorcinol-glued wood was approximately the same as that of the room-temperature-glued specimens. The average strength of the urea-melamine-glued wood was somewhat less than conventionally glued specimens.

In the soak condition, however, the average strengths of specimens made using both glues are significantly different than the dry strengths for 380 F (193 C) preheat temperature and higher. This indicates that, with the adhesive systems used, Douglas-fir at 9% moisture content heated at relatively low temperatures for one minute at 150 psi prior to gluing is weaker when wet and, therefore, presumably less durable in tension perpendicular to the glueline than conventional room-temperature-glued wood.

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