Strength Performance of Prestressed Glass Fiber–Reinforced Polymer, Glued-Laminated Beams

Rodrigo Silva-Henriquez Howard Gray Habib J. Dagher
William G. Davids Jacques Nader

Abstract

This article focuses on assessing the strength performance of glued-laminated (glulam) beams with E-glass fiber–reinforced polymer (GFRP) prestressing (prestressed GFRP-glulam beams) through bending tests and cross-sectional analysis. In addition to fifteen 6.7-m-long prestressed glulam beams, 15 GFRP-reinforced glulam beams and 15 unreinforced glulam control beams with nominally identical layups and 6.7-m lengths were tested to failure in four-point bending to provide direct performance comparisons. Load-displacement data and strains in the prestressed GFRP were monitored. The results of the tests show that the prestressed GFRP-glulam beams exhibited a 38 percent increase in allowable bending stresses compared with reinforced GFRP-glulam beams without prestress and an approximately 95 percent increase compared with unreinforced glulam beams. Both the prestressed and reinforced specimens exhibited an 8 percent increase in stiffness relative to the control specimens. Loss of prestress due to creep was examined for one specimen by monitoring GFRP strains over a 12-day period following fabrication. The total loss of prestress over this 12-day period was less than 2 percent, and the rate of prestress loss decreased during monitoring. The GFRP stresses predicted by a cross-sectional moment-curvature analysis of the prestressed and reinforced beams agree well with stresses inferred from measured strains. The results of this study show that prestressed GFRP reinforcement of glulam beams shows significant promise for practical applications.

Conventional glued-laminated (glulam) beams often fail in bending-induced tension. In an attempt to strengthen glulam beams and delay or prevent this failure mode, researchers have investigated the reinforcing of glulam timbers with different types of fiber-reinforced polymer (FRP) on the tension face (Triantafillou and Deskovic 1991, 1992; Dagher et al. 1996, 1998; Tingley et al. 1996; Tingley and Gai 1998; Gentile et al. 2002; Dagher and Lindyberg 2003; Davids et al. 2005). In contrast with metal reinforcing, FRP reinforcing offers good corrosion resistance and has a high strength to weight ratio. Increases in bending capacity of 50 percent or more when compared with unreinforced glulam have been achieved with FRP tensile reinforcing (Dagher et al. 1996, 1998). Ultimately, the use of FRP reinforcing permits the use of glulam beams made with low-grade laminations and/or a reduction in wood volume.

However, the strength can be further increased if the tensile reinforcing is pretensioned prior to bonding it to the glulam. This prestressing results in significant initial compressive stresses in the bottom of the beam that counteract the tensile bending stresses due to external loads (Bohannan 1962). Triantafillou and Deskovic (1992) tested three small, solid-sawn beech beams in three-point bending, one with 2.5 percent prestressed carbon FRP by volume, one with 2.5 percent carbon FRP reinforcing that was not prestressed, and one unreinforced control section. Their results showed strength gains relative to the unreinforced control of about 16 percent with carbon FRP reinforcing and over 40 percent with prestressed reinforcing. In a pilot study, Galloway et al. (1996) and Dolan et al. (1997) studied the reinforcing of glulam beams with prestressed aramid and E-glass yarns bonded to glulam. Their initial simulations

The authors are, respectively, Graduate Research Assistant, Dept. of Civil and Environmental Engineering and the AEWC Advanced Structures and Composites Center (rodrigo.silvahenriquez@umit.maine.edu), Associate Professor, Construction Management Technology, Dept. of Construction Management Technology (mac.gray@umit.maine.edu), Director, AEWC Advanced Structures and Composites Center and BIW Professor of Civil/Structural Engineering, Dept. of Civil and Environmental Engineering (habib.dagher@umit.maine.edu), John C. Bridge Professor of Civil/Structural Engineering, Dept. of Civil and Environmental Engineering (william.davids@umit.maine.edu), and Research Engineer, AEWC Advanced Structures and Composites Center (jacques.nader@umit.maine.edu), University of Maine, Orono. This paper was received for publication in June 2009. Article no. 10642.

Forest Prod. J. 60(1):33–39.

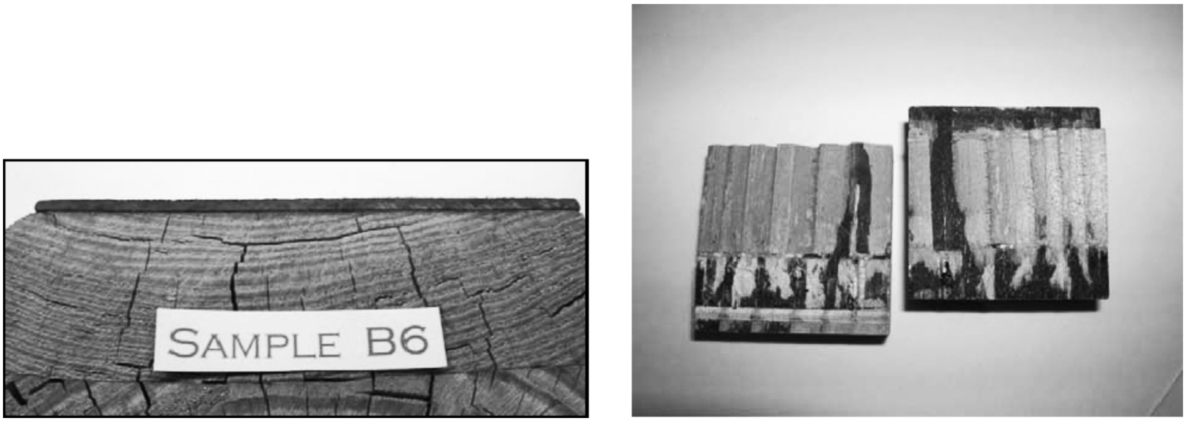

Figure 1.—Cyclic delamination and shear block specimens.

showed a theoretical strength gain of over 100 percent and a stiffness gain of about 25 percent when 3 percent aramid yarn by volume was used for prestressing. Three full-scale prestressed glulam beams were fabricated and tested in three-point bending. The beam with prestressed E-glass reinforcing showed a strength gain of approximately 71 percent relative to the single unreinforced control specimen. Guan et al. (2005) fabricated and tested a single glulam beam with prestressed FRP tensile reinforcing to provide validation for a detailed finite-element model of their beam. A recommendation of their research is that prestressed FRP reinforcing can be used in lieu of higher-grade wood laminations in the tension zone.

The results of previous research on the prestressing of solid-sawn and glulam beams indicate significant promise for this technology. However, these prior studies tested small numbers of specimens, and did not definitively quantify the potential strength gains that may be realized through FRP prestressing. Further, not all studies have considered full-size beams. This study attempts to address these issues through the controlled laboratory testing of fifteen 6.7-m long glulam beams with externally bonded, prestressed E-glass fiber–reinforced polymer (GFRP) laminates, 15 nominally identical glulams with GFRP reinforcing that was not prestressed, and 15 unreinforced control specimens. A cross-sectional moment-curvature analysis of the prestressed and reinforced beams that accounts for compressive yielding of the wood was also performed to examine the effect of the prestressing in more detail.

Materials and Methods

Materials and specimen fabrication

The 45 glulam beams tested in this study were 130 mm wide by 305 mm high by 6.7 m long. This size was chosen to eliminate the need to consider reduction in strength due to volume effects. The beams were fabricated from Douglas fir using an unbalanced layup with two top L1 laminations and six L3 laminations. All lamstock was visually graded, and the beams were manufactured at Cascade Structural Laminators, Chehalis, Washington. This unbalanced layup was chosen for structural efficiency with GFRP reinforcing and has been used recently in another study of GFRP-reinforced glulam (Davids et al. 2005).

A longitudinal pultruded GFRP laminate with a phenolic resin was applied to the tension face of both the prestressed and conventionally reinforced glulams. This combination of GFRP and phenol resorcinol formaldehyde (PRF) adhesive has been used successfully for reinforcing glulam beams in prior studies (Dagher et al. 1998, Davids et al. 2000). The GFRP laminate was 3.3 mm thick and 121 mm wide with a modulus of elasticity of approximately 39.5 GPa and an ultimate tensile strength (UTS) of 828 MPa (Dagher et al. 1998). Strongwell Company of Chatfield, Minnesota, manufactured the GFRP laminates. The reinforcing volume was about 1.0 percent of the wood volume. The adhesive used to bond the GFRP laminate and glulam beams was PRF adhesive. The PRF adhesive was prepared with resin and hardener produced by Hexion Company of Springfield, Oregon. Prior to bonding, the wood surface was sanded and cleaned with acetone to remove dust. The GFRP bonding surface was cleaned with acetone and sealed with the PRF resin prior to being bonded to the wood. A clamping pressure of 1.0 MPa and a 1-day cure were used to bond the GFRP to the glulam.

Assessment of GFRP-wood bond quality

While this combination of GFRP and PRF adhesive has been used successfully in the past (Dagher et al. 1998, Davids et al. 2000), a small number of cyclic delamination and compression shear tests were conducted to assess the performance of the wood-FRP bond. These tests were not intended to be comprehensive but to verify the adequacy of the bonding protocol, assess bond strengths, and ensure that the GFRP-adhesive system would likely provide a reasonable level of durability under exterior exposure conditions.

Cyclic delamination tests were performed per ASTM D2559 (ASTM International 2004) on six 75-mm-long specimens cut from a small beam fabricated with four wood laminations and a single GFRP lamination. Figure 1, left, shows delamination of specimen 6 following completion of the test. Of the six specimens, five yielded reliable data (the results of one specimen were discarded due to the presence of a knot at the bond line which resulted in extensive delamination at the location of the knot). Based on the results from these five specimens, the average amount of delamination at the wood-FRP bond line was 4.7 percent. This exceeds the ASTM D2559 limit of 1 percent delamination for softwood–softwood bonds. However, as noted by Lopez-Anido et al. (2005), this 1 percent delamination limit may not be appropriate for wood-FRP bond lines, and additional long-term studies are needed to

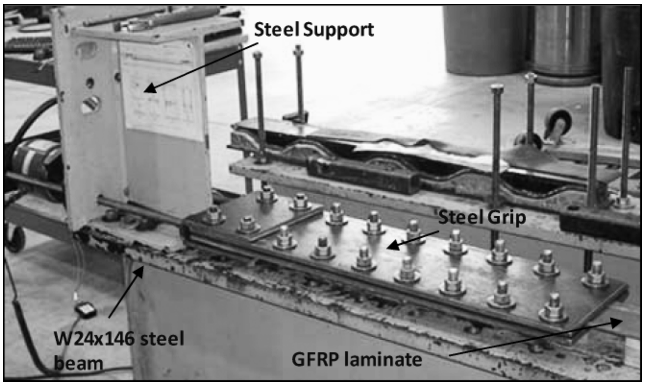

Figure 2.—Prestressing grips and support.

Figure 3.—General view of the four-point bending setup.

develop appropriate delamination limits that take into account actual in-service performance and the dissimilar hygrothermal movements of wood and FRP.

A total of 16 block shear tests were conducted to assess wood-FRP bond strength per ASTM D905 (ASTM International 2003b). Figure 1, right, shows a typical shear block specimen following the test. The shear block tests were performed on specimens conditioned to 12 percent moisture content (MC). The mean shear strength was 9.37 N/mm^2, and the observed coefficient of variation (CV) in shear strength was 15.2 percent. The average material failure was 87.3 percent, indicating that the bond strength generally exceeded the shear strength of the laminations.

Overall, the results of the cyclic delamination and compression shear tests indicate good wood-FRP bond performance. However, the assessment of the wood-FRP bond conducted in this study was not comprehensive. Further assessment and the consideration of different FRP-adhesive systems would be valuable.

Method of prestressing

The prestressed glulam beams were fabricated on a jig consisting of a longitudinal W 24 by 146 steel beam with a 6 by 2 by 3/16 hollow structural steel tube mounted on it (Fig. 2). The GFRP laminate was placed over the steel tube and clamped at its ends between two 12-mm-thick steel plates that were anchored to steel supports attached to the W 24 by 146 (Fig. 2). Clamping was achieved with nine evenly spaced pairs of 19-mm-diameter steel bolts that were torqued to 108 N-m, which was sufficient to prevent slippage of the GFRP. The inner faces of the plates were roughened, and 3 mm of neoprene was sandwiched between the GFRP and each steel plate to distribute clamping stresses and prevent localized damage of the GFRP. Adequate length was left between ends of the steel plates for placing the glulam beam on top of the GFRP laminate.

The 98 kN pretension load was applied with jacks at both steel supports that were connected to independent pumps. The pretension load was monitored with a 222-kN load cell, and strains in the GFRP were monitored with 15 unidirectional foil-strain gages with a 6.4-mm gage length that were attached to the bottom of the GFRP laminate. The gages were located symmetrically about the midspan of the beam, with the first gage at 610 mm from the beam end. The gages were spaced at either 305 or 610 mm. The GFRP strain gages were also monitored during the bending tests as discussed later.

The PRF adhesive was applied to the GFRP after pretensioning. The glulam beam was then placed on top of the GFRP and 24 clamps were placed along the beam spaced at 254 mm on center to apply an average clamping pressure of 1.0 MPa. After the adhesive cured and the GFRP laminate was cut, the clamps were released. After release of the clamps, an average camber of 10.9 mm with a CV of 13 percent was measured.

Test protocols

A quasi-static four-point bending test was conducted to failure for all 45 beams according to ASTM D198 (ASTM International 2005). Each specimen had a 6.4-m simple span, and a servo-hydraulic Instron machine with a 245-kN actuator was used to apply load through two radiused hardwood load heads located at the third points of the span as shown in Figure 3. Displacements were measured with a noncontact digital image correlation system to obtain the deflection at midspan of the beam (Fig. 4), and four linear variable differential transducers were used to measure displacements at the beam supports. Load and strain data were collected with LabView software for continuous data recording. Tests were conducted in displacement control at a rate of 9 mm/min.

Bending test results

Load-deflection response and failure mode.—The load-deflection response of the three groups of beams is shown in Figures 5 through 7. Response was essentially linear until failure for the unreinforced specimens, while some softening was observed for the reinforced and prestressed beams. All the groups of glulam beams tested in four-point bending exhibited tension failure in the wood with the exception of one prestressed glulam beam that failed in compression. The tension failure was observed in the central third of the beam (Figs. 8a, 8d, and 8f). This failure started in most cases with a finger-joint failure (Figs. 8e through 8h) followed in some cases by shear (Figs. 8a, 8d, and 8f). The tension failure in few cases was due to knots (Figs. 8b and 8c).

The experimental results for the beams are summarized in Table 1, which shows the mean and the CV of peak load, moment, bending modulus of elasticity (MOE), mean modulus of rupture (MOR), and allowable bending stress F_b. The allowable bending stresses were obtained using the fifth percentile of the MOR with a 75% of confidence according to ASTM D2915 (ASTM International 2003a)

Figure 4.—Reference points at midspan for digital image correlation displacement measurement.

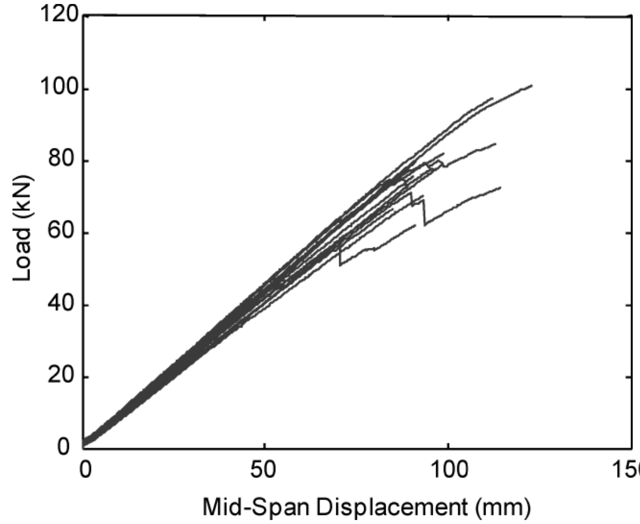

Figure 6.—Load-displacement response of reinforced beams.

and ASTM D1990 (ASTM 2000). The MOR, MOE, and F_b values shown in Table 1 have been adjusted to 12 percent MC according to ASTM D1990 and were computed based on the wood section only.

The results in Table 1 indicate that reinforcing beams with 1.0 percent by volume of GFRP laminate on the tension face increases the allowable bending stress F_b by 41 percent as compared with the unreinforced control beams. The MOE increases around 8 percent compared with the control beams. Prestressing glulam beams with 1.0 percent of GFRP laminate on the tension face with a pretension load equal to 30 percent of the GFRP UTS increased F_b by 38 percent compared with the glulam beams with reinforcement and 95 percent compared with the control beams. The stiffness stays nearly equal compared with the glulam beams with reinforcement, which is expected since stiffness is a function of the MOE of the wood and GFRP reinforcing and is independent of the prestressing.

GFRP stresses in the prestressed specimens.—The stresses in the GFRP laminate inferred from the strain gage data and the GFRP elastic modulus of 39.5 GPa are summarized in Table 2. The stress at tensioning was computed using the average of all strain gage readings for each beam. The mean value of 251 MPa corresponds to a pretension force of 101 kN, which agrees very well with the 98 kN applied pretension measured with the load cell during stressing. The stresses after release and at maximum load are computed based on the average of the six strain gages located in the middle third of each beam span. These six gages gave nearly equal strain readings. The average loss of prestress following release of the clamps due to camber was 16.1 percent. Loading produced an average additional GFRP tensile stress of $371 - 210 = 161$ MPa at maximum load. The total average stress at maximum load of 371 MPa is about 45 percent of the UTS of the GFRP.

One concern with prestressing is strain loss in the GFRP laminate due to bending creep. The creep behavior of GFRP-glulam beams in general is dominated by the creep of wood (Plevris and Triantafillou 1995, Davids et al. 2000), and creep results in small increases in the camber of the unloaded beam. This is accompanied by increased curvatures and a loss of tensile strain in the GFRP. To assess these strain losses, strains in the GFRP of one prestressed specimen were monitored for 12 days following release of

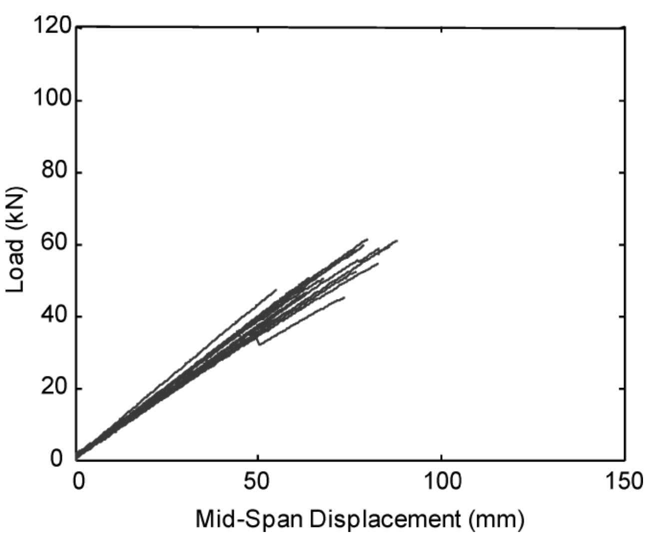

Figure 5.—Load-displacement response of control beams.

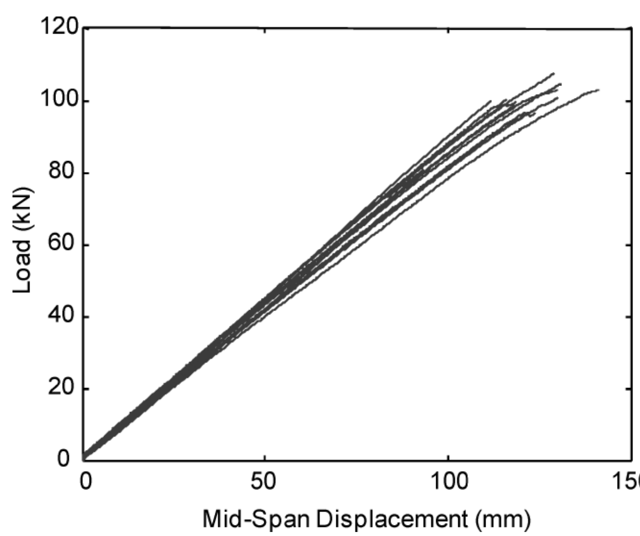

Figure 7.—Load-displacement response of prestressed beams.

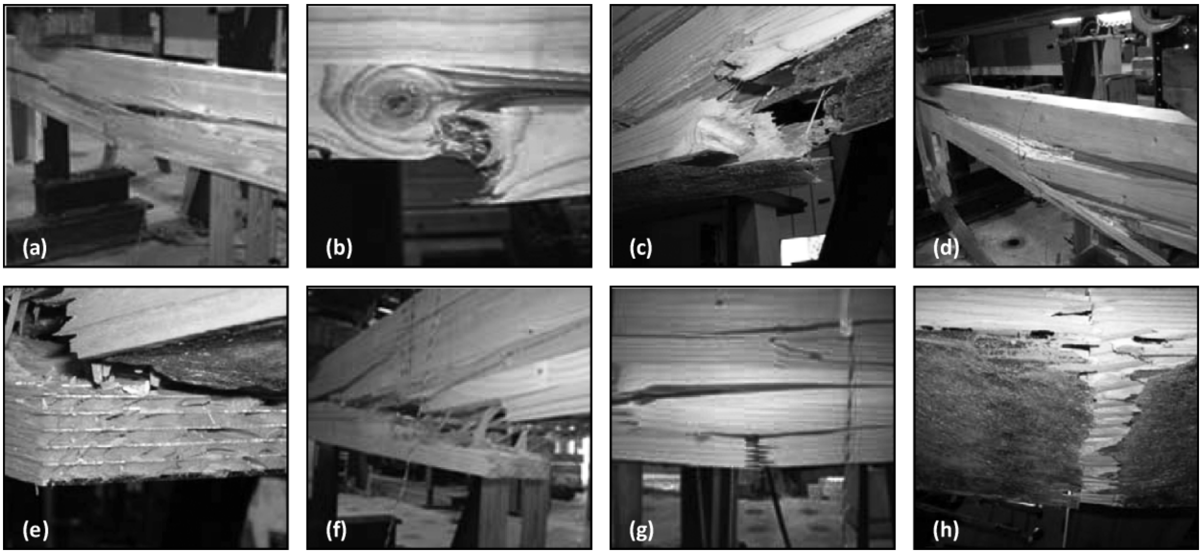

Figure 8.—Beam failure modes.

the clamps. Figure 9 shows the percent loss in average GFRP tensile strain over the center third of the beam relative to the strain at release. While the results from only one specimen cannot be generalized, the maximum loss was less than 2 percent, and the rate of loss decreased significantly over the 12-day monitoring period. It must also be noted that the role of creep of the wood-GFRP bond was not assessed in this study, and its effects should be quantified in future studies.

Analysis of beam response

The response of the prestressed beams may be analyzed in a manner similar to that used for the analysis of prestressed concrete beams (see, e.g., Nawy [2009] for an introduction to the mechanics of prestressed concrete beams). The MOE of the wood was fixed at 11.7 GPa based on the results of the four-point bending tests of the unreinforced control specimens. The MOE for the GFRP was taken as 39.5 GPa based on testing by Dagher et al. (1998). To account for potential compression failures, the wood was treated as elastic-plastic in compression. The limiting compressive stress was fixed at 41.7 MPa based on the compressive strengths reported by Dagher and Lindyberg (2003) for mixed L2/L3 grade laminations of Douglas fir at 12 percent MC.

After the initial jacking of the GFRP to a force $P_j = 98$ kN and releasing the clamps from the cured beam, the prestress force will decrease to a smaller value P_i due to the resulting upward camber. During prestressing and release, the beam behaves linearly elastically, and simple equations derived from elastic bending theory may be used to compute the effective initial prestressing force P_i after release of the clamps. Equation 1 relates P_j and P_i using the transformed cross-sectional area A_t, the area of the GFRP lamination A_{frp}, the section modulus S corresponding to the center of the GFRP, and the distance e from the centroid of the GFRP to the beam neutral axis. All cross-sectional properties are based on a transformed section with wood as the base material, giving a modular ratio $n = 39.5/11.7 = 3.38$.

Table 1.—Summary of experimental results from four-point bending tests.

	Maximum load (kN)	Deflection at maximum load (mm)	Maximum moment (kN-m)	MOE (GPa)	MOR (MPa)	F_b (MPa)
Control						
Mean	52.3	72.3	55.8	11.7	27.6	10.0
CV (%)[a]	11.9	13.9	11.9	6.22	12.0	—
Reinforced						
Mean	78.0	98.5	83.2	12.6	39.9	14.1
CV (%)	13.1	11.8	13.1	4.77	13.1	—
Prestressed						
Mean	97.1	119	103.5	12.6	49.0	19.5
CV (%)	8.16	11.2	8.16	3.82	8.19	—

[a] CV = coefficient of variation.

Table 2.—Stresses in GFRP for prestressed specimens.

Prestressed specimen no.	Stress at tensioning (MPa)	Stress after release of clamps (MPa)	Stress at maximum applied load (MPa)
1	250	206	362
2	252	203	382
3	250	218	385
4	247	206	397
5	251	209	386
6	246	212	359
7	248	208	395
8	251	211	375
9	257	218	384
10	254	220	382
11	245	193	355
12	251	216	342
13	253	190	316
14	261	224	365
15	257	214	384
Mean	251	210	371
CV (%)[a]	1.8	4.5	5.9

[a] CV = coefficient of variation.

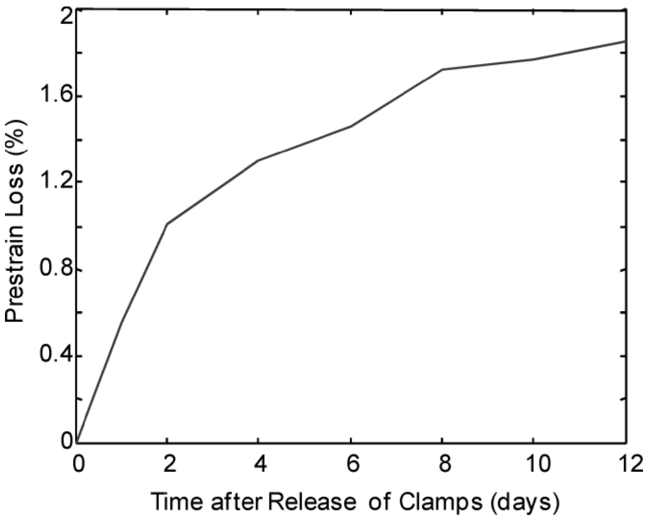

Figure 9.—Measured prestrain losses.

$$P_i = P_j - \left(\frac{P_i n}{A_t} + \frac{P_i e n}{S}\right) A_{\mathrm{frp}} \quad (1)$$

The negative term in Equation 1 accounts for the elastic shortening of the GFRP after release of the clamps due to axial deformation of the total cross section in compression and bending compression due to the eccentricity of P_i. Solving Equation 1 for P_i gives Equation 2.

$$P_i = \frac{P_j}{1 + nA_{\mathrm{frp}}\left(\frac{1}{A_t} + \frac{e}{S}\right)} \quad (2)$$

Equation 2 predicts a value of 87.2 kN for P_i, which is equivalent to an average stress in the GFRP of 214 MPa. This value is in excellent agreement with the mean stress in the GFRP of 210 MPa inferred from the measured strains at release of the clamps (Table 2).

To analyze the prestressed beams over the full range of loads, a nonlinear moment-curvature analysis was used to account for compressive yielding of the wood. While only one prestressed beam exhibited a clear compression failure, some nonlinear softening was observed in the load-displacement response of the prestressed and reinforced beams (Figs. 6 and 7), which was likely due to compressive yielding. The moment-curvature analysis predefines a range of curvatures and solves for the location of the neutral axis corresponding to each predefined curvature by enforcing horizontal force equilibrium. Once the neutral axis location is determined, the internal moment is computed by numerically integrating over the cross section. Using this approach, the elastic-plastic stress-strain response of the lumber in compression is easily incorporated; all required computer code was developed using MATLAB (MathWorks 2002). We note that other studies have used similar approaches when analyzing lumber (Buchanan 1986) and FRP-reinforced glulam (Davids 2001, Dagher and Lindyberg 2003).

The aforementioned moment-curvature analysis predicts compression yielding of the wood in the prestressed beams at an applied load of 91.5 kN during a four-point bend test. This load is 5.8 percent less than the average maximum load carried by the prestressed glulams of 97.1 kN (Table 1), and is consistent with the small degree of softening load-deformation response observed in some tests. The maximum stress in the GFRP at the average maximum load of 97.1 kN predicted by the model is 343 MPa, which is only 7.5 percent less than the average stress of 371 MPa based on the strain gage readings. The peak tensile stress in the wood immediately above the GFRP at the average maximum load of 97.1 kN predicted by the model is 37.4 MPa.

For comparison, analyzing the response of the same cross section with the unprestressed reinforcing (i.e., $P_i = 0$) gives a much lower predicted tensile stress in the GFRP of 125 MPa at the maximum average four-point bending load of 78.0 kN. However, the maximum tensile stresses in the wood for the unprestressed reinforced beams at the average maximum load is predicted to be 36.2 MPa, which is very close to the 37.4 MPa expected in the prestressed beams. Compressive yielding is predicted to occur at a load of about 95.6 kN. The load-deflection response of the reinforced beams shown in Figure 6 indicates that the two strongest beams, which failed at loads of 97.2 and 99.7 kN, did exhibit some softening load-deflection response that may have been caused by compressive yielding.

Taken as a whole, the results of these analyses indicate that for the prestressing scheme used here, a straightforward nonlinear moment-curvature analysis method that accounts for compressive yielding of the wood can give reasonable predictions of FRP and wood stresses. Further, the close agreement in the tensile stresses predicted in the wood at failure for the conventionally reinforced and prestressed beams supports the experimental observation that the beams failed largely in tension. However, it must be emphasized that this analysis has not accounted for creep losses in the prestressing, which may continue to accrue with time and be exacerbated by moisture changes due to mechanosorptive effects. In addition, a single cross-sectional analysis cannot take into account the random variations in wood strength due to defects, finger joints, etc., within the finite region of high bending stresses.

Summary and Conclusions

This article reports the results of a testing program designed to assess the strength performance of prestressed GFRP-reinforced glulam beams. Details of the fabrication and prestressing method were given. In addition to the prestressed specimens, unreinforced control beams and conventionally reinforced glulams were tested. A moment-curvature analysis was conducted to assess its ability to predict stress in the GFRP and the wood and to compare the response of the conventionally reinforced and prestressed beams.

The prestressing of the GFRP laminate increased beam strength by approximately 95 percent relative to the control specimens and 38 percent relative to the conventionally reinforced beams. These results indicate that prestressing can be a very effective method for increasing glulam bending strength, allowing greater utilization of the FRP. Prestress losses were examined over a 12-day period for one specimen, and measured GFRP strains indicated that losses were less than 2 percent of the original prestressing force.

Moment-curvature analyses of the beam cross section gave good predictions of both the initial effective prestressing force and the stresses in the GFRP at the average maximum load sustained by the prestressed specimens.

Computed tensile stresses in the wood for both the prestressed and unprestressed specimens at failure were similar. Computed compressive stresses indicate that some compressive yielding of the beam was likely in the prestressed specimens. The development of more refined modeling techniques that account for loss of prestress due to creep and the random spatial variation in lamination properties are needed to fully quantify prestressed beam response with a wider range of GFRP types, prestress levels, and reinforcing percentages.

Acknowledgments

This research was sponsored by State of Maine Department of Transportation (MDOT). The authors thank this sponsor for their support. The contents of this article reflect the views of the authors who are responsible for the facts and accuracy of the data reported herein. The contents do not necessarily reflect the official views or policies of the MDOT. This article does not constitute a standard, a specification, or a regulation.

Literature Cited

American Society for Testing and Materials (ASTM). 2000. Standard practice for establishing allowable properties for visually-graded dimension lumber from in-grade tests of full-size specimens. ASTM D1990. ASTM, West Conshohocken, Pennsylvania.

ASTM International. 2003a. Standard practice for evaluating allowable properties for grades of structural lumber. ASTM D2915. ASTM International, West Conshohocken, Pennsylvania.

ASTM International. 2003b. Standard test method for strength properties of adhesive bonds in shear by compression loading. ASTM D905. ASTM International, West Conshohocken, Pennsylvania.

ASTM International. 2004. Standard specification for adhesives for structural laminated wood products for use under exterior (wet use) exposure conditions. ASTM D2559. ASTM International, West Conshohocken, Pennsylvania.

ASTM International. 2005. Standard test method of static tests of lumber in structural sizes. ASTM D198. ASTM International, West Conshohocken, Pennsylvania.

Bohannan, B. 1962. Prestressed wood members. *Forest Prod. J.* 12(12): 596–602.

Buchanan, A. H. 1986. Combined bending and axial load in lumber. *J. Struct. Eng*. 112(12):2592–2609.

Dagher, H. J., B. Abdel-Magid, R. Lindyberg, J. Poulin, and S. Shaler. 1998. Static bending test results of Douglas-fir and western hemlock FRP-reinforced glulam beams. AEWC Report No. 98-4. University of Maine AEWC Center, Orono.

Dagher, H. J., T. E. Kimball, S. M. Shaler, and B. Abdel-Magid. 1996. Effect of FRP reinforcement on low grade eastern hemlock glulams. *In:* General Technical Report FPL-GTR-94, National Conference on Wood Transportation Structures, M. A. Ritter, S. R. Duwadi, and P. Lee (Eds.), October 23–25, 1996, Madison, Wisconsin; USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 207–214.

Dagher, H. J. and R. Lindyberg. 2003. Development of the AASHTO specifications for FRP-reinforced glulam beams. *In:* Proceedings of the 82nd Annual Meeting of the Transportation Research Board, January 12–16, 2003, Washington, D.C.; Transportation Research Board, National Research Council, Washington, D.C. (CD-ROM.)

Davids, W. G. 2001. Nonlinear analysis of FRP-glulam-concrete beams with partial composite action. *J. Struct. Eng*. 127(8):967–971.

Davids, W. G., H. J. Dagher, and J. Breton. 2000. Modeling creep deformations of FRP-reinforced glulam beams. *Wood Fiber Sci*. 32(4): 426–441.

Davids, W. G., M. Richie, and C. Gamache. 2005. Fatigue of glulam beams with fiber-reinforced polymer tension reinforcing. *Forest Prod. J*. 55(1):93–91.

Dolan, C., T. Galloway, and A. Tsunemori. 1997. Prestressed glued-laminated timber beam—Pilot study. *J. Composites Construct*. 1(1): 10–16.

Galloway, T. L., C. Fogstad, C. W. Dolan, and J. A. Puckett. 1996. Initial tests of kevlar prestressed timber beams. *In:* General Technical Report FPL-GTR-94, National Conference on Wood Transportation Structures, M. A. Ritter, S. R. Duwadi, and P. Lee (Eds.), October 23–25, 1996, Madison, Wisconsin; USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 215–224.

Gentile, C., D. Svecova, and S. H. Rizkalla. 2002. Timber beams strengthened with GFRFP bars: Development and applications. *J. Composites Construct*. 6(1):11–20.

Guan, Z. W., P. D. Rodd, and D. J. Pope. 2005. Study of glulam beams pre-stressed with pultruded GRP. *Comput. Struct*. 83:2476–2487.

Lopez-Anido, R., L. Muszynski, D. J. Gardner, B. Goodell, and B. Hezog. 2005. Performance-based material evaluation of fiber-reinforced polymer-wood interfaces in reinforced glulam members. *J. Test. Eval*. 33(6):1–10.

MathWorks. 2002. Using MATLAB V.6. MathWorks, Inc., Natick, Massachusetts.

Nawy, E. G. 2009. Reinforced Concrete: A Fundamental Approach. Pearson Education Ltd., Upper Saddle River, New Jersey.

Plevris, N. and T. C. Triantafillou. 1995. Creep behavior of FRP-reinforced wood members. *J. Struct. Eng*. 121(2):174–186.

Tingley, D. A. and C. Gai. 1998. FRP-reinforced glulam performance: a case study of the lighthouse bridge. *In:* Proceedings of the 5th World Conference on Timber Engineering, Vol. 2, J. Natterer and J.-L. Sandoz (Eds.), August 17–20, 1998, Montreaux, Switzerland; Presses polytechniques et universitaires romandes, Lausanne, Switzerland, pp. 177–181.

Tingley, D. A., P. C. Gilham, and S. M. Kent. 1996. Long term performance of FRP reinforced glulam bridge girders. *In:* General Technical Report FPL-GTR-94, National Conference on Wood Transportation Structures, M. A. Ritter, S. R. Duwadi, and P. Lee (Eds.), October 23–25, 1996, Madison, Wisconsin; USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 201–206.

Triantafillou, T. C. and N. Deskovic. 1991. Innovative prestressing with FRP sheets: mechanics of short-term behavior. *J. Eng. Mech*. 117(7): 1652–1672.

Triantafillou, T. C. and N. Deskovic. 1992. Prestressed FRP sheets as external reinforcement of wood members. *J. Struct. Eng*. 118(5): 1270–1283.