Effect of FRP Reinforcement on Low Grade Eastern Hemlock Glulams

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Abstract

The benefits of reinforcing glulam beams made with eastern hemlock, an under-utilized wood species in the state of Maine, are discussed. Nine beams reinforced with fiber-reinforced plastics (FRP) on the tension side and three unreinforced controls were instrumented and tested to failure in four-point bending. Low, medium, and high quality wood were used in the experimental study. FRP reinforcement ratios ranged from 0.3% to 3.1%. A nonlinear numerical model that predicts the performance of the FRP-glulam beams through the entire load range was developed and its predictions are compared with the test results.

Keywords: glulam, FRP, reinforcement, nonlinear model, strength, stiffness, ductility.

Introduction

Glued laminated wood (glulam) has been in use since the late 1800's. Research on glulam at the USDA Forest Products Laboratory in Madison, Wisconsin began in the 1930's. Development of glulam in following years in the United States was encouraged by the lack of adequate solid timbers and the high demand for large timbers created by the World War II effort (Freas and Selbo, 1954).

Glulam can be fabricated in many shapes and sizes, and has been used in numerous applications including keels for boats, arches for airplane hangers, churches, timbers for floor and roof systems, dome structures, transmission poles, along with girders and decks for timber bridges.

With recent changes in availability of forest resources, high quality laminations necessary for glulam design "have become increasingly difficult to procure, and more expensive as well." (Leichti, 1993, p. 3) Moreover, glulam, like reinforced concrete, can be reinforced in tension to more efficiently utilize the wood's compressive strength. Fiber reinforced plastics (FRP) offer good promise to serve both as a substitute for the high quality wood laminations and as reinforcement for glulam beams.

Over the past decades both FRP and non-FRP materials have been used to reinforce or prestress wood beams. With regard to non-FRP materials, Mark (1961) studied the effects of bonding aluminum to the compression and tension faces of wood core sections of eight different wood species. Sliker (1962) bonded aluminum sheets between various layers of laminated wood beams. Bohannan (1962) reinforced glulam beams of low-grade Douglas-fir using pretensioned steel wire strands in the tension zone.

Peterson (1965), in a study similar to Bohannan (1962), reinforced low-grade Douglas-fir glulam beams with a prestressed flat steel strip bonded in the tension zone. Lantos (1970) reinforced rectangular laminated wood beams with steel rods. Stem and Kumar (1973) studied the effect of steel plate reinforcement for vertically laminated timber beams. Coleman and Hurst (1974) reinforced No.2 southern pine beams with light gage steel reinforcement. Hoyle (1975) tested members composed of nominal dimension lumber with toothed steel plates between lumber pieces. Bulleit, Sandberg, Woods (1989) reported on Spruce-Pine-Fir glulam beams reinforced in the tension zone with special steel-reinforced tension laminations.

Prior to 1990, a number of studies on wood beams reinforced with fiber and FRP materials were also conducted. Wangaard and Biblis (Wangaard, 1964; Biblis, 1965) studied the effect of bonding unidirectional fiberglass/epoxy reinforced plastic to the compression and tension faces of wood cores of various species. Theakson (1965) studied the feasibility of strengthening both laminated and solid wood beams with fiberglass. Krueger and Sandberg (1974 b) studied laminated timber reinforced in the tension zone with a composite of high-strength bronze coated woven steel wire and epoxy. Krueger and Eddy (1974 a) carried out research similar to that of Kruegar and Sandberg (1974 b). Spaun (1981) studied finger-jointed western hemlock cores reinforced with wood veneers and fiberglass rovings.

In the nineties, research on wood beams reinforced with fiber and FRP materials has increased. Plevris and Triantafillou (1992) studied the effect of reinforcing fir wood with carbon/epoxy fiber-reinforced plastics. Plevris and Triantafillou (1995) also discussed the creep behavior of FRP-reinforced wood. Triantafillou and Deskovic (1992) studied the effect of prestressed carbon/epoxy FRP (CFRP) reinforcement bonded to European beech lumber. Davalos, Salim, Munipalle (1992) discussed the response of small yellow-poplar glulam beams reinforced on the tension side with glass/vinylester FRP. Tingley and Leichti (1993) discussed glulam made from lower grade ponderosa pine reinforced in the tension zone with pultruded kevlar and carbon FRP. Abdel-Magid, Dagher, and Kimball (1994) studied nominal 2x4 hemlock beams reinforced tension with carbon/epoxy and kevlar/epoxy FRP. Sonti, Davalos, Hernandez, Moody, and Kim (1995) discussed yellow-poplar glulam reinforced with pultruded glass/vinylester FRP in tension or both in tension and compression. Dailey, Allison, Minneci, and Bender (1995) studied glulam reinforced in the tension zone with pultruded glass/resorcinol-modified phenolic FRP sheets.

While timber has been successfully reinforced over the past few decades using various materials and reinforcing techniques, very few of these methods of reinforcing timber have reached the commercial market (Bulleit, 1984). As argued by Bulleit et. al. (1989, p. 433), there are several possible reasons for this lack of commercialization of reinforced timber: “(l) The material used to reinforce the wood was not commonly used in building applications; (2) the reinforcing material was too expensive; and (3) the fabrication required an additional and, thus, cost-increasing step in the laminating process. ” Another reason may be the incompatibility between the reinforcing material and the wood.

FRPs are a versatile class of materials that can be engineered to overcome the incompatibility problems with the wood. Because of FRPs falling cost and potentially simple incorporation into existing glulam manufacturing processes, this class of materials offers a good potential as a reinforcement for wood (Kimball, 1995). This paper describes an experimental and numerical study on reinforcing eastern hemlock glulams with FRP. Eastern hemlock is a relatively inexpensive, abundant and under-utilized Maine wood species with relatively low mechanical properties.

Experimental Work

A total of twelve glulam beams were fabricated and tested statically to failure (See Table 1). The beams had a clear span of 16 feet and a cross-section of 3 3/16 inches by 12 inches. The twelve beams consisted of three control (unreinforced) beams and nine beams reinforced with varying amounts and types of FRP in the tensile zone. Because of variations in lay up, three of the reinforced beams cannot be directly compared with the controls. These are described as Non-Comparison beams in Table 1.

All beams used No.2 and better 2x4 eastern hemlock. The No.2 visual grade material occupied over 75% of the sample. The lumber was condition to a 12 percent moisture content prior to laminating. Using MOE data, the wood was divided into three quality categories: Low, Medium and High. Both unreinforced controls and reinforced beams were constructed of each of the three wood categories.

Control Beams

Unreinforced control beams consisted of eight 1 3/8 inch laminations, with a 3/4 inch ‘bumper-strip’ lamination added to the outer wood tensile lamination.

FRP-Reinforced Glulam Beams

The reinforced beams were designed in the same way as the control beams with the exception of FRP placed between the ‘bumper strip’ and the outer tensile wood lamination. A transformed section of a typical reinforced beam is shown in Figure 1. Table 2 summarizes the properties of the two FRP types used in the beams.

Testing

The glulam beams were tested in four-point bending over a simple span as shown in Figure 2. The beams were braced to prevent lateral-torsional buckling and were tested according to the procedures outlined in ASTM D198-84.

Strain gages were applied throughout the depth of the beams within the constant moment region. A dial gage and LVDT were used to measure deflections. The beams were loaded at a rate of approximately 1000 pounds per minute. Readings included beam load, load head displacement, strain gage, LVDT and dial gage over the duration of the test.

Table 1 - Beam Characteristics

Beam No.	FRP Type	Beam Depth (in)	Reinforcement Ratio (%)	Wood Quality
Comparison Beams				
10	-	11.75	0	L
9	-	11.75	0	M
11	-	11.75	0	H
2	1	12.12	3.1	L
1	1	12.12	3.1	M
3	1	12.12	3.1	H
6	2	11.88	1.1	H,M
5	2	11.88	1.1	M
7	2	11.88	1.1	H
Non-Comparison Beams				
4	1	12.12	3.1	N/A
8	2	12.00	2.1	L
12	2	11.79	0.3	L

L=Low, M=Medium, H=High, N/A=Not Applicable

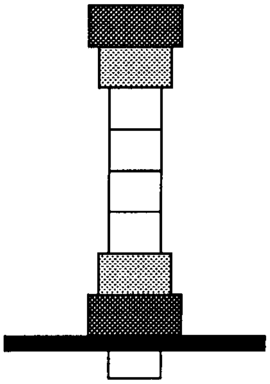

Figure 1 - Transformed Section

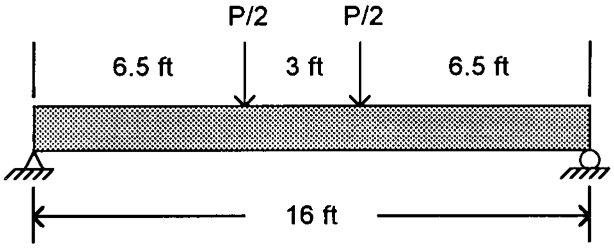

Figure 2 - Test Setup

Table 2 - FRP Properties

Property	FRP1	FRP2
Ultimate Tensile Strength (ksi)	114	137
Longitudinal Tensile MOE (Msi)	6.7	19.1

Load Deflection Data

For the low (L) quality comparison beams, the reinforced beam was 43% stronger and 31% stiffer than the control. In addition, the reinforced beam was more ductile than the control beam, deflecting 42% more at failure.

Figure 3 shows the experimental load-deflection curves for the medium (M) quality comparison beams including the control, FRPl and FRP2 reinforced beams. The FRPl reinforced beam was 51% stronger and 32% stiffer, while the FRP2 reinforced beam was **33%** stronger and 37% stiffer than the control. The FRPl reinforced beam showed improved ductility over the control beam.

Table 3 - Bending Test Data

Beam No.	FRP Type	Reinforcement Ratio (%)	Wood Quality	Max. Load (lb)	Max. Deflection (in)	Beam MOE (Msi)	Str. Increase (%)	MOE Increase (%)
Comparison Beams								
10	-	-	L	8200	2.12	1.28	-	-
9	-	-	M	10780	3.08	1.26	-	-
11	-	-	H	12040	3.25	1.38	-	-
2	1	3.1	L	11750	3.02	1.68	43	31
1	1	3.1	M	16250	4.48	1.66	51	32
3	1	3.1	H	14900	3.57	1.78	24	29
6	2	1.1	H,M	15070	3.82	1.61	25	28
5	2	1.1	M	14310	3.05	1.72	33	37
7	2	1.1	H	15270	3.76	1.72	27	25
Non-Comparison Beams								
4	1	3.1	N/A	9040	1.94	1.74	-	-
8	1	2.1	L	12800	3.29	1.58	56	23
12	2	0.3	L	10930	3.54	1.26	33	-2

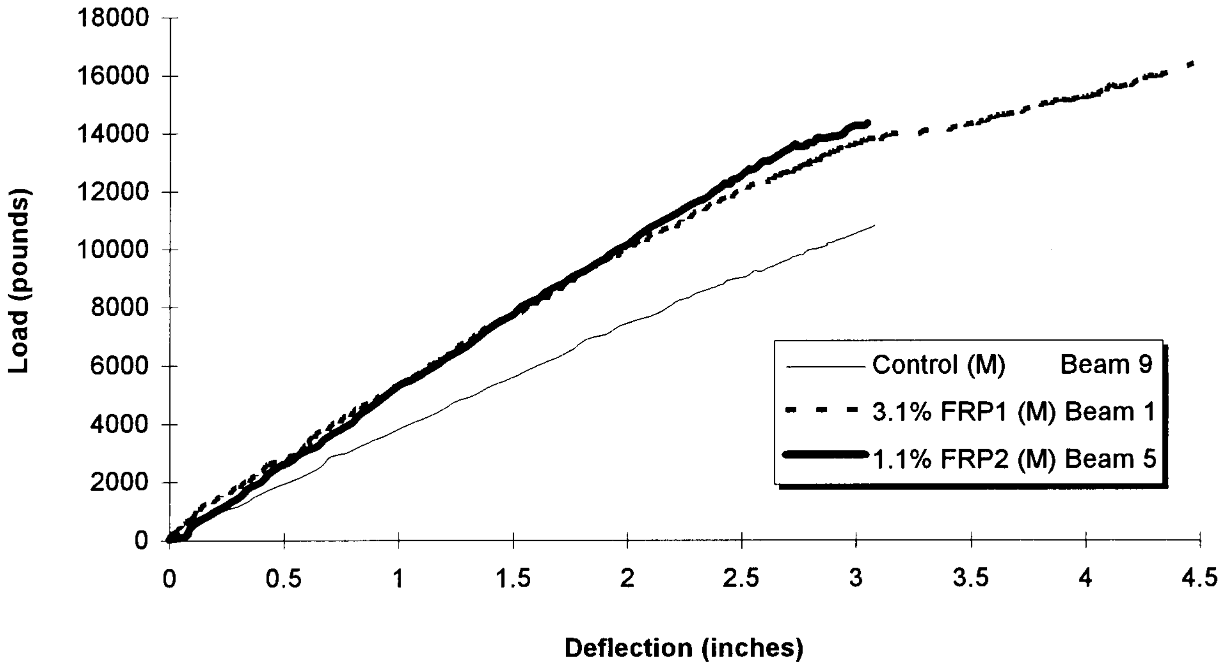

Figure 3 - Load-Deflection Curves for the Medium Quality Beams

The high (H) quality comparison beams include the control, FRP1 and FRP2 reinforced beams. The reinforced beams showed increases in strength of approximately 24 to 27% over the control. The reinforced beams showed increases in stiffness of 25 to 29% over the control.

With regard to the three non-comparison beams, the FRP1 reinforced beam with 3.1% reinforcement ratio failed prematurely in a wood tension lamination due to wood shake. Therefore, it is not compared to a control beam. The FRP1 reinforced beam with 2.1% reinforcement ratio showed an increase in strength and stiffness of 56% and 23%, respectively, over the low (L) quality control. Beam 12, which had only 0.3% FRP reinforcement, showed 33% gain in strength over the low (L) quality control beam but practically no change in stiffness.

Strain Gage Data

Stresses in the FRP at failure were calculated using strain data and beam MOE values. The tensile stresses in the FRP at onset of beam failure remained well below ultimate strengths in all cases. The stress in the FRP1 at beam failure was about 25% of its ultimate strength. The stress in the FRP2 at beam failure was less than 50% of its ultimate strength. However, the FRP2 reinforcement failed in interlaminar shear, thereby initiating overall beam failure.

Nonlinear FRP-Glulam Model

A nonlinear numerical model was developed to study the behavior of FRP-glulam beams for all stages of loading through failure. One objective of the model was to predict the full load-deflection curve of the laboratory beams. Using the nonlinear properties of the constituent materials, the moment-curvature relationship of a section is first determined. The moment-curvature relationship, together with the beam geometry and loading configuration, is then used to determine the load-deflection curve of the beam.

The model follows in some respects work by Plevris and Triantafillou (1992), Bazan (1980), and Buchanan (1990). The numerical model was implemented using two computer programs. The first computer program determines the moment-curvature relationship of a FRP-glulam section. The second computer program uses this moment-curvature relationship to determine the load-deflection curve for a beam loaded in four-point bending.

Comparison of Numerical and Experimental Results

To illustrate the application of the numerical model, the numerical and experimental load-deflection curves for reinforced beam 1 are compared in Figure 4. Also, the actual and predicted ultimate loads and deflections for the three medium (M) quality beams (beams 1, 5 and 9) are compared in Table 4.

Figure 4 - Comparison of Experimental and Numerical Load-Deflection Curves for Beam 1

Table 4 - Comparison of Experimental and Numerical Results for Beams 1, 5 and 9

Beam Type	Analytical Load (lb)	Experimental Load (lb)	Error (%)	Analytical Deflection (in)	Experimental Deflection (in)	Error (%)
Beam 1	17,430	16,250	7.3	4.43	4.48	-1.1
Beam 5	15,990	14,310	11.7	2.96	3.05	-3.0
Beam 9	10,240	10,780	-5.0	2.52	3.08	-18.2

Discussion

Glulam made from one of Maine's relatively weak and under-utilized wood species, eastern hemlock, was reinforced with FRP in the tension zone. The reinforced beams performed very well and showed substantial gains in strength (up to 56%) and stiffness (up to 37%) by the addition of 1-3% FRP reinforcement.

The increased beam strength was due in part to the more efficient utilization of the compressive strength of the wood. Using familiar reinforced concrete terminology, the beams tested performed as over-reinforced beams. In an over-reinforced beam, failure occurs by compression of wood fibers near the top of the beam. The region of failed wood in compression propagates from the top of the beam down until the beam ultimately fails. The ductile failure of wood in the compression zone leads not only to increased strength but also to increased ductility of the reinforced beam. It should be noted that in contrast with reinforced concrete, an over-reinforced wood beam is ductile whereas an under-reinforced concrete beam is ductile.

In general, the largest increases in strength were obtained with the lower grades of wood. It appears therefore that the highest value-added benefits resulting from this technology may occur with the lower grades of wood. This is due to the lower grades of wood having a larger difference in relative tension/compression strength values, which can be remedied by adding FRP tension reinforcement.

A nonlinear numerical model was developed to study the ultimate strength behavior of FRP-glulam beams. The model was relatively successful in predicting the performance of the beams. It will be a useful tool in optimizing the lay-up of glulam beams.

Concluding Remarks

Fiber reinforced plastics appear to have good potential to serve as a substitute for the high quality wood laminations necessary in glulam. Placing the FRP in the beam tension zone uses the FRP's high tensile strength and stiffness to boost the strength and stiffness and ductility of the hybrid beam. Commercial success will ultimately depend upon the future savings of removing wood laminations being greater than the future expense of adding FRP reinforcement.

In addition to the cost/benefit issue, further research is necessary before FRP-reinforced wood beams are widely used in bridge applications. One major concern is the long-term durability of the FRP-wood interface in a bridge environment. The in-service hygro-thermal mechanical stresses that will develop at the wood-FRP interface need to be evaluated carefully. In addition, the interaction between moisture, temperature, fatigue, and their effect on bond strength and creep behavior of the system are not entirely understood. Fundamental research at the University of Maine is on-going to address these and other related issues.

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