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Compressive and tensile properties of a butt-jointed lamination model

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Abstract A study was undertaken to evaluate the effect of glue application and placement of butt-joints on the compressive and tensile properties in a butt-jointed lamination. The aim was to provide background information for producing butt-jointed, glued, laminated timber. Three butt-jointed lamination models were prepared from spruce-pine-fir (S-P-F) dimension lumber with glued and nonglued butt joints, with different placements of the butt joints in the models. The axial stiffness and strength properties were assessed using both compressive and tensile tests. The results of the study indicated that for the compressive lamination model the application of glue at the butt joint gave more stiffness than the nonglued butt joint. Neither glue application nor placement of the joint had a statistically significant effect on the compressive strength. There were no significant differences between the glued and nonglued butt joint for either tensile strength or stiffness.

Key words Butt joint · Glued joint · Glulam · Compression · Tension

Introduction

The feasibility of upgrading small, low-quality timber resources for the production of glulam is currently an important subject in the timber industry. Butt-jointed glulam is one of the solutions to utilizing small-diameter, underutilized timber resources.

ASTM-D3737¹ forms the basis for assigning design stresses to glulam timber. Because glulam beams are usually used for bending members, emphasis is placed on design strength and stiffness during bending, with the primary

design loads applied perpendicular to the wide face of the laminations. Glulam can also be used as tension members in truss chords or as compression members in columns²; and in that case the load-carrying capacity is specifically determined from the axial forces and the effective cross section.

In one of our previous tests the bending stiffness and strength of a five lamination butt-jointed glued laminated timber (glulam) were studied.³ A model equation based on the strain energy distribution in a notched wood beam^{4,5} was developed to predict the bending stiffness and strength reduction caused by the butt joint in a glulam. The bending stiffness and strength properties of beams with different placement of a butt joints were investigated.

The strength reduction effect of a butt joint at the compression side of the glulam was observed from the initial stage of the loading process up to when the contact ends of the lamination at the butt joint have closed enough to transmit compressive stress across the butt joint.³ This experiment was conducted to study further the effect of compressive and tensile stresses on butt joints in a laminated model using glued and nonglued butt joints. The application of glue at the butt joint, which has been observed to provide more compressive stiffness than that of a nonglued butt joint in short wood columns,⁶ can increase the bending strength of the glulam beam.

To arrive at a rational design for glulam beams containing laminated butt joints made from low-grade timber resources, compression and tensile properties of the butt jointed lamination should be studied. The objective of this study was to determine the effect of glue application and placement of a butt joints on compressive and tensile strength properties of a butt-jointed lamination model.

Materials and methods

Material selection

The materials used for the test were 2 × 4 inch spruce-pine-fir (S-P-F), NLGA grade stamped as no. 1 and no. 2 S-dry

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lumbers. The lumbers were planed to 33×88 mm cross section to expose the visible defects that could adversely affect the tensile and compressive properties. A total of 45 wood samples were selected from 80 lumbers. The dynamic modulus of elasticity (MOE) for each of the selected wood samples was determined by the longitudinal vibration technique. The samples were ranked by their dynamic MOE. The test pieces were carefully matched on the basis of the dynamic MOE in the various butt joint variables for the compression and tension tests. This was done to ensure equal distribution of MOE values among the butt joint variables for the tension and compression samples.

Experimental design

The joint variables were specifically designed to assess the effect of glue application at the butt joint and the placement of butt-jointed lamination on the performance of compressive and tensile laminated models. In this experiment, specimens with glue application at the butt joint were identified as glued butt-jointed lamination, and those without glue application at the butt joint were identified as nonglued butt-jointed lamination. With regard to placement of the butt joints, specimens with the inner lamination-containing butt joint were identified as the inner butt-jointed lamination model, whereas specimens with outer lamination-containing butt joints were identified as the outer butt-jointed lamination model.

Compression test specimen

For compression, 300 mm length wood pieces were cut from the originally selected wood samples. Models of three-lamination compression test samples were prepared by gluing three of the 300-mm cut pieces for each model. One-component polyurethane glue (Sunstar no. 930; Sunstar, Japan) was used. The butt-joint placements and the glue application at the butt joint for the three-lamination model were fabricated according to the following specifications (Fig. 1).

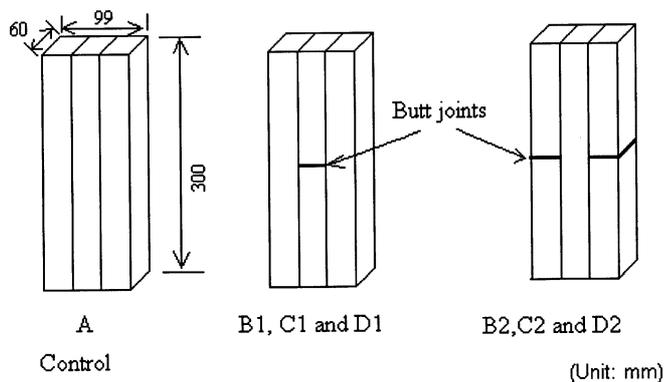


Fig. 1. Design of the butt joint in the compression test. *A* is the control sample. *B1* and *B2* have glue application at the butt joints. *C1* and *C2* have no glue application at the butt joint. *D1* and *D2* have 2 mm clearance between the ends of the lumber pieces in the lamination

- A: continuous lamination without a butt joint as a control
- B1: glued butt joint in the inner lamination
- B2: glued butt joints in the outer laminations
- C1: nonglued butt joint in the inner lamination
- C2: nonglued butt joints in the outer laminations
- D1: 2 mm clearance in the inner lamination
- D2: 2 mm clearance in the outer laminations

The thickness of the individual lamination for the compression samples was 33 mm. The final dimensions of the laminated model were $60 \times 99 \times 300$ mm. All the butt joints were located at the middle of the laminated model. Groups D1 and D2, which had 2 mm clearance, were designed to determine the highest strength reduction effect of butt joints on the laminated model. Ten specimens were prepared for each group.

Tension test specimen

To determine the tension, the selected lumber samples were further planed into 30 mm thickness. Wood pieces of 800 mm length were cut from the lumber samples. The three-lamination model containing butt joints were prepared by gluing three of the 800-mm cut pieces using the same polyurethane glue type that was used for preparing the compression specimens. Each of the lamination models was further cut through the wide face into three test pieces. Final planing was done to produce a smooth-faced, glued, lamination tension piece.

The application of glue at the butt joints and the butt-joint placements for the three-lamination model for the tension test were grouped as follows (Fig. 2).

- A: small sample specimen as a control
- B1: glued butt joint in the inner lamination
- B2: glued butt joints in the outer laminations
- C1: nonglued butt joint in the inner lamination
- C2: nonglued butt joints in the outer laminations

The cross-sectional area of the lamination containing a butt joint was 10×30 mm. The dimensions for lamination models containing an inner butt joint (i.e., groups B1 and C1) were $10 \times 60 \times 800$ mm, and that of lamination models containing outer butt joints (i.e., groups B2 and C2) were $10 \times 90 \times 800$ mm. All the butt joints were located at the

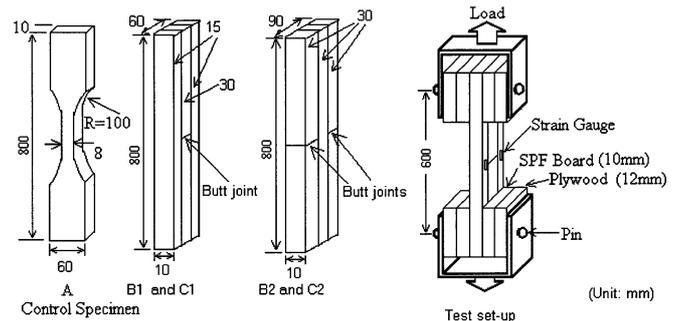


Fig. 2. Design of butt joint in the tension test. *A* is small sample control specimen. *B1* and *B2* have glue application at the butt joints. *C1* and *C2* have no glue application at the butt joints

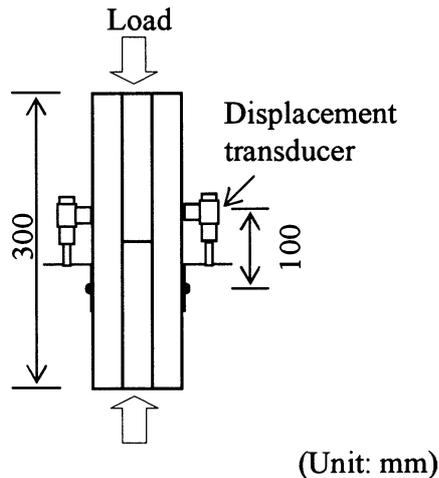


Fig. 3. Compression test setup

middle of the laminated model. To reduce the effect of bearing stress due to pin connections during the tension test, 10-mm S-F-P board and 12-mm plywood were glued to either side of the test piece at the top and bottom parts, as shown in Fig. 2. Two 30-mm diameter holes were drilled over a span of 600 mm across the center of the specimen for the pin connections of the test setup (Fig. 2). Twelve specimens were prepared for each group.

Test method

The compressive and tensile tests were conducted using hydraulic test machines with static loading capacities of 500 and 100 kN, respectively. The compression test setup is shown in Fig. 3, and the tension test setup is shown in Fig. 2. Displacement for the compressive test was measured using two displacement transducers over a distance of 100 mm with the butt joint at the center. The displacement transducer was at least 0.001 mm.

For the tension test, the specimen was set between the grips such that the butt joint was at the mid-span position of the 600 mm free span. Displacement for the tensile test was measured using two strain gauges placed at the center of the specimen. The length of the strain gauge used for the tension test was 10 mm.

Each specimen was tested to failure to determine the ultimate compressive and tensile stress and the static MOE. After the test, the moisture content and specific gravity of the specimens were measured using ASTM 2395-93 methods.⁷ The specific gravity measurement was based on the oven-dried weight and volume at the moisture content during the test.

Method of evaluation

To determine the effect of the butt-joint variables, the glued butt-jointed lamination model was compared with the nonglued butt-jointed lamination model, and the inner butt-jointed lamination model was compared with the outer

butt-jointed lamination. The apparent stiffness was calculated from the basic stress – strain relation. To assess the reduced cross section due to the 2-mm clearance in groups D1 and D2 during the compression test, the model calculation developed by Dansoh et al.³ for butt-jointed glulam was applied to estimate the effective stiffness. The ultimate stress was calculated from the maximum load during the test. The butt-joint efficiencies for both the compression and tension tests were calculated as a ratio of the ultimate stress of the butt-jointed specimens to the ultimate stress of the control specimens. The load–displacement curves of the compression test were used to analyze the deformation characteristic of the joints in the lamination as subjected to compressive stress.

A two-sample *t*-test assuming equal variance^{8,9} was performed at the 5% significance level to assess whether statistically significant differences existed between the stiffness and strength properties of the various butt-joint placements and glue applications applied during the test. An attempt was made to estimate the 5% exclusion lower limits of the strength values using normal and Weibull distributions. For the parameters of the normal distribution, Student's *t*-distribution was used considering the small sample size. The mean and sample standard deviation for each test group was calculated, and the 5% exclusion lower limit was calculated as follows

$$X_{0.05} = \mu - ts$$

where $X_{0.05}$ is the 5% exclusion lower limit; t is the Student's *t* statistic; μ is the mean; and s is the sample's standard deviation. A computer program was written to construct the probability plot, which was used to estimate the parameters of the Weibull probability function.¹⁰ The 5% exclusion limits can be calculated¹¹ as follows

$$X_{0.05} = x_0 + \eta[(0.95)]^{1/\beta}$$

where x_0 , β , and η are the location, shape, and scale parameters of the Weibull distribution, respectively.

Results and discussion

Compression

The mean ultimate compressive stress of the control test was 29.96 MPa, whereas that for the butt-jointed groups ranged from 23.69 to 28.81 MPa (Table 1). The mean ultimate compressive stress for groups D1 and D2 were 23.69 and 27.11 MPa, respectively. With the exception of groups D1 and D2, the differences in ultimate compressive stress between the butt-joint groups were small, with butt-joint efficiency ranging from 0.94 to 0.96. The *t*-test analysis indicated that both placement of the joints (i.e., inner or outer joint) and the glue application (i.e., glued or nonglued) had no significant effect on the ultimate compressive stress at the 0.05 significance level (Table 2). The 5% exclusive lower limits calculated from the Weibull distribution were generally lower than that of the normal distribution (Table 1).

Table 1. Mean ultimate compressive stress, strength efficiency, and 5% exclusive limits for the compression test

Group ^a	Mean (MPa)		Butt joint efficiency (σ/A)	5% Lower limits (MPa)			
	σ	SD		Normal		Weibull	
				$L_{5\%}$	$L_{5\%}/A$	$L_{5\%}$	$L_{5\%}/A$
A	29.96	5.15	1.00	26.08	1.00	24.24	1.00
B1	28.81	4.47	0.96	25.51	0.98	22.86	0.94
B2	28.38	3.22	0.95	25.95	0.99	25.73	1.06
C1	28.60	3.48	0.95	25.97	1.00	25.64	1.06
C2	28.17	2.29	0.94	26.44	1.01	26.44	1.09
D1	23.69	3.52	0.70	21.04	0.81	18.80	0.78
D2	27.11	4.56	0.90	23.67	0.91	20.55	0.85

σ , ultimate compressive stress; σ/A , joint efficiency for ultimate compressive stress; $L_{5\%}$, 5% lower limits for ultimate compressive stress using normal and Weibull distributions

^aThere were 10 specimens tested for each group

Table 2. Two-sample *t*-test assuming equal variance for differences in butt-joint variables for the compression test at 0.05 significance level

Constant variable	Source of variation	MOE		Strength		$t_{critical}$
		<i>P</i>	<i>t</i>	<i>P</i>	<i>t</i>	
Inner joint	B1,C1	0.129	1.592	0.908	0.117	2.101
Outer joint	B2,C2	0.000	7.309	0.867	0.169	2.101
Glued joint	B1,B2	0.770	0.297	0.805	0.250	2.101
Nonglued joint	C1,C2	0.001	4.225	0.746	0.329	2.101

MOE, modulus of elasticity

Table 3. Stiffness properties for the compression test

	MOE (GPa)	CV
A	9.8	0.19
B1	11.4	0.22
B2	11.6	0.11
C1	9.9	0.15
C2	7.1	0.22
D1	7.0 ^a (10.4) ^b	0.10 ^a (0.10) ^b
D2	4.7 ^a (10.7) ^b	0.13 ^a (0.12) ^b

CV, coefficient of variation

^aCalculation assuming full cross section without considering the 2-mm clearance

^bModel calculation considering the 2-mm clearance³

The apparent stiffness of the glued butt-jointed laminations (groups B1 and B2) was higher than the nonglued laminations (groups C1 and C2) by 13% and 39% for the inner and outer butt joints, respectively (Table 3). In a compression test on short butt-jointed columns, Sasaki et al.⁶ indicated that the glued butt-jointed column had 15% higher stiffness properties than the nonglued butt-jointed column. The increase in stiffness was due to the fact that the glued butt joint acted as a hardened plate, enabling stress transmission through the glued butt joint, resulting in improved stiffness. The *t*-test analysis (Table 2) performed indicated that glue application had a statistically significant effect on stiffness for the outer butt-joint placement but not for the inner butt-joint placement ($\alpha = 0.05$). The average moisture content and specific gravity for the compressive test were 15.4% and 0.43%, respectively.

Characteristics of load–displacement curves for the compression test

Typical load–displacement curves for the compression test are illustrated in Fig. 4. Groups A, B1, B2, and C1 had identical load–deflection curves, increasing linearly at the beginning and changing to a smooth curve up to the ultimate load. The load–displacement curve of group C2 with outer butt joints and the 2-mm clearance lamination model (D1 and D2) gave not only larger deflections per unit load, they exhibited two linear phases. Group C2 showed an apparent yield point between the two linear phases. Groups D1 and D2 had a large displacement with a reduced load between the linear phases, indicating clearance in the laminations of the specimen. The yielding between the two linear phases in C2 indicates the loading processes when the butt joints in the compression face have closed up enough to transmit compressive stress across the contact ends of the lumber pieces in the lamination. In effect, this raised the effective load-carrying capacity of the specimen. The results obtained for the load–displacement curve seemed to agree with the previous study conducted on butt-jointed lamination glulam by Dansoh et al.³

Tension

The mean ultimate tensile stress of the control test was 90.07 MPa (Table 4). The glued butt-jointed lamination groups had apparent tensile strengths of 47.38 and

Table 4. Mean ultimate tensile stress, strength efficiency, and 5% exclusive limits for the tension test

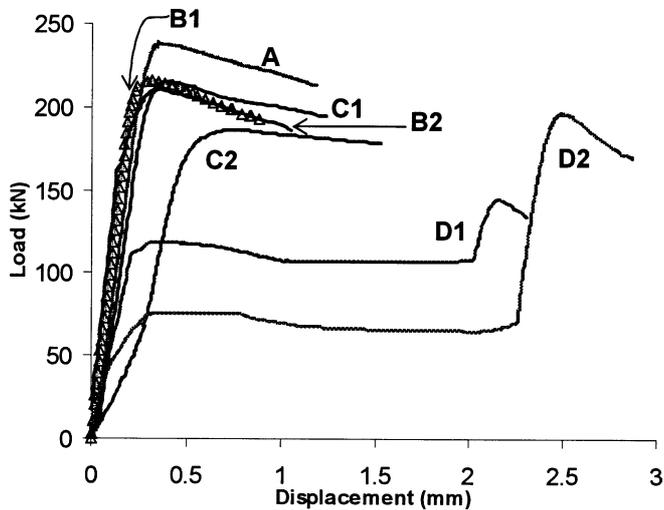
Group ^a	Mean (MPa)		Butt joint efficiency (σ/A)	5% Lower limits (MPa)			
	σ	SD		Normal		Weibull	
				$L_{5\%}$	$L_{5\%}/A$	$L_{5\%}$	$L_{5\%}/A$
A	90.07	16.81	1.00	78.92	1.00	66.77	1.00
B1	47.38	9.87	0.53	40.83	0.52	34.64	0.51
B2	40.42	7.69	0.45	35.32	0.45	33.87	0.51
C1	47.21	7.69	0.53	38.52	0.49	28.97	0.43
C2	40.99	13.11	0.46	37.33	0.47	35.60	0.53

σ , ultimate tensile stress; σ/A , joint efficiency for ultimate tensile stress; $L_{5\%}$, 5% lower limits for ultimate tensile stress using normal and Weibull distributions

^aThere were 12 specimens tested for each group

Table 5. Two-sample *t*-test assuming equal variance for differences in butt joint variables for the tension test at 0.05 significance level

Constant variable	Source of variation	MOE		Strength		$t_{critical}$
		<i>P</i>	<i>t</i>	<i>P</i>	<i>t</i>	
Outer joint	B2,C2	0.218	1.269	0.836	0.210	2.074
Glued joint	B1,B2	0.113	1.653	0.067	1.928	2.074
Nonglued joint	C1,C2	0.572	0.574	0.144	1.515	2.074

**Fig. 4.** Typical load–displacement curves for the compression test

40.42 MPa for groups B1 and B2, respectively, and the nonglued butt-jointed lamination groups had 47.21 and 40.99 MPa for groups C1 and C2, respectively. The butt-jointed groups exhibited a considerable reduction in tensile strength compared to the control specimen. The butt-joint efficiency ranged from 0.45 for B2 to 0.53 for B1 and C1 (Table 4). Failure in the butt-jointed laminations was observed to be initiated at the tips of the butt joints, propagating along the weak grain direction, which in effect reduced the effective cross section to produce a brittle failure. Dur-

Table 6. Stiffness properties for the tension test

Group	MOE (GPa)	CV
A	11.66	0.07
B1	11.81	0.09
B2	11.12	0.09
C1	10.88	0.17
C2	10.51	0.13

ing the loading process the internal stress path is deviated at the butt joints, resulting in stress concentration at the tips of the butt joints to initiate failure, resulting in reduced tensile strength. The groups containing inner butt-jointed lamination (i.e., B1 and C1) had higher strength values than the outer-jointed lamination groups (i.e., B2 and C2) (Table 4). The *t*-test analysis showed that both placement of the butt joint and glue application had no significant effect on the apparent tensile strength of the butt-jointed lamination model at the 0.05 significance level (Table 5). The 5% exclusive lower limits of the apparent tensile strength values calculated from the Weibull distribution were lower than that of the normal distribution.

The apparent stiffness for the tension test ranged from 10.51 GPa for C2 to 11.81 GPa for B1 (Table 6). The *t*-test analysis, however, showed no significant differences in the stiffness properties among the tension groups. The average moisture content and specific gravity for the tension test were 13.0% and 0.44, respectively.

Conclusions

The application of glue at the butt joint in a compressive lamination model has a performance advantage in terms of stiffness over the nonglued butt joint for the outer-joint lamination model. For the glued butt joint, placement of the joint had no statistically significant effect on the stiffness of the compression; whereas for the nonglued butt joint, placement of the joint had a statistically significant effect on the stiffness of the compression. Neither glue application nor placement of the joint had a statistically significant effect on compressive strength. There were no significant differences between the glued and nonglued butt joints in terms of either tensile strength or stiffness.

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