Initial Tests of Kevlar Prestressed Timber Beams

Terrel L. Galloway, Christian Fogstad, Charles W. Dolan P. E., PhD., J. A. Puckett P. E., PhD., University of Wyoming

Abstract

The high strength, high modulus of elasticity, and the increased availability of composite fibers and fiber reinforced plastics makes them a fitting candidate for reinforcement in many structural timber components. Advanced methods of wood construction utilizing composite reinforcement may enable timber to be put to more efficient structural applications. In this work, the authors establish a procedure for reinforcing glued laminated timber beams by bonding woven layers of non-stressed and prestressed bare unidirectional Kevlar fibers between selected laminations. This research evaluates the flexural performance of the reinforced and prestressed beams as compared to similar unreinforced control beams. Additional studies are presented that examine the shear strength of the Kevlar-wood bond, finger joint effects, and time-dependent behavior of the non-stressed and prestressed Kevlar reinforced timber beams.

Keywords: glulam, timber, beams, prestressed, Kevlar, FRP

Introduction

The ability to utilize laminated wood members for certain structural applications is often limited by their relatively low bending strength and stiffness when compared to other materials such as concrete and steel. A possible method for improving these properties is to use high strength fiber reinforced plastic (FRP) to reinforce timber glued laminated timber (glulam) members. Advances in fiber-reinforced plastics coupled with the increased availability of synthetic fibers have made fiber reinforced wood composites a viable alternative for reinforcing and prestressing timber. Glulam beams reinforced with FRP materials, when designed to fail plastically, generally exhibit higher bending stiffness, bending strength, and ductility while also displaying a reduction in mechanical variability. In addition, initial prestress of the member by pre-tensioning the FRP reinforcement may further increase the bending strength of the member. Initial prestress of the member may be used to control deflections and tension failures in much the same way it does for prestressed concrete. These advances in the structural properties and behavior of glulam beams may enable smaller wood members or members with lower grades of wood to be substituted for larger members made completely of wood.

Past research indicates that as the grade of lumber decreases in glued laminated timber beams, the beams become more dependent on the tensile strength of the wood rather than the compressive strength. Therefore, the placement of reinforcement with a high modulus of elasticity and high tensile strength in the tension zone of flexural members may improve the flexural strength, stiffness, ductility, and potentially lower the mechanical variability of beams when compared to unreinforced beams. Generally, to achieve a higher flexural strength and ductility, the reinforcement ratio and placement of the reinforcement are designed so that the beams have the equivalent of a very high tensile lamina. This shifts the failure to wrinkling in compression zone prior to failure of the tension laminates.

In addition to non-stressed reinforcement, prestress has been utilized in flexural timber members to allow such members to develop their full bending strength. Through the prestressing process, stresses are induced in the member to offset a proportion of the stresses due to an applied load. One method of prestressing that may produce these desired stresses is to place highly stressed Kevlar reinforcement longitudinally between laminations. The prestressed reinforcement is placed in the area where tensile stress develops in the beams under expected loading. By placing the prestress in the tension zone of glued laminated beams, the prestress force creates compressive stress in the tension zone. The compressive stress helps to counteract tensile stress expected under loading. Figure 1 illustrates Kevlar reinforced and prestressed glued laminated timber beams.

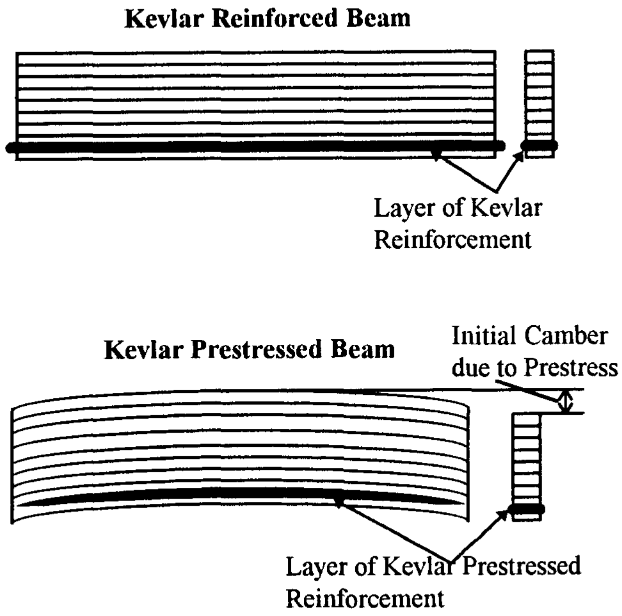


Figure 1 - Kevlar Reinforced and Prestressed Glued Laminated Beams

Research Objectives and Approach

This research examines the performance of glued laminated timber beams reinforced with non-stressed and prestressed Kevlar reinforcement. The primary objective is to determine how the Kevlar reinforcement and prestress affect the flexurat strength and stiffness of glued laminated beams. The flexural stiffness and strength of both non-stressed and prestressed Kevlar reinforced glulam beams are compared against non-reinforced control beams. Other research objectives include the bond strength of the Kevlar fiber reinforcement to wood interface, finger joint effects, and the time-dependent behavior of prestressed Kevlar reinforced timber beams.

In order to achieve these objectives, a series of prestressed reinforced, unstressed reinforced and control beams were constructed and tested in flexure. The test matrix, shown in Figure 2, illustrates the different types of beams that were tested. Glued laminated beams with one and two layers of prestressed reinforcement were evaluated. In addition, a set of beams with non-stressed Kevlar reinforcement was also evaluated. Most of the beams were constructed with No. 2 grade Southern Pine (SP) lumber. However, one set of beams was tested that included one layer of prestressed Kevlar glued between two No. 1 Grade Southern Pine laminations on the bottom of the beam.

The beams were constructed from 9 laminations of nominal 51 mm by 102 mm Southern Pine lumber. The test beams have a width of 90 mm, a height of 314 mm, and a length of 5.49 m. Indspec R600 adhesive was used in the manufacture of the beams to glue laminations together. The layers of Kevlar reinforcement consist of a woven tape of bare unidirectional Kevlar fibers. The area of one layer of Kevlar reinforcement is 29.4 sq. mm. The prestressed beams were manufactured by pre-tensioning the layer of Kevlar reinforcement prior to gluing it between selected laminations in the beams. Typical prestressing forces range from 40-47 kN for beams with one layer of prestressed reinforcement and from 67-79 kN for beams with two layers of prestressed reinforcement.

Flexural Tests

The beams were tested according to the flexure test standard specified by the ASTM D 198-84 “Standard Method of Static Tests of Timber in Structural Sizes”.

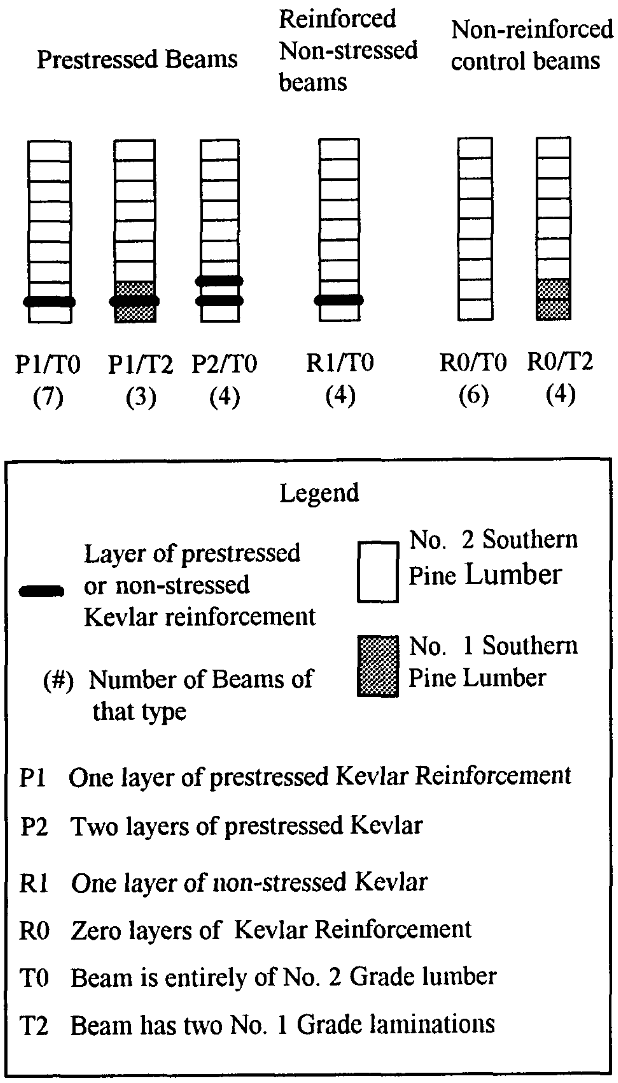


Figure 2 - Test Matrix of Reinforced, Prestressed, and Control Beams

The test setup is illustrated in Figure 3. The beams are supported by pinned and roller supports at the ends. Lateral supports prevent any lateral torsional buckling in the beams as they are tested. The load was determined using a 245 kN load cell and recorded by using the Keithley data acquisition system. The deflection was found by using a direct current displacement transducer (DCDT). The curvature was determined by mounting three DCDTs longitudinally in the constant moment section on one side of the beam. The data from the DCDTs were also recorded by using the Keithley data acquisition system. All beams were fabricated and tested at a moisture content less than 15%. The load, P, was then used to calculate the moment. The moment, rotational strains, and deflection were recorded for each beam.

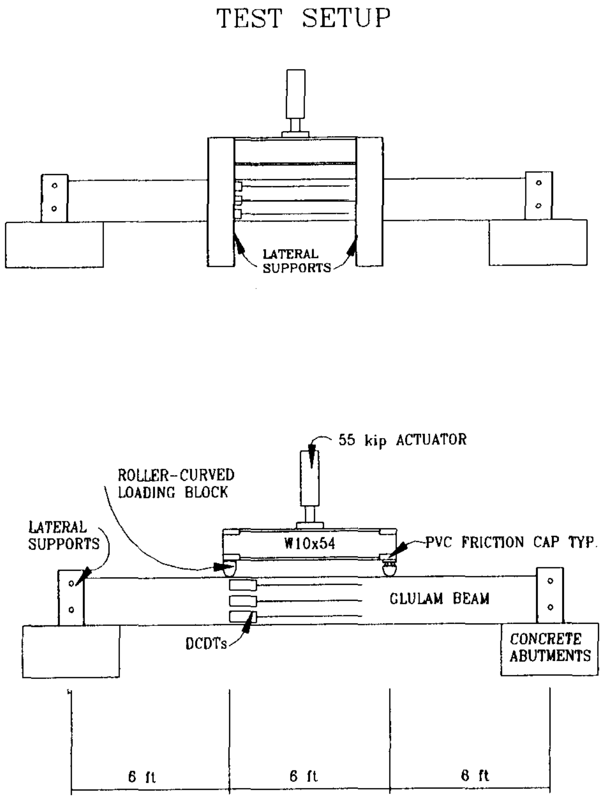


Figure 3 - ASTM D 198 Flexural Test Setup

The of the flexural tests compared the ultimate moment capacities of the prestressed and non-stressed reinforced Kevlar beams to similar unreinforced control beams. In addition to the moment, rotation, and deflection data, the failure mode, the stresses at failure, and the initial camber of the prestressed beams were measured.

Shear Test of Kevlar-Wood Interface

In addition to the flexural tests, a series of shear tests were conducted to determine the bond strength of the FRP-wood interface. These tests were conducted in accordance with ASTM D 905 - 86 “Standard Test Method for the Strength Properties of Adhesive Bonds in Shear by Compression Loading.” Several shear block specimens were constructed by gluing blocks of wood together using several different adhesives. A compressive force was then applied to shear the blocks apart. In addition, shear block specimens without Kevlar and with both non-stressed and prestressed Kevlar were also constructed. The objective of the shear test research is to determine which adhesive produces the highest shear bond between the layer of Kevlar reinforcement and the wood. Results from this research also determine the limiting level of initial prestress that can be applied so that the Kevlar-wood bond will not fail due to the shear under expected loads.

Finger Joint Test

To determine the effect of the finger joints on the flexural performance of the Kevlar non-stressed and prestressed beams, a series of tensile tests were conducted on the finger joints and the wood in the beams. Tension strips of timber from the beams with and without finger joints were constructed and tested in accordance with ASTM D 4688 “Standard Test Methods for Evaluating Structural Adhesives for Finger Jointing Lumber.” This test gives higher strengths for clear lumber than a full size finger joint, however, the test has the benefit that samples may be prepared from the actual beams. The tensile strength of the finger joints was compared to the tensile strength of the clear wood and wood with knots.

Sample sets of tension strip specimens that failed due to knots, finger joints, and clear wood failure were prepared and tested, The sample size of tension strip specimens that failed at a knot, a finger joint, and in clear wood were 45, 40, and 80 specimens, respectively. From this data, the comparative tensile strength of the knots, finger joints and clear wood in the beams was determined. In addition, a sample set intended to represent the timber in the beams was computed. This sample set combines an appropriate percent of knot and clear wood test specimens and represents the percentage of knots in the beams. The tensile strength of the representative wood sample set of tension strips was then compared against the tensile strength of the finger joint sample set. From this data, more information was determined as to how the finger joints and strength reducing characteristics of the lumber (such as knots) affected the flexural performance of the beams.

Time-Dependent Properties

Time-dependent properties, such as the creep deflection and the loss of prestress force, are vital to the performance of the non-stressed and prestressed Kevlar reinforced glued laminated timber beams. To address these concerns, tests were conducted to evaluate the midspan deflection and the strain in the bond line between the Kevlar and the wood. These parameters beams were measured over an extended period of time.

Midspan Creep Deflection Test - The mid-span creep deflection of both prestressed beams with one layer of prestressed Kevlar reinforcement (P1/T0) and corresponding control (R0/T0) beams loaded with a uniform load were measured over a period of 245 days. Three prestressed beams (Pl/T0) and three control (R0/T0) beams were loaded with a uniform load of 1.68 kN/m. All six beams spanned 5.49 m between simple supports. See Figure 4 for the midspan creep deflection test setup.

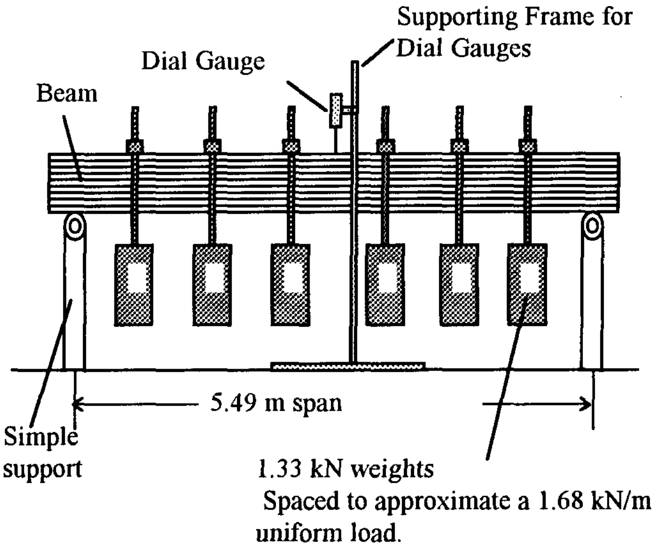


Figure 4 - Midspan Creep Deflection Test Setup

Dial gauges were used to measure the midspan deflection of the beams. Initial deflections due to the application of the load were measured. Then the deflection was continually measured over a period of 245 days after the application of the load. Both the initial and long-term deflections of the prestressed beams were compared to the control beams.

Bond Line Strain Test - In addition to the midspan deflections, the strain in the bond line between the prestressed Kevlar and the timber was evaluated over an extended period of time. Strain gauges were placed on the top of the bottom wood lamination of one prestressed beam with one layer of Kevlar reinforcement (P1/T0), Figure 5. A separate strain gauge was placed on a glue line in a small wood sample to serve as a control for moisture change and glue effects. The strain gauges measured the strain in the wood at the interface between the prestressed Kevlar layer and the wood. Strain gauges were placed at several points along the length of the beam from the end of the beam to midspan of the beam. The strains were measured before and after the release of the prestress into the beam. Then the beam was loaded with a uniform load identical to the test setup shown in Figure 4. The strains were measured before and after the application of the load. The strains were continually measured over a period of 245 days after the application of the uniform load.

Strain gauge # 1 is located near the end of the P1/T0 beam while strain gauge # 10 is located near midspan, The beam was placed on the simple supports so that strain gauges # 1 through # 10 were located 25 mm, 89 mm, 165 mm, 241 mm, 394 mm, 546 mm, 851 mm, 1.156 m, 1.765 m, and 2.832 m from the end of the beam, respectively.

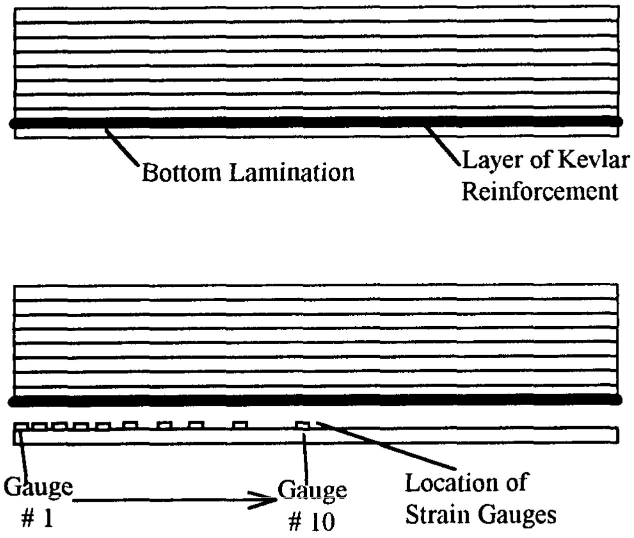


Figure 5 - Location of Strain Gauges on Prestressed (P1/T0) Beam.

Test Results

Flexural Test Results

The ultimate moment capacities determined experimentally from the ASTM D 198 flexure test do not match well with predicted ultimate moment capacities of the glued laminated beams based on the mean tensile strength of SP lumber provided by the Forest Products Research Lab. The ultimate moment capacities of the prestressed beams without tension laminations (P1/T0 and P2/T0) are much lower than predicted. Alternatively, the non-stressed reinforced beams (R1/T0) and the prestressed beams with one layer of Kevlar reinforcement and two grade one tension laminations (Pl/T2) exhibited a significant increase in bending strength compared to the anticipated strength gain. The prestressed beams with number 1 grade SP also exhibited larger strength gains than originally anticipated. These strength gains were determined by comparing the average ultimate moment capacities of the non-stressed and prestressed Kevlar reinforced timber beams to the ultimate moment capacities of the comparative unreinforced control beams. Table 1 compares the experimentally determined strength gains and the predicted strength gains.

Table 1 - Strength Gains from the ASTM D 198 Flexure Test Compared to Predicted Strength Gains

Beam Type	Average Strength Gain (%) (From Flexure Test)	Predicted Strength Gain (%) (Based on FPL mean values for SP lumber)
P1/T0	1.3	20
P2/T0	16.3	36
R1/T0	22.9	3
P1/T2	24.3	13

One possible explanation for the deviation of experimental results from the theoretical predictions is the influence of finger joints and knots. Every beam failed within the elastic region due to a tension failure of the bottom laminations. Results indicate that 15 of 28 test beams failed at a finger joint on the bottom lamination, 5 of the 28 test beams failed at a knot on the bottom lamination, and 8 of the 28 test beams failed on the bottom lamination due to clear wood tension failure. The modulus of rupture for knot failure is lower than the modulus of rupture for finger joint failures of the bottom lamination. The modulus of rupture for the clear wood failure of the bottom lamination is greater than both the modulus of rupture for both knot and finger joint failures. Table 2 provides failure modes and corresponding moduli of rupture from the flexural tests.

Table 2 - Failure Mode of Bottom Lamination and Corresponding Moduli of Rupture

Failure Mode	Modulus of Rupture (MPa)	No. of test beams that failed (#/28)
Knot	32.0	8
Finger Joint	35.6	15
Clear Wood Tension	42.3	5

The difference in failure mode, clear wood, finger joint, or knot partially explains why the experimental strength gains did not match the predicted strength gains. The average ultimate capacities of the seven P1/T0 beams was compared to the average moment capacity of the six R0/T0 beams. However, the failure modes of the seven Pl/T0 beams were different than that of the R0/T0 control beams, Table 3. All of the seven Pl/T0 beams failed due to a knot or a finger joint on the bottom lamination. Alternatively, of the six R0/T0 control beams, 1 failed at a knot, 3 at a finger joint and 2 due to clear wood tension on the bottom lamination. Since the two sets have different failure modes, it is difficult to compare the average strengths.

Table 3 - Failure Modes of Bottom Lamination for the Control, Non-stressed, and Prestressed Beams

Beam Type	No.	Knot Failure	Finger Joint Failure	Clear Wood Failure
P1/T0	7	3	4	0
P2/T0	4	0	3	1
P1/T2	3	0	1	2
R1/T0	4	0	2	2
R0/T0	6	1	3	2
R0/T2	4	1	2	1

To reduce the variability of data due to different failure modes, comparison of the beams that only failed at the finger joints was conducted. The predicted strength was based on the FPL mean values for SP lumber and were corrected to the stress levels determined by the strip finger joint tests. Restricting the data sample to just these beams provides very good correlation between actual strength gains and predicted strengths gains, Table 4. In analyzing Table 4, only 15 beams were in the sample set, so drawing statistically valid conclusions is not warranted.

Table 4 - Strength Gains from the ASTM D 198 Flexure Test Compared to Predicted Strength Gains for Beams Failing at Finger Joints Only

Beam Type	Average Strength Gain (%) (From Flexure Test)	Predicted Strength Gain (%)
P1/T0	30	25
P2/T0	29	44
P1/T2	9	5

Finger Joint Test Results

Tension strip tests conducted on sample sets of specimens with knots, finger joints, and clear wood appear to validate the findings from the modulus of rupture. There is a difference in the tensile strength of knots, finger joints, and clear wood. In addition, the variation and standard deviation of the tensile strength of the finger joints is much less than the variation in the tensile strength of the knot and clear wood sample sets, Table 5. The average tensile strength of a “typical” wood sample set was established by combining proportional parts of clear, finger joint, and knot samples. The difference in tensile strength between the “typical” wood in the beams and the finger joints is approximately 7.6 MPa.

Table 5 - Tension Strip Test Results

Sample Group	No.	Average Tensile Strength (MPa)	Standard Deviation (MPa)
Knot	45	21.7	11.8
Finger Joint	40	31.2	6.7
Clear Wood	80	48.9	14.5
"Typical" Wood	125	39.1	18.9

Shear Strength of Kevlar-Wood Interface Results

ASTM D 905 shear tests reveal that the shear strength of the Kevlar-wood interface decreases with increased pretension force in the Kevlar. Shear block specimens with Kevlar tape glued between them had a higher shear stress than shear block specimens without Kevlar, if the pretension is low (0-7.5 kN). However, as the pretension in the Kevlar tape increases (20-52 kN) the shear strength is lower than the shear tests without Kevlar. Tables 6 and 7 present shear strength results.

Table 6 - ASTM D 905 Shear Stress Tests Without Kevlar

No. Tested	Adhesive (Hardener)	Average Stress (psi)	Shear (MPa)
13	Indspec R600 (H30M)	715	4.9
15	Borden LT-75 (FM260)	574	4.0
5	Indspec R600 (H30M)	634	4.4
5	Borden LT-75 (FM 260)	421	2.9

Table 7 - ASTM D 905 Shear stress tests with Kevlar

No. Tested	Adhesive (Hardener)	Kevlar Pretension (kN)	Average Shear Stress (MPa)
5	Indspec R600 (H30M)	0	7.8
5	Borden LT-75 (FM260)	0	8.5
10	Indspec R600 (H30M)	7.5	5.6
10	Borden LT-75 (FM260)	6.4	5.6
9	Borden RS 240 MD (FM 124D)	7.5	6.2
8	Indspec R600 (H30M)	20.0	2.9
9	Indspec R600 (H30M)	52.3	2.3

All adhesive tests were conducted following the manufacturer's recommendations for proportioning and mixing. No attempts were made to modify or optimize the mix proportions.

Midspan Creep Deflection Test Results

The midspan creep deflection test results are shown in Figure 6. The initial deflections of the beams after the uniform load was applied were approximately the same for both the prestressed and the control beams, Table 8. In addition, the average creep deflections for both the prestressed and the control beams are similar. However, the prestressed beams had an initial camber so that the relative deflection from horizontal for the P1/T0 beams is less than that of the R0/T0 control beams..

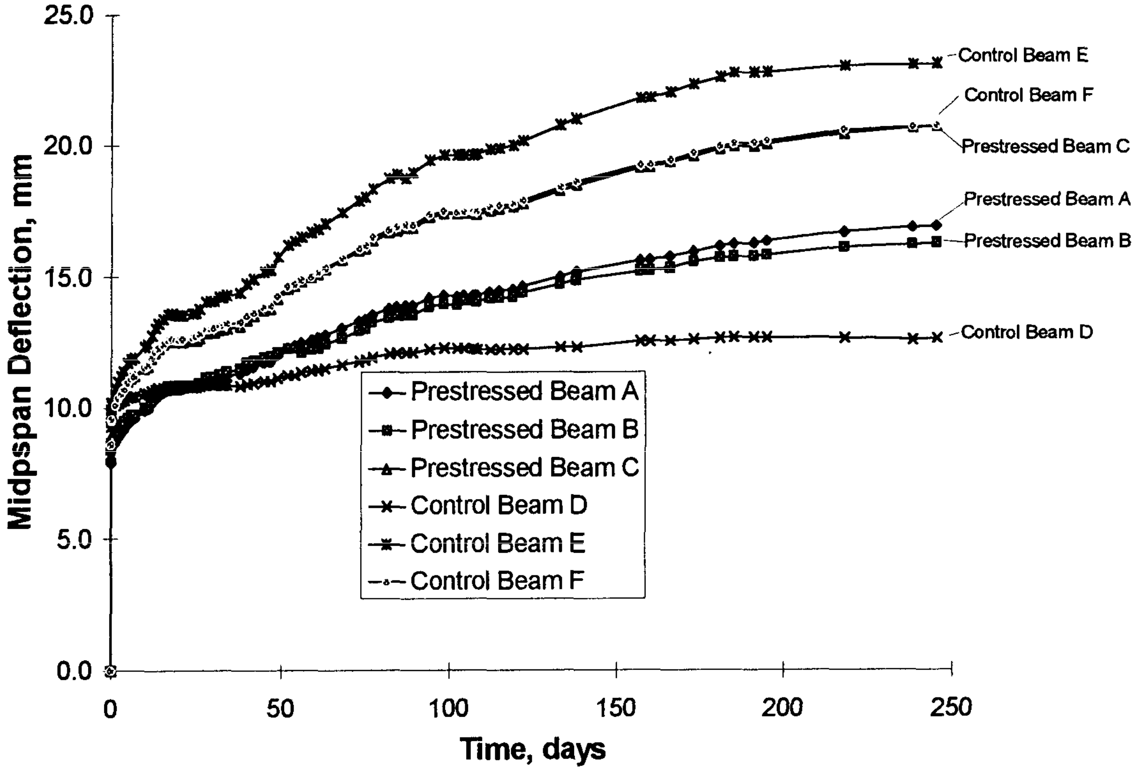
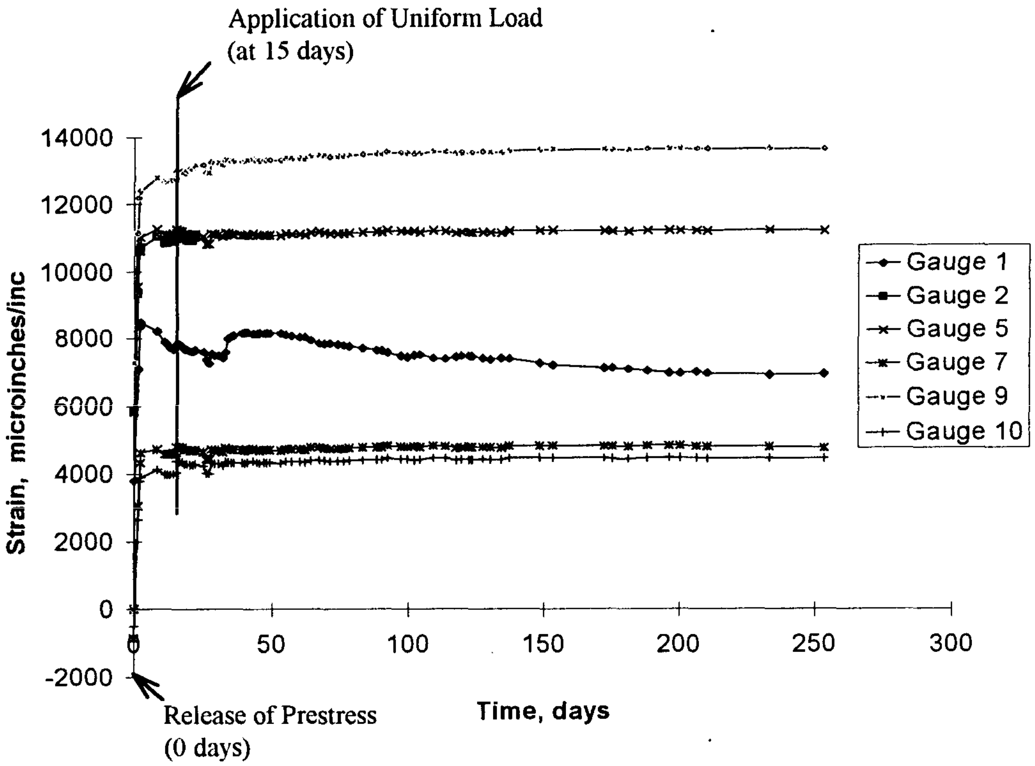


Figure - 6 Midspan Creep Deflection Test Results


Application of Uniform Load (at 15 days)

Release of Prestress (0 days)

Figure - 7 Bond Line Strain Test Results

Table 8 - Initial, Total, and Creep Deflections of Prestressed and Control Beams Due to Uniform Loading

Beam Type	Initial Deflection due to Uniform Load (mm)	Total Deflection after 245 days (mm)	Creep Deflection (mm)
P1/T0	7.93	16.9	8.97
P1/T0	8.41	16.2	7.82
P1/T0	8.92	20.7	11.79
R0/T0	9.63	12.6	3.00
R0/T0	9.30	23.1	13.82
R0/T0	8.59	20.7	12.14

The average initial deflection of the prestressed (P1/T0) beams due to the application of the uniform load is 8.42 mm while the average initial deflection of the control (R0/T0) beams is 9.17 mm. The average creep deflection of the prestressed (Pl/T0) beams due to the application of the uniform load is 9.53 mm while the average initial deflection of the control (R0/T0) beams is 9.65 mm. (See Table 7) However, the average initial camber of the prestressed beams is 7.78 mm. Therefore, the total deflection from horizontal for the prestressed beams is 10.8 mm while the average total deflection from horizontal for the control beams is 18.82 mm, Table 9.

Table 9 - Initial Camber and Total Deflection from Horizontal for Prestressed and Control Beams

Beam Type	Initial Camber due to Prestress (mm)	Total Deflection after 245 days (mm)	Total Deflection from horizontal after 245 days (mm)
P1/T0	8.13	16.9	8.76
P1/T0	3.20	16.2	14.86
P1/T0	12.01	20.7	8.69
R0/T0	-	12.6	12.62
R0/T0	-	23.1	23.11
R0/T0	-	20.7	20.73

Bond Line Strain Test Results

The bond line strain test results are shown in Figure 7. Initial strain readings before and after the release of the prestress were highly variable due to the large strains, the possibility that the glue was not fully cured, and the vibrations in the manufacturing plant. Therefore, the accuracy of the initial strain readings are questionable. However, once the beams were returned to the University of Wyoming structural research lab, the strains became more constant. From Figure 7, it can be seen that after the application of the uniform load, the strains in all of the strain gauges increased. After the application of the uniform load, approximately 15 days after the release of the prestress into the beam, the strains in the wood near the prestressed Kevlar layer became fairly constant and remained constant for the remainder of the test.

Conclusions

Flexural Strength

The coefficient of variation in the test results and the small number of total samples must be considered when evaluating the following conclusions. Examining the entire data set of 28 beams indicated that the flexural strength gains determined experimentally did not agree well with predicted results. This was due to the influence of the finger joints and knots. Every beam tested failed in an elastic-type tension failure of the bottom lamination. There is a distinct difference between the ultimate moment capacity and the moduli of rupture for beams that failed due to a knot, finger joint, or clear wood failure of the bottom lamination. The Pl/T0 beams failed due to knots and finger joints and had lower moduli of rupture than that of the comparative control beams. Examination of beams that failed only at the finger joints suggest that the strength gain predictions were more reliable than an examination of the total test data and that the prestressing did strengthen the beams.

Shear Strength of Kevlar-Wood Interface

ASTM D 905 shear tests reveal that the shear strength of the Kevlar-wood interface decreased with an increase of the pretension force in the Kevlar. Shear block specimens with Kevlar tape glued between them show a higher shear stress than shear block specimens without Kevlar, if the pretension is low (0-7.5 kN). However, as the pretension in the Kevlar ribbon increases (20-52 kN) the shear strength is lower than the shear tests without Kevlar. Therefore, as the prestress is increased, the shear strength of the wood-Kevlar bond decreases. The initial prestress must not be so high that it decreases the shear strength at the Kevlar-wood layer below expected shear stresses due to the applied loads.

Finger Joint Effects

The finger joint and knots did affect the flexural behavior of the beams. Both the modulus of rupture and the tension strip test results revealed a difference in tensile strength between knots, finger joints, and clear wood. In addition, there appears to be a difference in tensile strength between the actual timber in the beams to the finger joints. The finger joints were weaker than the surrounding wood. This is why many of the flexural test beams failed at a finger joint on the bottom lamination. To account for this weakness in finger joints, additional prestress or additional non-stressed reinforcement is required to strengthen the finger joints.

Time-Dependent Properties

The initial camber in the beams matched what the predicted camber based on the prestress force in the beams. The initial and creep deflections of the beams under the application of the load are approximately the same for both prestressed and control beams. The initial camber of the prestressed beams were retained over sustained loading over an extended period of time. Therefore, the prestress was not lost over time. The prestressed Kevlar reinforcement did not appear to reduce the initial deflections or deflections over time. This is due to the fact that there is only a small difference in stiffness between the P1/T0 beams and the R0/T0 beams because of the small area fraction of Kevlar reinforcement used.

Current and Future Research

Currently, research is being conducted to examine the initial camber and stiffness (EI) of the prestressed beams and correlate this information to the amount of prestress force in each prestressed beam. In addition, examination of weak axis bending (sweep) due to accidental eccentricity of the Kevlar layer in the weak direction in the beams is being investigated. Future research must address the minimum reinforcement and prestressing levels to effectively control the tensile failures of these beams.

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