Effect of Fiberglass Reinforcement on the Behavior of Bolted Wood Connections

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Abstract

Bolted connections often fail by a shear plug or by splitting beneath the bolt caused by tension perpendicular-to-grain stress as the bolt wedges its way through the wood. Preventing this type of failure enhances both the capacity and reliability of bolted connections. This research investigated the use of fiberglass reinforcement to enhance the load-carrying capacity of bolted wood connections. Matched specimens were reinforced with one, two, or three layers of bidirectional fiberglass cloth and configured to ensure a Mode I failure as defined by the yield theory in the National *Design Specification.* A total of 80 single-bolt, double-shear connections were tested, with 40 loaded parallel-to-grain and 40 perpendicular-to-grain. For parallel-to-grain loading, the 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. These results are applicable to Mode I failures where surface reinforcement is most effective; smaller increases in strength are expected for thicker main members that experience Modes III and IV failures.

Introduction

Failures in wood structures often occur at the connections. Bolted connections with relatively small length-to-diameter bolt ratios often fail by a shear plug or by splitting beneath the bolt caused by tension perpendicular-to-grain stress as the bolt wedges its way through the wood. Preventing this type of failure enhances both the capacity and reliability of bolted connections. Improving a connection's capacity increases the overall integrity of a timber structure and enables wood to compete favorably with other engineering materials.

This study examined the technical feasibility of reinforcing the wood at bolted connections with fiberglass and epoxy resin. Test results are given for connections loaded both parallel- and perpendicular-to-grain. Additional shear parallel-to-grain and tension perpendicular-to-grain strength test results are given to gain insight into how material properties correlate with connection behavior.

Background

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

Bulleit (1984) reviewed past studies and concluded that reinforcing wood was technically feasible for improving strength and stiffness properties, but typically uneconomical. Unidirectional fiberglass was the preferred reinforcing material of the studies reviewed. There was no consensus on the use of woven or nonwoven strands or mat reinforcing systems, nor was there a preferred resin. Most investigators used epoxy, but acceptable results were also obtained with phenolic, polyester, and phenol-resorcinol formaldehyde resins.

Only two of the studies summarized by Bulleit related to reinforcement of connections. Spaun (1981) tested composite members made with a western hemlock lumber core overlaid with Douglas-fir veneer. The core was fingerjointed at midlength; FRP layers were placed between the core and veneer. The FRP reinforcement significantly increased both the stiffness and tension strength of the fingerjointed composite. Poplis and Mitzner (1973) tested the strength of bolted connections in plywood overlaid with FRP. They conducted bolt bearing tests that included varying plywood thickness, bolt diameter, double- versus single-shear connections, FRP overlay type and glass content, edge distance, torque on fasteners, wet versus dry panel, clean joint versus joint with mastic, and face grain direction of the plywood. 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 by 54 to 117 percent.

Recently, Meierhofer (1995) tested the tension and bending strength of small specimens spliced with three different lengths of carbon fibers. Unfortunately, no information regarding strength is given. Miyatake and Fujii (1995) studied the use of FRP reinforced internal gusset plates for timber structures. Test results indicate that strength increased as the length of the gusset plate increased.

Haller et al. (1996) examined reinforced bolted connections of densified wood (wood that is thermomechanically treated to increase its density). The glass fiber fabric reinforcement was placed at 45° and 90° to the direction of loading. Ultimate strength and ductility of the connections increased about two times.

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

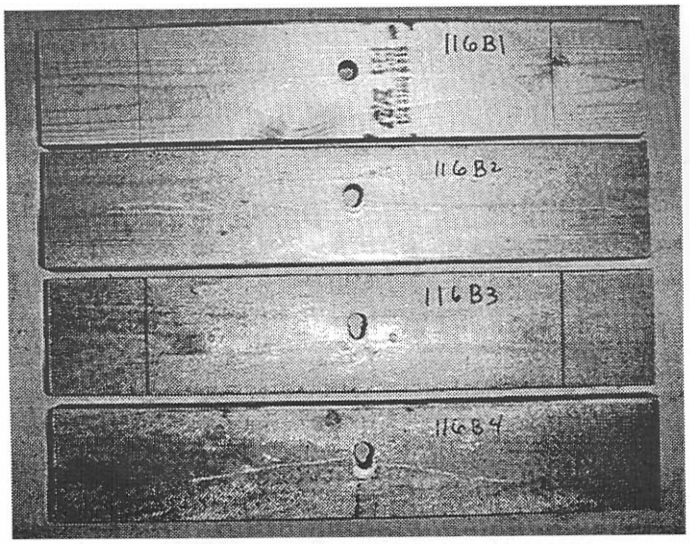

Figure 1.–Specimens (from top to bottom) with no reinforcement, and one, two, and three layers of fiberglass reinforcement.

Experimental Procedure

A total of 80 single-bolt, double-shear connections with a wood main member and steel side members were tested. Forty connections were loaded parallel-to-grain and 40 perpendicular-to-grain in accordance with *ASTM D 5652 Standard Test Methods for Bolted Connections in Wood and Wood Based Products* (ASTM 1995). Each set of 40 tests consisted of 10 replications of four types of connections: a control having no reinforcement; and one, two, and three layers of fiberglass cloth reinforcement bonded to both wide faces of the specimen (Fig. 1).

In addition, 80 shear parallel-to-grain and 80 tension perpendicular-to-grain specimens both with and without reinforcement were tested in accordance with *ASTM D 143 Standard Methods of Testing Small Clear Specimens of Timber* (ASTM 1995). These specimens were cut from, and thus matched to, those used for the connection tests.

Wood specimens were Cut from 20 2-by-4-inch by 16-foot Spruce-Pine-Fir No. 2 & Better boards. All boards were lodgepole pine (*Pinus contorta*). The specific gravity of the specimens varied from 0.46 to 0.48. The moisture content at time of test was approximately 12 percent. A detailed description of specimen matching and testing is given in Windorski et al. (1997).

Both the fiberglass cloth and epoxy adhesive were commercial products. As per the manufacturer's technical data, the bidirectional woven fiberglass cloth had a unit weight of 6 oz./yd.^{2}, a modulus of elasticity of 6.7 × 10^3 ksi (46.19 × 10^3 MPa), and a tensile strength of 200 lb./in. of width. The reinforcing system (adhesive and cloth) was applied in accordance with the manufacturer's recommendations. One, two, and three layers of fiberglass increased the specimen's volume by 2.2, 3.3, and 4.6 percent, respectively. The cloth was oriented perpendicular to the load direction for all tests.

The bolts were 1 inch in diameter for the parallel-to-grain tests and 0.5 inch in diameter for the perpendicular-to-grain tests. The smaller 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 45 ksi (310.3 MPa). Bolt lengths were selected to ensure 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. This corresponds to a Mode I failure as defined by the yield theory in the *National Design Specification* (AF&PA 1991).

Results and Discussion

Load versus displacement curves were generated for each connection test. Ultimate strength, strength at 5 percent offset, and failure mode were recorded. Strength at 5 percent offset is the load before or at the point where the load/displacement curve intersects a he drawn parallel to the initial linear part of the plot, but offset from it by 5 percent of the fastener diameter. The 5 percent offset is the method currently used in the United States for defining the yield strength of a connection.

The average 5 percent offset and ultimate strength for each of the four types of connections are summarized in Table 1. The average ultimate strength of the Connection increases as the number of layers of fiberglass increases, regardless of whether it is loaded parallel- or perpendicular-to-grain. The improvement is particularly significant for specimens loaded perpendicular-to-grain. A comparison of the ultimate strength of specimens with three layers of reinforcement with nonreinforced specimens shows an increase of 33 percent for parallel-to-grain loading and more than a doubling for perpendicular-to-grain loading.

While the increase in ultimate strength due to fiberglass reinforcement in this study is more for perpendicular-to-grain loading and less for parallel-to-grain loading than that reported by Poplis and Mitzner, a direct comparison of results is not justified. Poplis and Mitzner used from 2 to 11 times more fiberglass by weight per unit thickness, and the grain of plywood's veneer's runs in both directions.

The average percent increase in 5 percent offset and ultimate strength of the connections gained with each additional layer of reinforcement is presented in Table 2. Adding one layer produced the largest increase in average strength in specimens loaded in both the parallel- and perpendicular-to-grain directions. Addition of succeeding layers resulted in much smaller increases in strength. The perpendicular-to-grain ultimate strength showed the largest increase.

The failure mode for specimens loaded parallel-to-grain depended on the number of layers of fiberglass. All nonreinforced specimens failed by splitting beneath the bolt. Approximately half of the specimens reinforced with one layer failed by a combination of splitting of the wood and tearing of the fiberglass along the split. The remainder of the specimens reinforced with one layer, and all specimens with two or three layers, failed by crushing of the wood beneath the bolt. The failure mode for both nonreinforced and reinforced specimens loaded perpendicular-to-grain was crushing of the wood under the bolt.

The fiberglass reinforcement increased the ductility of the connection in both grain directions. This increased ductility is apparent from load versus deformation curves (Figs. 2 and 3). Though the effect of the amount of epoxy resin on 5 percent offset and ultimate strength was not studied here, Datoo (1991) concluded that the resin alone contributes little to load capacity

The average ultimate shear parallel-to-grain and tension perpendicular-to-grain strength of the matched specimens cut from the same boards as the connection specimens are summarized in Table 3. The nomeinforced shear parallel-to-grain specimens had an average ultimate strength greater than the published value of 6,067 kPa (880 psi) for lodgepole pine (FPL 1987). At 0.46 to 0.48, the specimens' average specific gravity was about 17 percent greater than the published value of 0.41. It is assumed that the higher shear strength is related to the higher specific gravity of the material tested.

The nonreinforced tension perpendicular-to-grain specimens had an average ultimate strength equal to the published value of 1,999 kPa (290 psi). Tension perpendicular-to-grain does not appear to be as sensitive to specific gravity as are wood's other strength properties. Values for coefficient of variation are similar to published values.

Table 1.–Average 5 percent offset and ultimate strength of single-bolt connection specimens.[a]

	Parallel-to-grain loading		Perpendicular-to-grain loading	
Layers of reinforcement	5 percent offset	Ultimate	5 percent offset	Ultimate
	(kN)			
None	31.3 (0.14)	31.7 (0.14)	7.5 (0.18)	10.0 (0.14)
1	35.2 (0.14)	36.2 (0.14)	9.6 (0.14)	16.0 (0.10)
2	37.5 (0.15)	39.2 (0.17)	10.6 (0.14)	20.3 (0.10)
3	39.4 (0.14)	42.1 (0.16)	11.6 (0.13)	22.9 (0.16)

[a] Coefficient of variation in parentheses.

Table 2.–Average increase in average 5 percent offset and ultimate strength of single-bolt connection specimens with each additional layer of reinforcement.

	Parallel-to-grain loading		Perpendicular-to-pin loading	
Layers of reinforcement	5 percent offset	Ultimate	5 percent offset	Ultimate
	(%)			
1 vs. none	12.5	14.4	27.5	59.7
2 vs. 1	6.3	8.1	10.4	26.6
3 vs. 2	5.2	7.4	10.2	13.1

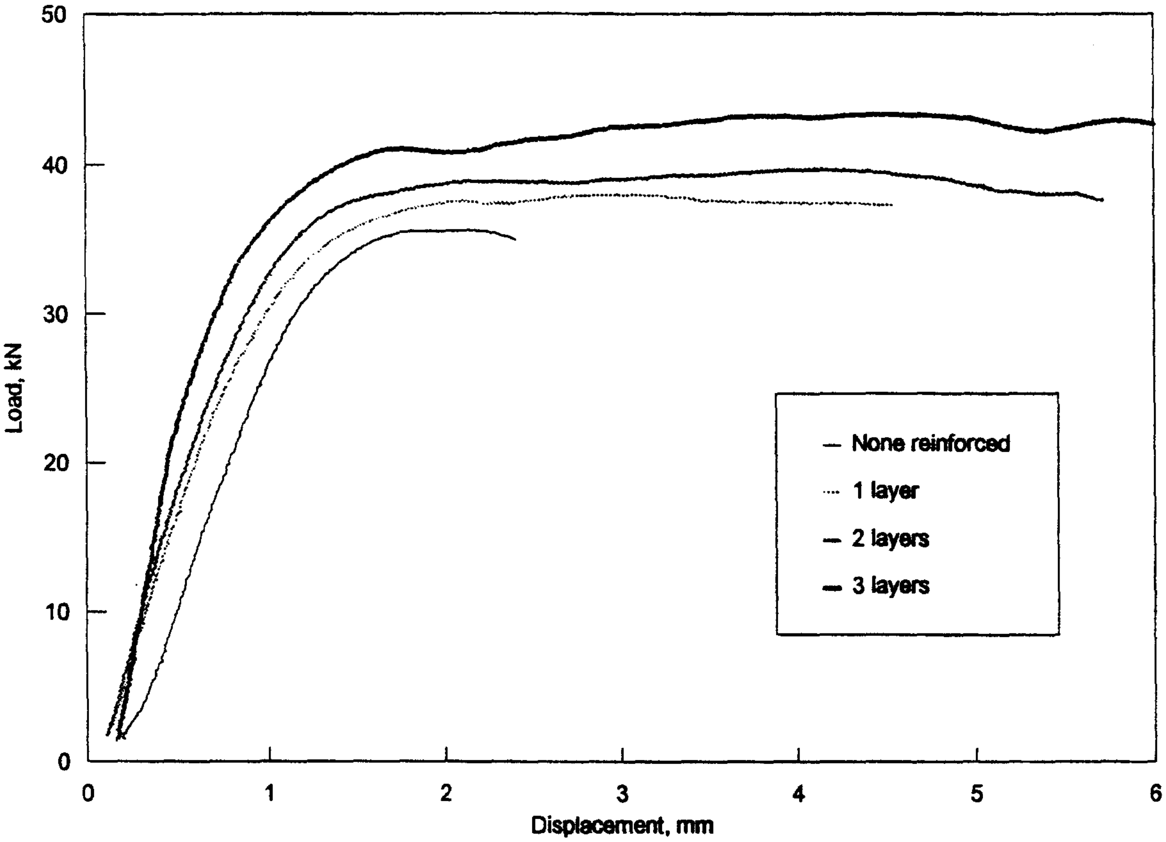

Figure 2.–Typical load versus displacement curve for fiberglass reinforced bolted connection loaded parallel-to-grain.

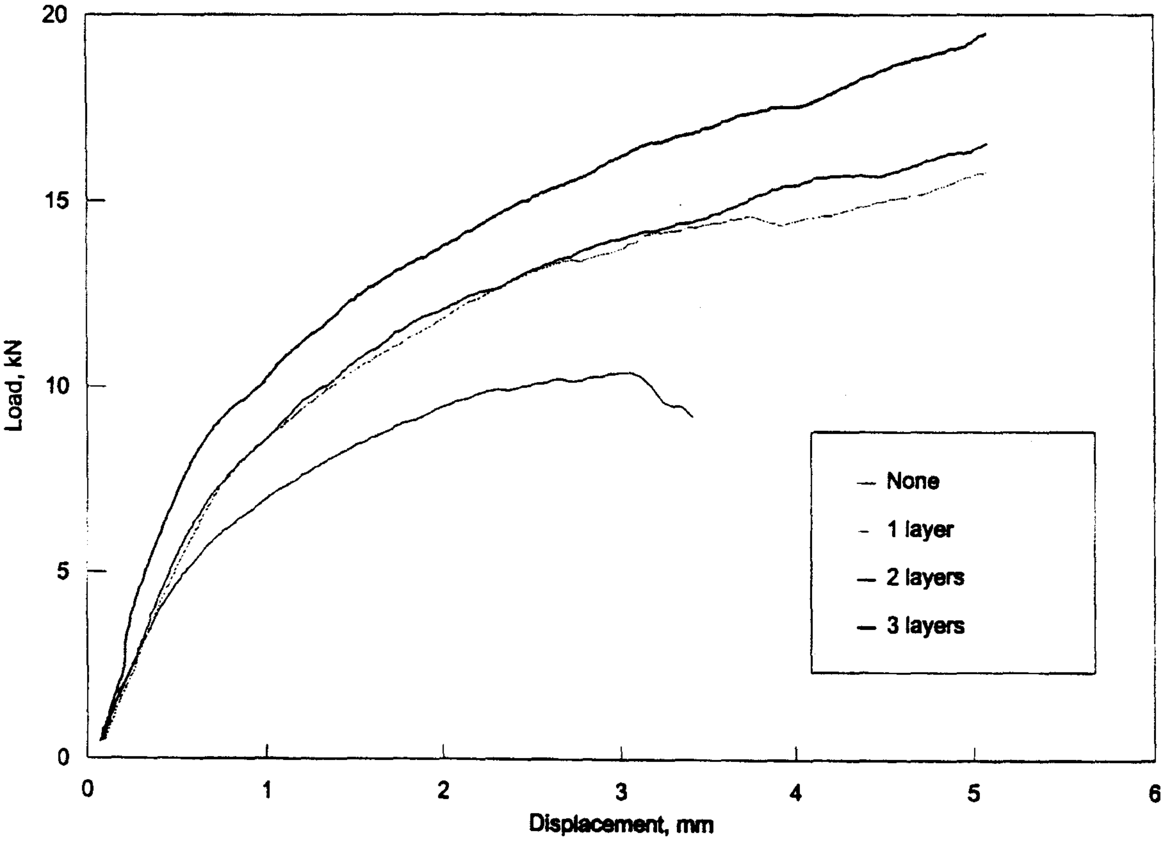

Figure 3.–Typical load versus displacement curve for fiberglass reinforced bolted connection loaded perpendicular-to-grain.

The average percent increase in ultimate strength for shear parallel-to-grain and tension perpendicular-to-grain specimens gained with each additional layer of reinforcement is presented in Table 4. Adding one layer of reinforcement resulted in a 3 to 13 percent increase in shear strength. The addition of a second layer actually produced a slight decrease in strength due to the wide variability in the measured strength. Addition of the third layer had a minimal effect.

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

Summary

Eighty single-bolt connections were tested with the load applied either parallel- or perpendicular-to-grain. Ten replications were tested of specimens with no reinforcement, and one, two, and three layers of fiberglass reinforcement. Matched shear parallel-to-grain and tension perpendicular-to-grain specimens were also tested.

Test results indicate that connection strength and ductility increase as the number of layers of reinforcement increases. The largest increase occurred with the addition of the first layer of reinforcement. Additional layers of reinforcement further increased strength, but at a decreasing rate. The ultimate strength of a connection reinforced with three layers of fiberglass was 33 percent greater than the nonreinforced connection for parallel-to-grain loading, and more than double that 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 occurred.

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

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Table 3.–Average shear parallel-to-grain and tension perpendicular-to-grain strength of nonreinforced specimens matched with single-bolt connection specimens.[a]

	Parallel-to-grain loading connection tests		Perpendicular-to-grain loading connection tests	
Layers of reinforcement	Shear	Tension	Shear	Tension
	(kPa)			
None	7,739 (0.11)	1,997 (0.28)	8,221 (0.12)	2,061 (0.31)
1	8,771 (0.10)	2,597 (0.27)	8,503 (0.17)	3,318 (0.12)
2	8,594 (0.12)	3,191 (0.18)	8,381 (0.12)	3,391 (0.21)
3	9,308 (0.13)	4,009 (0.16)	8,845 (0.11)	4.360 (0.14)

[a] Coefficient of variation in parentheses.

Table 4.–Average percent increase in average shear parallel-to-grain and tension perpendicular-to-grain strength of nonreinforced specimens matched with single-bolt connection specimens with each additional layer of reinforcement.

	Parallel-to-grain loading connection tests		Perpendicular-to-grain loading connection tests	
Layers of reinforcement	Shear	Tension	Shear	Tension
	(%)			
1 vs. none	13.3	30.0	3.4	61.0
2 vs. 1	–2.0	22.9	–1.4	2.2
3 vs. 2	8.3	25.6	5.5	28.6

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