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Feasibility of Fiberglass-Reinforced Bolted Wood Connections

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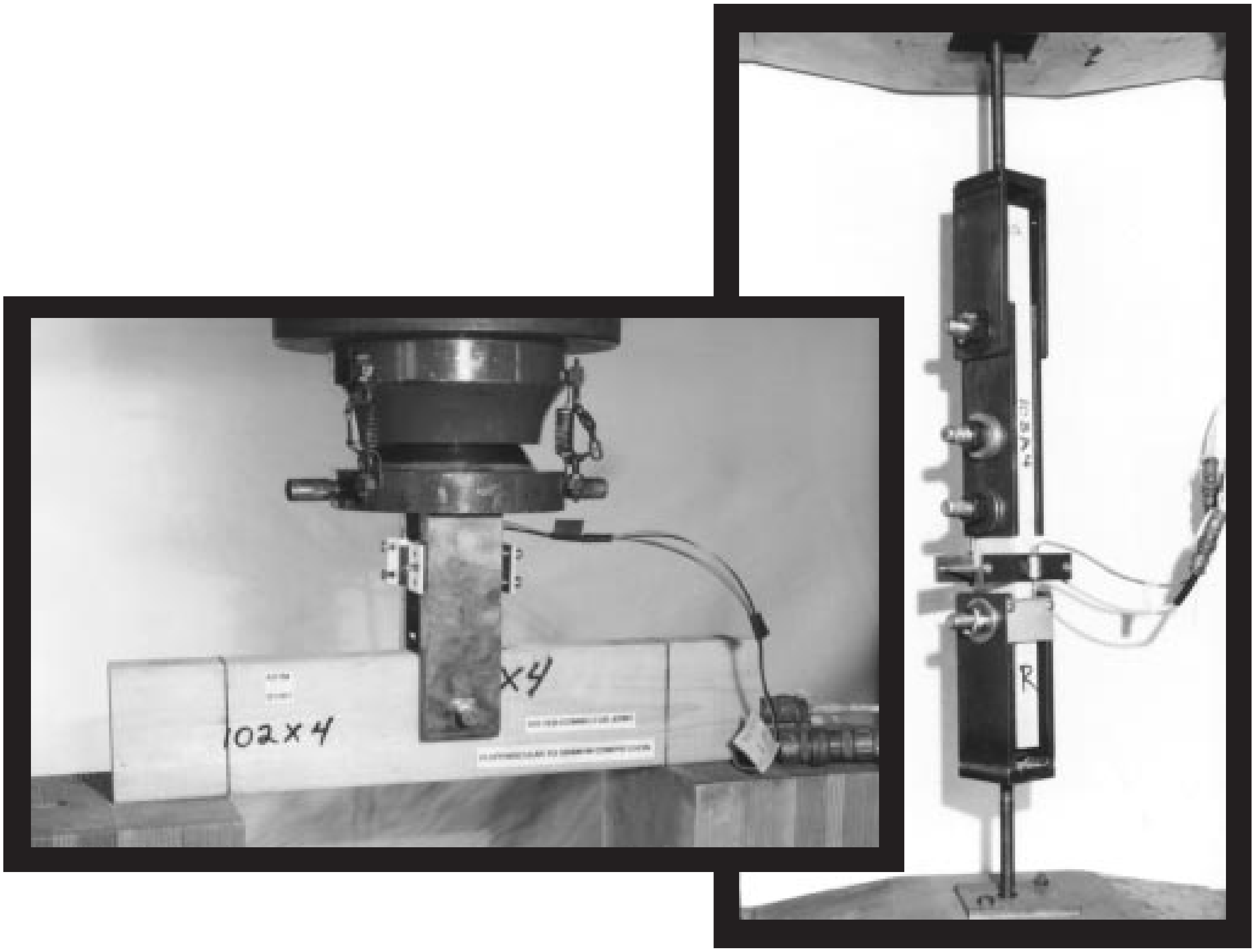

Abstract

Bolted connections often fail by a shear plug or a splitting beneath the bolt caused by tension perpendicular-to-grain stresses as the bolt wedges its way through the wood. Preventing this type of failure would enhance the capacity and reliability of the bolted connection, thus increasing the overall integrity of a timber structure and enabling wood to compete favorably with other engineering materials. This research investigated the use of fiberglass reinforcement to enhance the load-carrying capacity of bolted wood connections. A series of specimens were prepared from standard 38- by 89-mm (nominal 2- by 4-in.) lumber from the Spruce–Pine–Fir lumber grouping. Matched specimens were reinforced with one, two, or three layers of bi-directional fiberglass cloth. Resulting test specimens were configured as a connection that was in accordance with current design specifications. A total of 80 single-bolt, double-shear connections were tested; 40 parallel to grain and 40 perpendicular to grain.

Results indicate that connection strength increases as the layers of fiberglass reinforcement increase. The largest increase occurred when adding the first layer to the nonreinforced connection. Additional layers increased strength at a decreasing rate. The ultimate strength of a three-layer reinforced connection was 33 percent greater than the nonreinforced connection for parallel-to grain loading and more than 100 percent for perpendicular-to-grain loading. More importantly for parallel-to-grain loading, the reinforcement changed the mode of failure from an abrupt, catastrophic type associated with tension perpendicular-to-grain stresses to a ductile type associated with bearing stress.

Keywords: Bolt, wood connection, fiberglass, reinforcement

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Feasibility of Fiberglass-Reinforced Bolted Wood Connections

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Introduction

Failures in wood structures often occur at the connections. Bolted connections often fail by a shear plug or a splitting beneath the bolt caused by tension perpendicular-to-grain stresses as the bolt wedges its way through the wood. Preventing this type of failure enhances bolted connection capacity and reliability. Enhancing the capacity of a connection increases the overall integrity of a timber structure, which enables wood to compete favorably with other engineering materials.

This study examined the technical feasibility of reinforcing wood at bolted connections with fiberglass and epoxy resin. Test results are given for connections loaded both parallel and perpendicular to grain. In addition, shear block and tension perpendicular-to-grain strength results are given to gain insight to how material properties correlate with connection behavior. The scope is limited to one wood species, one type of fiberglass reinforcing system, one epoxy resin, one connection configuration, and three layers of reinforcement. The limited scope is in keeping with the objective of determining technical feasibility.

Background

Several studies have examined how various reinforcing systems contribute to the performance of a wood member, exclusive of the connection. The earliest studies used metal reinforcement. More recently, fiberglass-reinforced polymer (FRP) has been investigated. For example, Triantafillou and others (1992) studied nonprestressed and prestressed FRP sheets bonded with epoxy to the tension zone of a wood beam. Rowlands and others (1986) studied tension and flexure of internally reinforced laminated wood. Ten adhesives and several types of fiber reinforcement were evaluated. They reported an increase up to 45 percent in tensile strength over that of nonreinforced Douglas-fir beams by using 18 percent by volume glass reinforcement. They also noted that “fiber reinforcement could be advantageous in regions of stress concentration (bolted joint, etc.).”

Bulleit (1984) reviewed past studies and concluded that reinforcing wood was technically feasible for improving strength and stiffness properties but economically nonfeasible. Unidirectional fiberglass was the preferred reinforcing material of the pre-1984 studies reviewed. There was no consensus as to use of a woven or nonwoven, strand or mat reinforcing system. In addition, there was no preferred resin. Most studies used epoxy, but acceptable results were also obtained using phenolic, polyester, and phenol-resorcinol formaldehyde resins.

Only two studies, summarized by Bulleit, related to connection reinforcing. Spaun (1981) tested composite members using western hemlock cores with Douglas-fir veneers and FRP layers between the core and veneers; the members were finger jointed at midspan. Poplis and Mitzner (1973) tested bolted connection strength of plywood overlaid with FRP. They conducted bolt-bearing tests that included varying the plywood thickness, bolt diameter, double- or single-shear connections, FRP overlay type and glass content, edge distance, torque on fasteners, wet or dry panel, clean joint or joint with mastic, and face grain direction of the plywood. The use of FRP typically increased strength and stiffness.

Several aspects of the Poplis and Mitzner study are significant. The FRP wet overlays, of equal thickness on both sides, were polyester resin and two weights of woven roving fiberglass. Three plywood thicknesses and three bolt diameters were tested. The overlaid reinforcement increased the ultimate strength of the connections 54 to 117 percent.

There are several recent studies on FRP connections. Meierhofer (1995) tested tension and bending of small FRP-spliced specimens; splices were made using three lengths of carbon fibers. No strength increase information was given. Miyatake and Fujii (1995) studied the use of FRP internal gusset plates for timber structures. Test results indicated that strength increased with length of gusset plate.

Haller and others (1996) studied reinforced bolted connections using densified wood (wood that is thermo-mechanically treated to increase its density). The glass fiber fabric reinforcement was about half the weight of that used in our study and was placed at 45 and 90 degrees to the load direction. They found an approximately twofold increase in ultimate strength and deformability.

Larsen and others (1996) studied doweled and nailed connections reinforced with glass fibers glued to the side of the main member. They observed more ductile connection behavior, with some increase in ultimate strength, compared to nonreinforced connections. They concluded that spacings and end distances can be reduced.

Experimental Procedure

A total of 80 single-bolt, double-shear connections with wood main member and steel side members were tested: 40 tested parallel to grain and 40 perpendicular to grain in accordance with ASTM D5652-95 (ASTM 1995). Each set of 40 tests consisted of 10 replications of four types of reinforced connections: a control having no reinforcement and one, two, and three layers of fiberglass cloth reinforcement bonded to both wide faces of the specimens (Fig. 1).

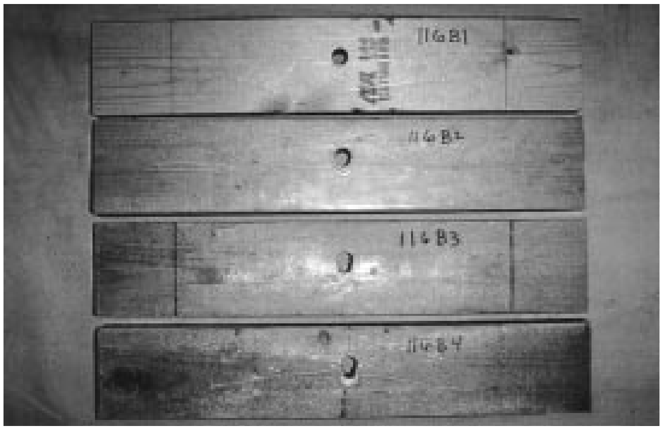

Figure 1—Specimens having (top to bottom) no reinforcement and one, two, and three layers of fiberglass reinforcement.

In addition, 80 shear block and 80 tension perpendicular-to-grain specimens were tested in accordance with ASTM D143-83 (ASTM 1983). These specimens were cut from and correlated with the same specimens used for the connection tests.

The lumber used for the connection tests was cut from twenty 38- by 89-mm by 4.9-m (2- by 4-in. by 16-ft.) Spruce–Pine–Fir No. 2 or better boards. Anatomical examination determined the species to be lodgepole pine. A transverse vibration nondestructive method determined the flatwise modulus of elasticity (MOE) of each board. The boards were ranked by MOE and divided into two groups of 10 each for the parallel- and perpendicular-to-grain tests. Four matched specimens were cut from each board for the four types of reinforced connections. The boards were cut such that the connection area had no defects.

Both the fiberglass cloth and epoxy adhesive system that we used are commercially available products. The bi-directional woven fiberglass cloth had a unit weight of 6.2 by 10^{-5} kg/mm^2 (6 oz/yd^2), an MOE of 46.19×10^3 MPa (6.7×10^6 lb/in^2), and a tensile strength of 35.0 N/mm of width (200 lb/in), per the manufacturer's technical data. The reinforcing system (adhesive and cloth) was applied in accordance with manufacturer's recommendations. One, two, and three layers of fiberglass increased the volume of the specimen by 2.2, 3.3, and 4.6 percent, respectively. The cloth was oriented perpendicular to the load direction for all tests.

The bolts had a 25.4-mm (1-in.) diameter for the parallel-to-grain tests and a 12.7-mm (0.5-in.) diameter for the perpendicular-to-grain tests. The small diameter bolts were necessary to have adequate end distance in the perpendicular-to-grain tests. All bolts were low carbon steel conforming to SAE 1020 steel, with a minimum yield tensile stress of 310.3 MPa (45×10^3 lb/in^2). Bolt lengths were selected to ensure that threads were excluded from bearing against the wood. The ratio of member thickness to bolt diameter was small enough to induce failures in the wood with minimal bending displacement of the bolt.

Prior to testing, the specimens were stored in a constant temperature and relative humidity room to equilibrate at approximately 12-percent moisture content.

Tension parallel-to-grain (Fig. 2) and compression perpendicular-to-grain (Fig. 3) connection tests were in accordance with ASTM D5652 (ASTM 1995). Rates of load were applied to achieve failure in 5 to 15 min. Two linear variable differential transducers continuously monitored and averaged displacements on both sides of the connection. One of the following defined failure:

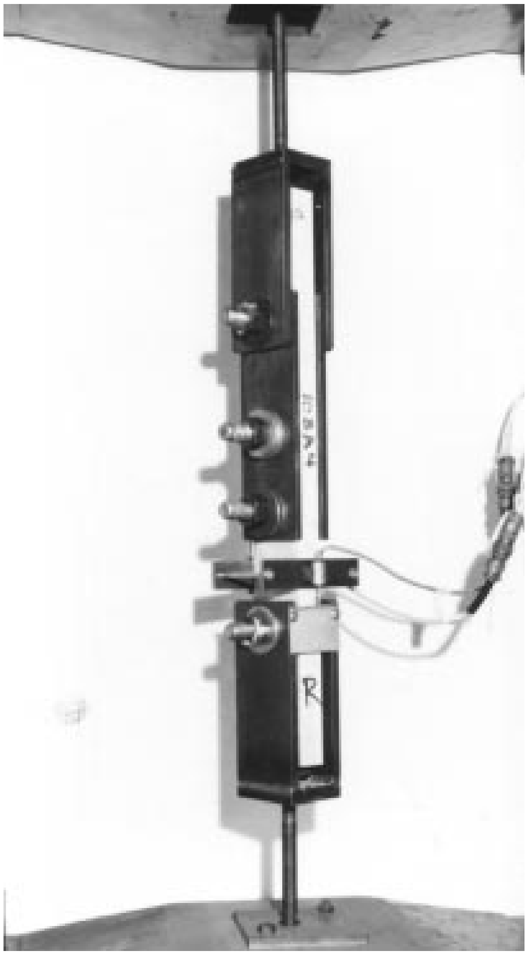

Figure 2—Test setup for tension parallel-to-grain connection tests.

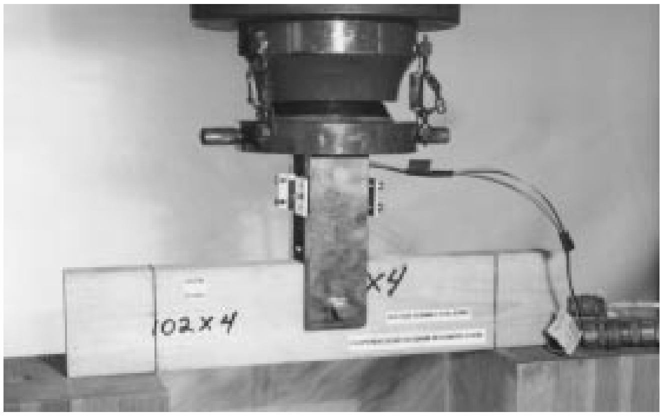

Figure 3—Test setup for compression perpendicular-to-grain connection tests.

- Specimen split under the bolt.
- Load resistance of the connection steadily decreased.
- Displacement of the bolt exceeded 7.62 mm (0.3 in.) or 5.08 mm (0.2 in.) for parallel- and perpendicular-to-grain loading, respectively.

The shear block specimens were tested in accordance with ASTM D143 (ASTM 1983). Shear blocks were cut with the same grain orientation as in the corresponding connection tests. The thickness of the specimens was 38 mm (1.5 in.) rather than the 51 mm (2 in.) specified. Moisture content and specific gravity were determined from the shear blocks after testing and removal of the fiberglass.

The tension perpendicular-to-grain specimens were tested in accordance with ASTM D143 (ASTM 1983), except the thickness was again less than that specified.

Both shear block and tension specimens were conditioned to approximately 12-percent moisture content before testing. The load was continuously applied at a rate of 0.76 mm/min (0.03 in/min) for the shear tests and 2.5 mm/min (0.1 in/min) for the tension tests. Specific gravity of the specimens varied from 0.46 to 0.48.

Results and Discussion

Curves comparing load with displacement were generated for each test. We were primarily interested in data on ultimate strength, strength at 5-percent offset, and failure mode. Strength at 5-percent offset is the load before or at the point where the load–displacement curve intersects a line that is parallel to the initial part of the plot. This line is offset from the linear part of the plot by 5 percent of the fastener diameter. The 5-percent offset is the current U.S. method for defining the yield strength of a connection.

Table 1 summarizes average 5-percent offset and ultimate strength from the connection tests; Figure 4 shows data for each of the four types of reinforced connections. Numerical values are given in the Appendix. The average strength increased as the number of fiberglass layers increased. This was significant for those specimens loaded perpendicular to grain. A comparison of ultimate strength using three layers of reinforcement to nonreinforced specimens showed an increase of 33 percent for parallel-to-grain loading and more than 100 percent for perpendicular-to-grain loading.

The increase in ultimate strength as a result of fiberglass reinforcement was more for perpendicular-to-grain loading and less for parallel-to-grain loading than that reported by Poplis and Mitzner (1973). However, a comparison with our study is not justified because they used 2 to 11 times more fiberglass by weight per unit thickness to reinforce plywood that had plies in both grain directions.

Table 1—Average 5-percent offset and ultimate strength from the parallel- and perpendicular-to-grain connection tests

	Strength (kN) (COV[a])			
	Parallel to grain		Perpendicular to grain	
Reinforcement	5-percent offset	Ultimate	5-percent offset	Ultimate
None	31.3 (0.14)	31.7 (0.14)	7.5 (0.18)	10.0 (0.14)
One layer	35.2 (0.14)	36.2 (0.14)	9.6 (0.14)	16.0 (0.10)
Two layers	37.5 (0.15)	39.2 (0.17)	10.6 (0.14)	20.3 (0.10)
Three layers	39.4 (0.14)	42.1 (0.16)	11.6 (0.13)	22.9 (0.16)

[a] COV is coefficient of variation.

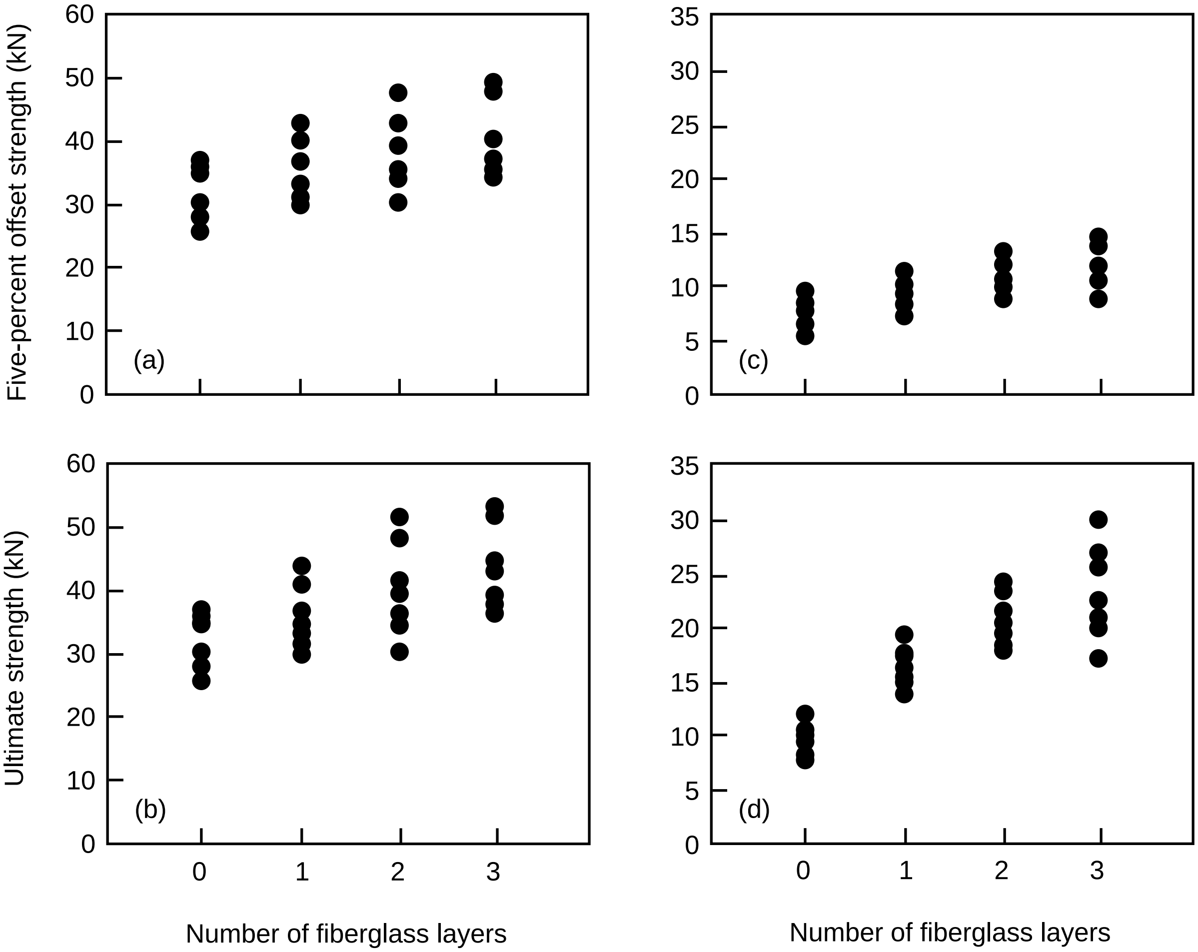

Figure 4—(a) Five-percent offset strength and (b) ultimate strength of 10 replications for each of four types of reinforced connections loaded parallel to grain. (c) Five-percent offset strength and (d) ultimate strength of 10 replications for each of four types of reinforced connections loaded perpendicular to grain.

Table 2—Increase in average strength with each additional layer of reinforcement

Reinforcement comparison	Strength increase (percent)			
	Parallel to grain		Perpendicular to grain	
	5% offset	Ultimate	5% offset	Ultimate
1 layer with none	12.5	14.4	27.5	59.7
2 layers with 1 layer	6.3	8.1	10.4	26.6
3 layers with 2 layer	5.2	7.4	10.2	13.1

Table 2 summarizes the increase in 5-percent offset and ultimate strength values with additional layers of reinforcement. Adding one layer resulted in the largest increase in average strength in both parallel- and perpendicular-to-grain directions. Additional layers resulted in smaller increases in strength. The perpendicular-to-grain ultimate strength showed the largest increase.

The observed failure modes for specimens loaded parallel to grain varied dependent on the number of fiberglass layers. All nonreinforced specimens failed by a split beneath the bolt. Approximately half the specimens reinforced with one layer failed by a combination of splitting of the wood and tearing the fiberglass along the split. The remainder of the specimens reinforced with one layer and all the specimens with two or three layers failed by crushing of the wood beneath the bolt.

The observed failure modes for specimens loaded perpendicular to grain failed by crushing of the wood under the bolt-type for all types of reinforcement.

The fiberglass reinforcement increased the ductility of the connection in both grain directions. This increased ductility is apparent from the load–displacement curves (Fig. 5).

The effect of the amount of epoxy resin was not studied. Datoo (1991) concluded that resins alone contribute little to load-bearing capacity.

Table 3 summarizes average shear block and tension perpendicular-to-grain strength values. The results are the average of 10 replications corresponding to the connection tests. Figures 6 and 7 show data for each of the four types of reinforced connections. Numerical values are given in the Appendix.

The nonreinforced shear block specimens had an average strength greater than the published value for lodgepole pine of 6,067 kPa (880 lb/in^2) (Forest Products Laboratory 1987). The specific gravity of the specimens was also greater than the published value of 0.41. We assumed that the greater strength value was related to the higher specific gravity material that was tested (0.46 to 0.48).

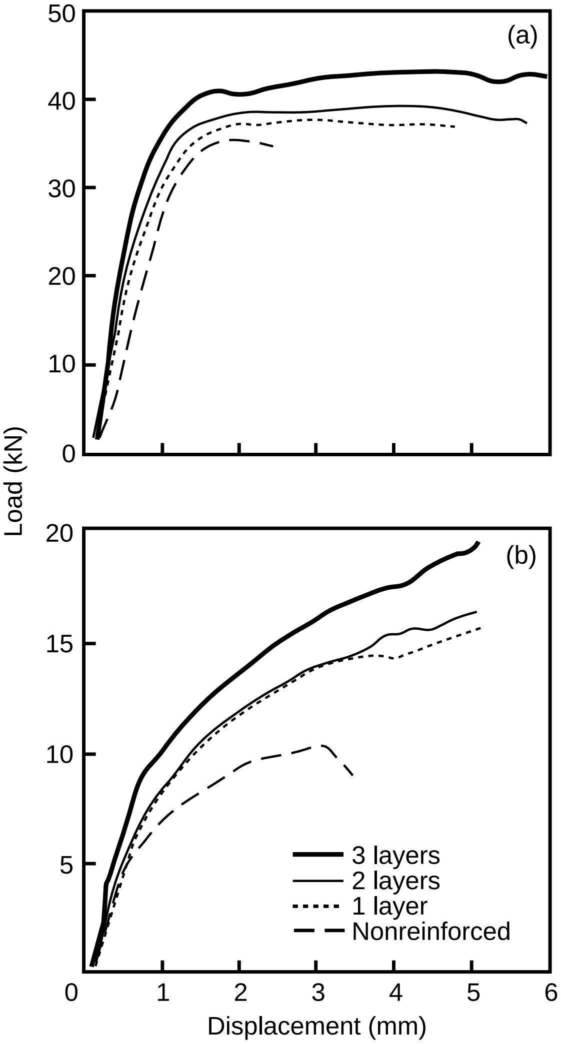

Figure 5—Typical load–displacement curves for (a) parallel- and (b) perpendicular-to-grain loading.

The nonreinforced tension perpendicular-to-grain specimens had an average ultimate strength equal to the published value of 1,999 kPa (290 lb/in^2). Tension perpendicular to grain did not appear to be as sensitive to specific gravity as did the other strength properties. The large coefficients of variation (COVs) that occurred are similar to published values.

Table 3—Average strength from shear block and tension perpendicular-to-grain specimens that were matched from the parallel- and perpendicular-to-grain connection tests.

	Strength (kPa) (COV)			
	Parallel-to-grain connection tests		Perpendicular-to-grain connection tests	
Reinforcement	Shear	Tension	Shear	Tension
None	7739 (0.11)	1997 (0.28)	8221 (0.12)	2061 (0.31)
One layer	8771 (0.10)	2597 (0.27)	8503 (0.17)	3318 (0.12)
Two layers	8594 (0.12)	3191 (0.18)	8381 (0.12)	3391 (0.21)
Three layers	9308 (0.13)	4009 (0.16)	8845 (0.11)	4360 (0.14)

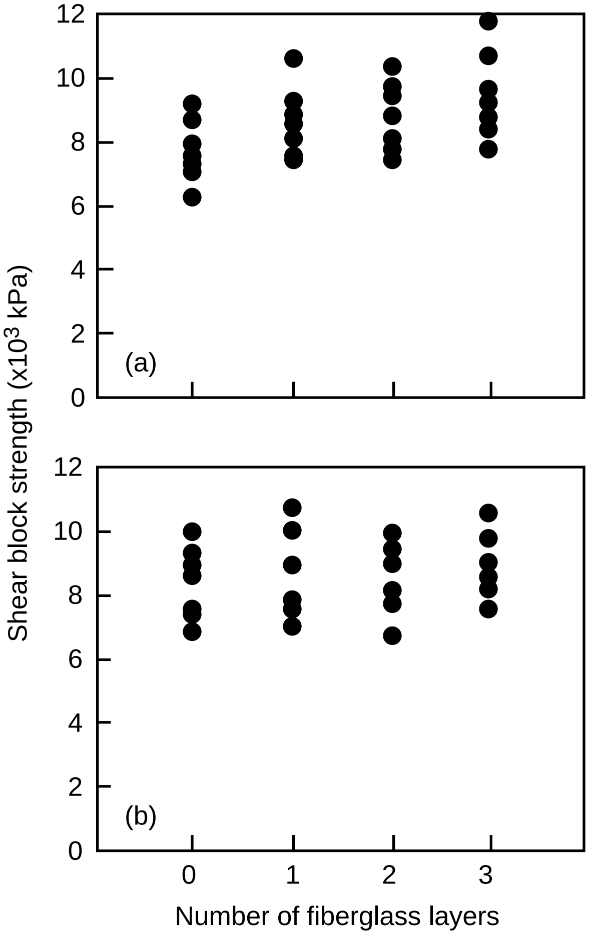

Figure 6—Shear block strength of 10 replications for each of the four types of reinforcements from the (a) parallel- and (b) perpendicular-to-grain connection tests.

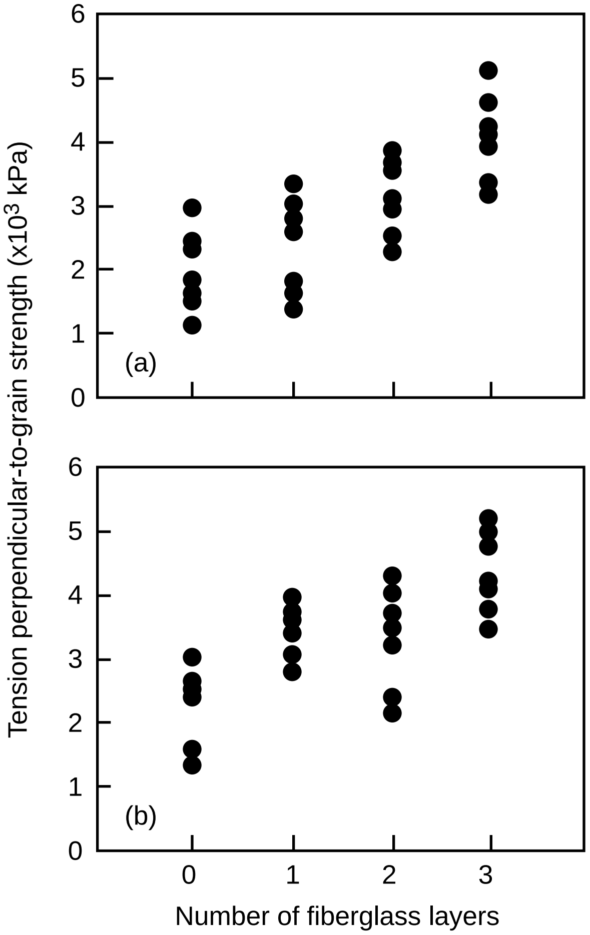

Figure 7—Tension perpendicular-to-grain strength of 10 replications for each of the four types of reinforcements from the (a) parallel- and (b) perpendicular-to-grain connection tests.

Table 4—Increase in average shear block and tension perpendicular-to-grain strength with each additional layer of reinforcement (from matched parallel- and perpendicular-to-grain connection tests)

Reinforcement comparison	Percentage of strength increase (%)			
	Parallel to grain		Perpendicular to grain	
	Shear	Tension	Shear	Tension
1 layer with none	13.3	30.0	3.4	61.0
2 layer with 1 layer	−2.0	22.9	−1.4	2.2
3 layer with 2 layers	8.3	25.6	5.5	28.6

Table 4 summarizes the strength increase for shear block and tension perpendicular-to-grain specimens with additional layers of reinforcement.

Adding one layer of reinforcement resulted in a 3- to 13-percent increase in shear strength. Adding a second layer had no effect; in fact, there was a slight decrease due to variability. Adding a third layer of reinforcement had minimal effect.

Adding one layer of reinforcement resulted in a 30- to 60-percent increase in tension perpendicular-to-grain strength. This large variation is related to the COV. However, even with the large variation, much larger increases in strength were observed in tension perpendicular to grain than in shear strength. Additional layers of reinforcement resulted in additional larger increases than were observed in shear.

Conclusions

Eighty single-bolt connections were tested with parallel- and perpendicular-to-grain loading. Ten replications were tested on specimens with no reinforcement and one, two, and three layers of fiberglass reinforcing. Corresponding shear block and tension perpendicular-to-grain specimens were also tested.

Test results indicate connection strength and ductility increase as the number of layers of reinforcement increase.

The largest increase occurred when adding the initial layer of reinforcement to the nonreinforced connection. Additional layers of reinforcement further increased strength but at a decreasing rate. The ultimate strength of a three-layer reinforced connection was 33 percent greater than the nonreinforced connection for parallel-to-grain loading and more than 100 percent for perpendicular-to-grain loading.

More importantly for parallel-to-grain loading, the fiberglass reinforcement changed the mode of failure from an abrupt, catastrophic type associated with tension perpendicular-to-grain stress to a ductile type associated with bearing stress. Two layers of reinforcement were necessary to achieve this change in failure mode. For perpendicular-to-grain loading, no difference in failure mode was observed, but large increases in strength and ductility did occur.

Test results indicate a small increase in average shear block strength, but a large increase in average tension perpendicular-to-grain strength as the number of layers of reinforcement increase. This large increase in tension strength corresponds to the large increase in the reinforced connection strength when loaded perpendicular to grain.

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Appendix—Additional Data

This Appendix contains the average 5-percent offset and ultimate strength values for each specimen from the parallel- and perpendicular-to-grain connection tests. Also listed are the strength values from each shear block and tension perpendicular-to-grain specimen that was matched from the parallel- and perpendicular-to-grain connection tests.

Average 5-percent offset and ultimate strength values for each specimen from the parallel- and perpendicular-to-grain connection tests.

	Strength (kN)			
	Parallel to grain		Perpendicular to grain	
Number of layers	5% offset	Ultimate	5% offset	Ultimate
0	30	30	8	10
	36	36	7	9
	28	28	8	11
	36	37	9	12
	27	27	5	8
	26	26	6	8
	36	37	8	10
	37	37	6	10
	28	28	10	12
	30	31	9	11
1	33	33	11	17
	41	42	9	16
	30	31	9	15
	43	44	11	17
	31	34	7	14
	30	31	9	14
	37	37	10	17
	40	42	9	16
	33	36	11	19
	33	33	10	16
2	36	36	13	24
	43	48	9	18
	34	37	10	20
	48	52	12	23
	31	32	9	18
	30	31	9	18
	39	40	11	21
	40	42	10	19
	40	41	12	21
	34	35	10	21
3	37	38	12	25
	48	52	11	21
	35	36	11	22
	49	54	15	30
	35	37	9	17
	34	37	11	20
	41	43	11	22
	40	45	12	20
	37	40	14	27
	37	40	12	25

Ultimate strength values from each shear block and tension perpendicular-to-grain specimen that was matched from the parallel- and perpendicular-to-grain connection tests.

	Strength (kPa)			
	Parallel-to-grain connection tests		Perpendicular-to-grain connection tests	
Number of Layers	Shear	Tension	Shear	Tension
0	8136	2413	9280	3020
	8674	1606	7564	1544
	7191	2441	8874	2565
	9156	2399	8584	1606
	7791	1848	6922	1331
	7639	1696	8639	2579
	8108	3034	7357	2654
	7184	1220	7419	1544
	6295	1669	10,018	2386
	7212	1641	7557	1379
1	8122	2848	10701	3737
	9329	1717	7667	2827
	7495	2648	8956	3344
	10,597	3082	10,053	3592
	8660	2648	7060	2792
	7715	3006	7550	3937
	8956	3392	7012	3420
	8660	1469	7536	3061
	8901	1827	10,694	3509
	9273	3330	7805	2965
2	8811	3592	9646	4261
	8901	3737	8060	2365
	8225	3833	8846	3420
	10,363	2489	9260	3702
	7515	2979	7715	3958
	7936	2558	6688	3468
	9784	3565	7564	4095
	9425	3116	8081	3192
	7564	2303	9887	3323
	7419	3737	8067	2124
3	8936	4282	10,563	4737
	10,790	3158	8563	3820
	9053	3951	9811	4950
	11,825	3309	9742	5171
	8474	5088	8136	3399
	7839	4151	8074	4213
	9715	4123	7488	4709
	9453	4206	8956	3709
	8481	4606	—	4082
	8515	3227	8274	4813