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Wetpreg Reinforcement of Glulam Beams

Andrew R. Jordan

WETPREG REINFORCEMENT

OF GLULAM BEAMS

By

Andrew R. Jordan

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A THESIS

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Advisory Committee:

Habib J. Dagher, Professor of Civil & Environmental Engineering, Advisor

Beckry Abdel-Magid, Associate Professor of Composite Materials Engineering, Winona State University, Minnesota

Stephen Shaler, Professor of Wood Sciences & Forest Engineering

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Thesis Advisor: Dr. Habib J. Dagher

An Abstract of the Thesis Presented

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Glued-laminated timber (glulam) is an engineered wood product made by adhering dimension lumber together to form a larger structural member. By combining fiber reinforced polymer (FRP) technology with glulam, it is possible to dramatically increase glulam strength and stiffness, to negate the need for high quality tension laminations, to reduce beam size, to decrease strength variability, to increase ductility, and possibly to reduce glulam cost. A "wetpreg" process was used to form the FRP, by impregnating E-glass fabric with a phenolic resin. Following impregnation, the wetpreg FRP was applied to glulam made from eastern hemlock timber.

Strength and durability were tested for wood-wood, wood-FRP, and FRP-FRP bonds for several different materials and processes. Full scale beams were tested to ultimate failure in bending. Reinforced beam results were compared against unreinforced beam results.

ACKNOWLEDGMENTS

I would like to acknowledge the sponsors of the project: the United States Department of Agriculture (USDA) and the National Science Foundations (NSF) EPSCoR program. I would also like to thank Georgia Pacific and Brunswick Technologies, Inc. for supplying materials as well as technical assistance.

I would like to give a special thank-you to my advisor, Professor Habib Dagher, for all of his effort and assistance with all aspects of the project. Thanks go to my committee, Professor Beckry Abdel-Magid and Professor Stephen Shaler, for sharing their expertise of FRP and wood science.

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1 INTRODUCTION AND OBJECTIVES

1.1 Objectives

The goal of this research is to create an inexpensive, high strength, reinforced glulam beam. The requirements that must be met for this to happen are: 1) use of low cost, high strength reinforcement material, 2) simple and inexpensive method of reinforcement application, 3) use of inexpensive wood material, and 4) significant increase in bending strength and stiffness.

Many materials could be used as reinforcement to increase the strength and stiffness of glulam, but there are few materials that are inexpensive and easy to apply. Fiber reinforced polymers (FRP) can be both inexpensive and easy to apply. FRP using E-glass fibers were chosen because E-glass provides the greatest tensile strength for the cost.

FRP can be pre-manufactured through a process called pultrusion. Pultrusion forms a high quality product under controlled conditions. The disadvantage is that it is a slow, relatively expensive process. A different process that takes a fabric of high strength fibers and impregnates it with a resin, applies it in an uncured state to the desired surface for cure at room temperature is called wetpreg. Wetpreg simply means wet-impregnating the fibers. How you use it later has no bearing on the name of the process. A wetpreg FRP is typically lower quality than that made by pultrusion, but it is a less expensive process. The wetpreg process of forming FRP was chosen for this research.

Eastern Hemlock was chosen as an attractive Maine species to use in reinforced glulam (Lanpher, 1995). It is an abundant species with a limited market, making it a relatively inexpensive material.

The objective of this project was to use Eastern Hemlock and E-glass FRP formed with a wetpreg process to produce high strength and low cost glulam beams.

1.2 Introduction

An unreinforced glulam beam, loaded in bending, typically fails in tension at a knot or finger-joint. The tension strength of high quality wood (i.e. no knots, grain deviation, or defects) is higher than its compression strength, but the tension strength of lower quality wood is less than the compression strength. This is primarily because defects, such as knots, decrease wood's tension strength more dramatically than its compression strength.

A glulam beam reinforced on the tension side can fail in a number of ways depending on the quality of the wood and the beam layup, the strength of the reinforcement, how much reinforcement is used, where in the beam it is located, and how well the reinforcement bonds with the wood. If the bond is weak, the reinforcement can delaminate at stresses lower than ultimate, in which case the reinforcement is not fully utilized. Assuming the bond is good and the reinforcement is applied to the outermost tension lamination, then the performance of the beam depends on the tensile capacity of the reinforcement and the grade and layup of the wood. If a very small amount of reinforcement is

used, the reinforcement can fail in tension and the wood tension laminations will fail afterwards. If a large amount of reinforcement is used, the wood may fail in compression and/or shear while the reinforcement remains intact.

A good question is how much reinforcement should be used. Since low quality wood is weaker in tension than in compression, the most efficient use of materials is to provide just enough reinforcement to make the beam equally strong in tension as in compression. If a little more reinforcement is used such that the beam starts failing in compression, the beam will exhibit a more ductile failure. This is because wood in compression exhibits ductile behavior (see Figure 1.1). Since both efficient use of materials and ductile beam failure is desired, reinforcement should be provided such that compression failure results.

Tensile reinforcement decreases the effect of local defects such as knots and finger-joints because the stress at a failed region of the beam near a defect transfers to the reinforcement. It seems likely that the variability of beam strength would be reduced by adding reinforcement since a reinforced beam strength is affected less by random defects.

1.3 Obstacles

The greatest obstacle encountered in this work was developing a strong, low-cost, durable bond between the FRP and wood. In the wetpreg process, the matrix for the synthetic fibers also acts as the adhesive for the FRP to the wood. Two resin systems were tested extensively through shear and cyclic delamination testing (see Chapter 4).

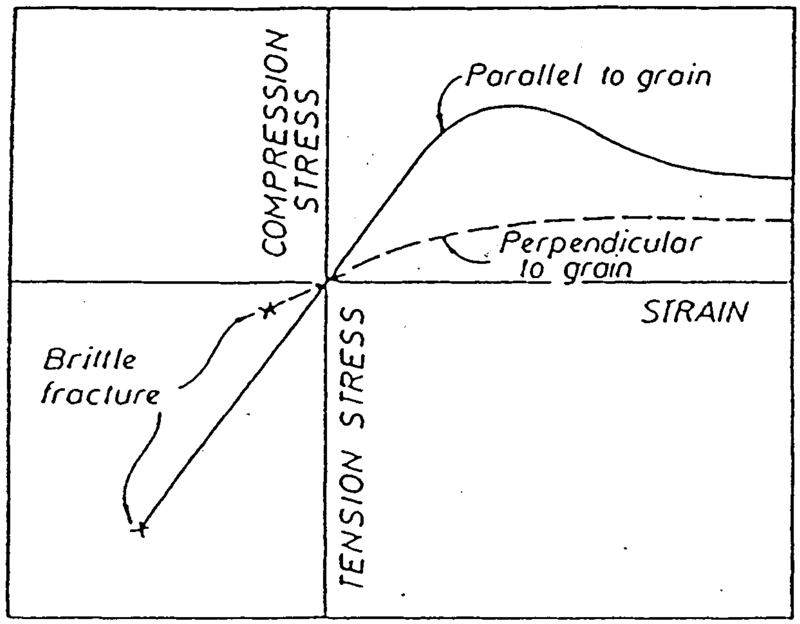


Figure 1.1: Stress-Strain Relationship for Wood

(from Buchanan 1990, 1215, Fig. 2.)

The glulam industry uses a phenolic-resorcinol-formaldehyde (PRF) adhesive for bonding wood laminations. It seemed to be a good candidate for application with wetpreg FRP. However, it was unknown how well it would bond to the glass fibers. Another resin system, an acid-cure phenolic resin designed for use with glass fibers, was evaluated. This resin's ability to bond to wood, however, was unknown. The two resin systems were evaluated to develop strong and durable bonds.

1.4 Organization of the Thesis

Chapter 1 introduces concepts behind the desirability of reinforcing glulam and also presents the research objectives. Chapter 2 provides a brief literature review of reinforced glulam beams. Chapter 3 describes the fabrication, testing, and results of pilot beams that show the feasibility of using wetpreg reinforcement with glulam. Chapter 4 discusses the shear, cyclic delamination, and tensile testing done with various fabrics and matrixes to identify suitable reinforcing materials and fabrication processes. Chapter 5 describes the fabrication and testing of 31 beams to provide a quantitative analysis of wetpreg reinforced glulams. Chapter 6 provides a summary, conclusions, and recommendations for future research.

2 LITERATURE REVIEW

2.1 Introduction

Efforts to reinforce wood have been on-going for many years. Metal plates were used as reinforcement as early as the 1940's. More recently, however, emphasis has been on the application of fiber reinforced polymers (FRP). Bulleit (1984) and later Dagher, Kimball, and Abdel-Magid (1995) reviewed the studies done on reinforcing wood materials. Their reviews were comprehensive, and a summary of their findings as well as new findings are described in this chapter.

2.2 Wood Beams with Non-FRP Material

Mark (1961) studied the effects of bonding aluminum to both compression and tension faces of wood sections, and showed that the strength and stiffness of wood-aluminum beams could be predicted to failure. Sliker (1962) bonded aluminum sheets between various layers of laminated wood beams. Sliker found advantages of increased stiffness, increased tensile and shear strength, and a reduction in variability, but had difficulty with delamination. Bohannan (1962) reinforced glulam beams with pretensioned steel wire strands in the tension zone, and found that beam stiffness didn't change but the reliability of ultimate

strength was increased. Peterson (1965) reinforced glulam beams with a prestressed flat steel strip in the tension zone, and saw an increase in strength and stiffness and a decrease in variability. Lantos (1970) reinforced glulam beams with steel rods, and concluded that, " 'poorer' quality lumber benefits more from the use of steel reinforcement." Stern and Kumar (1973) reinforced "flitch" beams with steel plates, and showed that reinforced beams were 28-48% more effective. Krueger and Sandberg (1974) reinforced glulam with bronze coated woven steel wire and epoxy, and concluded that the strength of a beam was heavily dependent upon the longitudinal modulus of elasticity and ultimate strain of the wood. Coleman and Hurst (1974) reinforced glulam beams with light gage steel. Coleman and Hurst discovered that nailed beams were stronger than unreinforced beams by 8% in moment and 22% in shear, while glue-nailed beams were 22% and 37% stronger in moment and in shear than unreinforced beams. Hoyle (1975) reinforced wood beams with steel plates, and found that repeated load cycles did not impair beam strength or stiffness. Bulleit, Sandberg, Woods (1989) reinforced glulam beams with steel rebar embedded in flakeboard, and showed increased stiffness and moment capacity in the reinforced beams.

2.3 Wood Beams with Fiber and FRP Material

2.3.1 Research Prior to 1990

Wangaard (1964) and Biblis (1965) bonded unidirectional fiberglass and epoxy to the compression and tension faces of wood, and concluded that core

shear strain be taken into account in order to get accurate elastic deflection predictions. Theakson (1965) reinforced wood beams with fiberglass fabric, rovings, and woven rovings. Theakson discovered that it was practical to reinforce beams with fiberglass, and that fiberglass strands should be used rather than mats or cloths. Spaun (1981) tested reinforcement of finger joints with fiberglass rovings. Spaun concluded that phenol based adhesives were adequate and that stiffness was increased with a small amount of fiberglass..

Rowlands, et al. (1984) reinforced glulam with several types of fibers and resins. Glulam stiffness was increased by 40% and bending strength increased by 100%. Bond shear strengths and environmental aging were evaluated. Phenol resorcinol formaldehyde (PRF) bonded well with glass. It was stated that, "flexed beams are probably more effectively reinforced with additional glass plies than with the more expensive graphite."

2.3.2 Research Post 1990

Plevris and Triantafillou (1992) reinforced wood with carbon/epoxy FRP. Triantafillou and Deskovic (1992) reinforced lumber with prestressed carbon/epoxy FRP, and discovered prestressing FRP improved durability, stiffness, strength, creep and fatigue behavior, and savings in materials over non-prestressed FRP. Davalos, Salim, and Munipalle (1992) reinforced beams with glass/vinylester FRP on the tension face, and found that resorcinol formaldehyde was adequate and that a 10% reinforcement addition could reduce beam depth by 30%. Tingley and Leichti (1993) reinforced glulam with pultruded

kevlar and carbon FRPs, and stated that, "The test results indicate that reinforced members are less variable in strength, stiffness is enhanced from 11 to 50%, and moment capacity may be increased by 85-115%."

Abdel-Magid, Dagher, and Kimball (1994) reinforced lumber with carbon and kevlar with epoxy, and found that small amounts of reinforcement could increase strength and that carbon/epoxy performed better than kevlar/epoxy. Dagher, Kimball, and Abdel-Magid (1995) reinforced glulam beams with pultruded E-glass and carbon FRP, and discovered that 3% E-glass reinforcement could increase beam strength by about 50% and stiffness by about 20%. Plevris and Triantifillou (1995) discussed creep in FRP reinforced wood, and concluded that creep behavior of FRP reinforced wood was dominated by the creep of the wood. Sonti, et al. (1995) reinforced glulam with pultruded glass/vinylester FRP, and found that 3% reinforcement increased strength by 21% and stiffness by 17%. Dailey, et al. (1995) reinforced glulam with pultruded glass/phenolic-resorcinol FRP, and stated that, "Economic analysis indicates that replacement of the high grade wood in the tension lamination section of the beam with lower grade wood, with pultruded FRP equal to 1.5% to 3% of the total thickness of the beam, can result in savings of 25% in production costs."

While most work was successful in improving strength and stiffness of wood beams, the major problem was the bond strength and durability of the interface between the wood and the reinforcing material.

3 PILOT BEAM TESTING

3.1 Objective

The purpose of conducting this pilot test program was to obtain a qualitative analysis of the performance of the wetpreg reinforcing system that had been developed to date. Hopefully, pilot beam testing would provide valuable information in identifying problems with the reinforcing system. Problem areas could then be focused upon and potential solutions devised, leading to new materials, processes, and testing.

3.2 Introduction

Seven glulam beams were fabricated. Three beams were unreinforced, or controls. Four were reinforced with wetpreg at a 3.3% reinforcement ratio. Reinforcement ratio is defined as the cross-sectional area of reinforcement divided by the cross-sectional area of the wood above the reinforcement (see Figure 3.1 and Equation 3.1). Beams were tested in four point bending to ultimate failure. Load and deflection data were collected through failure. A non-linear computer model was also used to predict the load-deflection curve of the beams through failure.

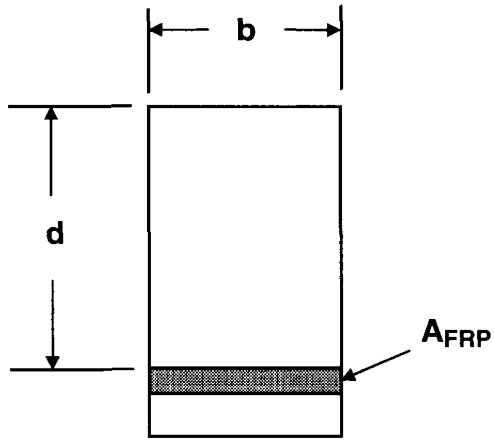


Figure 3.1: Reinforced Glulam Cross-Section

$$\rho = A_{FRP} / bd \qquad \text{(Eq. 3.1)}$$

where ρ = Reinforcement Ratio

A_{FRP} = Area of the FRP

b = Width of Section

d = Depth of Section to Reinforcement

3.3 Material Selection

3.3.1 Adhesives and Resins

The phenolic-resorcinol-formaldehyde wood laminating adhesive from Georgia Pacific (GP 4554/4242) was used as the matrix for the glass reinforcement. Acceptable shear strengths were obtained using this adhesive (see chapter 4).

3.3.2 Reinforcement

The wetpreg reinforcement was a unidirectional, E-glass, stitched fabric, with product designation U - 18 - 01 (obtained from Brunswick Technologies Inc.). Fabric weight was 18 oz/yd^2. A thin 1 oz/yd^2 polyester veil was present as backing.

The glass/resin content of the wetpreg was 50/50 by weight, or 69/31 by volume, at the time the wetpreg was applied to the glulam (i.e. in the wet state).

All wetpreg reinforced beams had a 3.3% reinforcement ratio. Thus for a beam of depth d = 16.0 cm (6.3 in), 5.3 mm (0.21 in) of reinforcement was required. From past use of our wetpreg, we knew that the final thickness after clamping and curing was 0.76 mm (0.030 in) for a single 18 oz/yd^2 ply. Seven plies of wetpreg reinforcement provided the 5.3 mm (0.21 in) thickness needed.

3.3.3 Wood

Eastern Hemlock 2x4's, No.2 and better visually graded, were used. Lumber was all 3.66 m (12 ft) lengths and was conditioned to 10-12% moisture content (MC) prior to gluing. The modulus of elasticity (MOE) of the lumber had been determined by a Metriguard dynamic MOE tester. The lumber used in the glulams had MOEs of 7.65 to 9.79 GPa (1.11 to 1.42 Msi).

3.4 Beam Design

A description of the pilot glulam beams is given in Table 3.1. "C" designates a control beam, and "R3" designates an E-glass reinforced beam with a 3.3% reinforcement ratio.

Table 3.1: Description of Pilot Glulam Beams

Beam Number	Beam Type	Notes:
C-1	Control	offset laminations
C-2	Control	offset laminations
C-3	Control	straight laminations
R3-1	Reinforced	3.3% wetpreg
R3-2	Reinforced	3.3% wetpreg
R3-3	Reinforced	3.3% wetpreg
R3-4	Reinforced	3.3% wetpreg

Beams were 3.66 m (12 ft) long, 17.8 cm (7 in) deep, and 8.64 cm (3.4 in) wide. Beams had four "full size" laminations, 3.56 cm (1.4 in) thick, on the compression side. To maintain a depth of 17.8 cm (7 in) for all beams, the last 3.56 cm (1.4 in) of beam depth was fabricated differently for the two beam types. The unreinforced control beams simply had a full lamination on the tension side. The reinforced beams had a "half lamination" of 1.78 cm (0.7 in) thickness, followed by 5.3 mm (0.21 in) of glass fabric, followed by a 1.27 cm (0.5 in) wood bumperstrip bonded together on the tension side of the beam. See Figure 3.2 for beam cross-sections. The "core" laminations used lumber of relatively low MOEs of 7.65 to 8.55 GPa (1.11 to 1.24 Msi). The compression laminations, tension

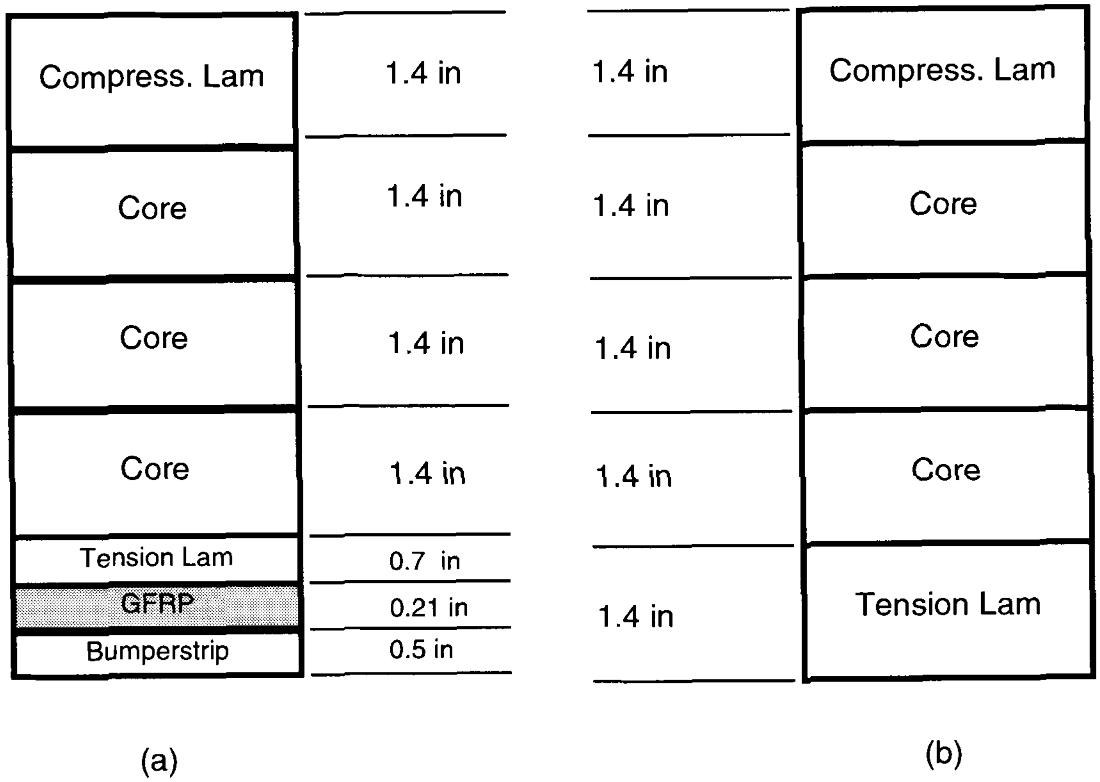


Figure 3.2: Pilot Beam Cross-Sections
(a) GFRP Reinforced (b) Unreinforced or Control

laminations, and bumperlams were made of lumber of higher MOEs than that used in the core, and was 8.27 to 9.79 GPa (1.20 to 1.42 Msi). See Figures 3.3 and 3.4 for beam layups.

The primary purpose of the bumperstrip would be to prevent damage to the reinforcement during handling/shipping and also protection from the environment and fire. A thin bumperstrip, rather than a full lamination, was used with the reinforced beams because the bumperstrip is expected to fail well before ultimate failure of the beam. The reinforcement is more effective when placed at the extreme tension fiber of the beam.

ASTM D198 states that, for beams intended for evaluation of flexural properties, one-half the shear span to depth ratio be 5:1 to 12:1. The ratio of half the shear span to depth was 6.9 for these test beams.

3.5 Beam Fabrication

All beams were fabricated at the University of Maine. Control beams had all five laminations glued and clamped at one time. Laminations were all full-length. Reinforced beams were fabricated such that four laminations were glued and clamped. Reinforced beams were removed from the clamps, and reinforcement and bumperlam were applied. The beams were clamped again. The amount of time needed to apply and clamp the wetpreg reinforcement required that all other gluelines be previously cured. This step-wise fabrication process is not believed to have detrimental effects on beam performance.

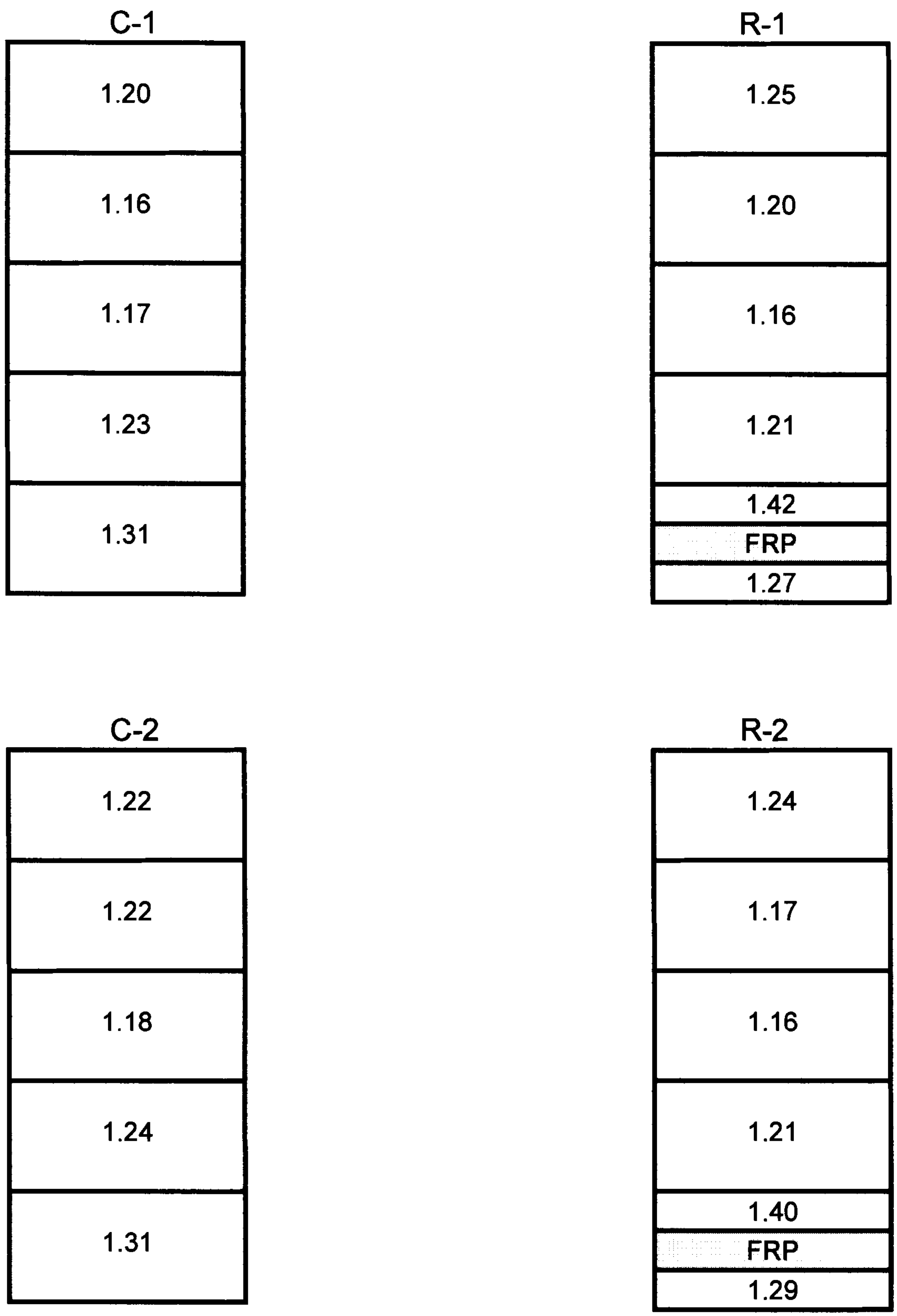


Figure 3.3: MOE Map of Pilot Beams (in million pounds per square inch, Msi)

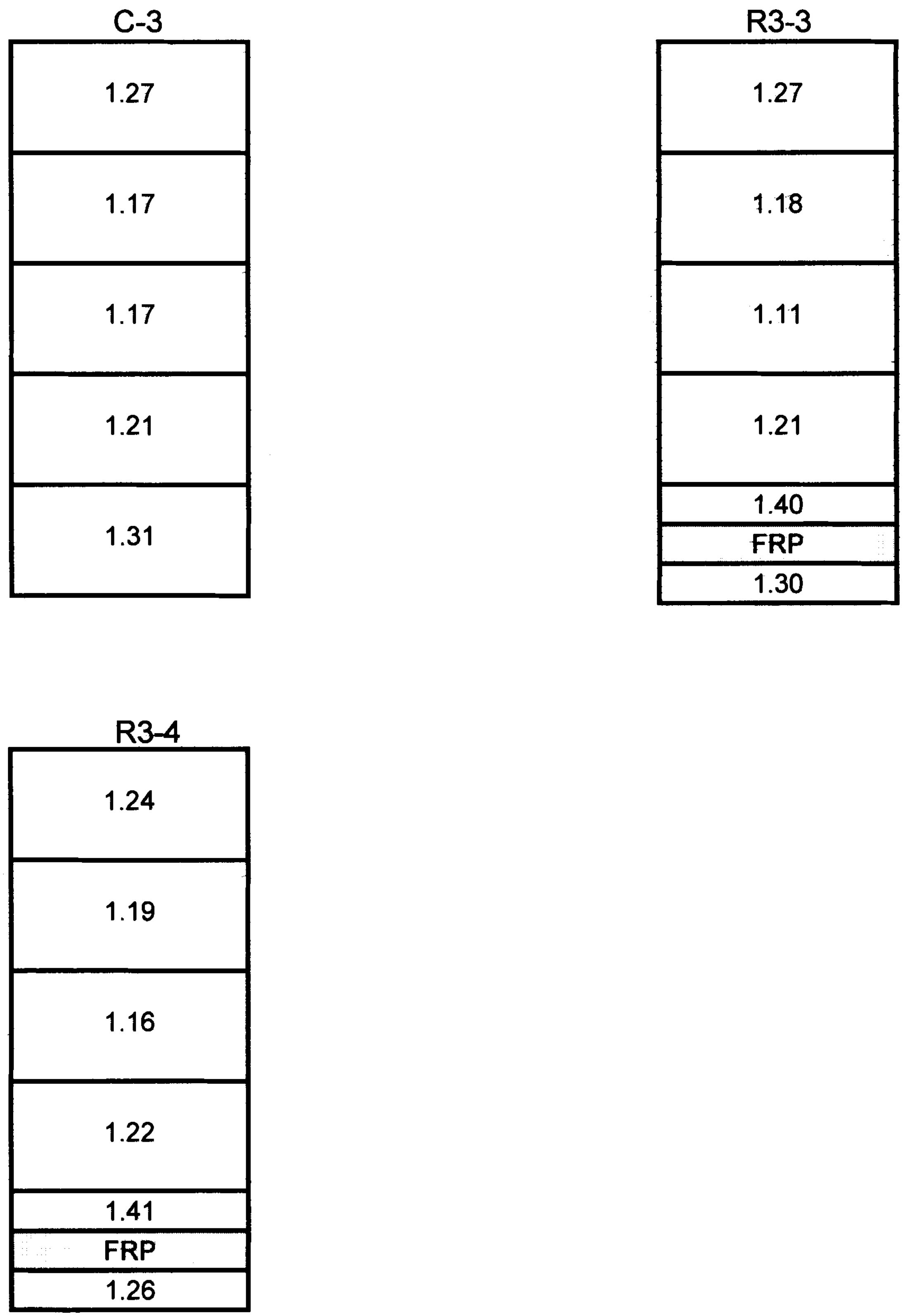


Figure 3.4: MOE Map of Pilot Beams (in million pounds per square inch, Msi)

3.5.1 Adhesive Application

An adhesive spread rate of 3.8 N/m^2 (80 lbs/1000 ft^2) was used between wood laminations. The resin in the wetpreg served as both matrix for the glass and as adhesive for bonding the FRP and wood. No adhesive was applied to the face of the tension lamination or the bumperstrip. Tests (see Chapter 4) have shown that the "squeeze-out" of resin from the wetpreg under glulam claming pressures provides adequate bonding, without having to apply adhesive directly to the wood.

3.5.2 Open/Closed Time

The amount of time that a glue-line or wet resin is exposed to the air is called "open time". The open time was not measured during fabrication, but short open times of five to ten minutes were used. This open time was the time it took to lay-up the seven plies of wetpreg reinforcement. Closed time is the time that a glue-line is covered but not yet under pressure. Closed time for beams was five to ten minutes.

3.5.3 Clamping

Clamping pressures used in the manufacturing of softwood glulams are typically 690-1040 kPa (100-150 psi). A mimimum clamping time of 8 hours is typically used as well.

Beams were clamped at 690 kPa (100 psi) for approximately 22 hours. The clamping system used was a series of steel frames with hydraulic cylinders. Frames were 61 cm (2 ft) on center. A 3.66 m (12 ft) long, 5.1 cm by 10.2 cm by 6.4 mm (2 x 4 x 1/4 in) steel tube was placed below and above the beam to ensure uniform pressure distribution. See Figure 3.5 for a view of the clamping system.

Only "vertical" clamping was applied to the wide face of the laminations. It is also common practice, however, to apply pressure on the side of the laminations. This lateral pressure is needed to produce a more uniform cross-section. A uniform cross-section provides better transfer of stresses between laminations. Future beams in this project were laterally clamped (Chapter 5).

3.6 Experimental Test Setup

The beams were tested in four point bending. The beams were 3.66 m (12 ft) long with a clear span of 3.35 m (11 ft). The distance between the center load heads was 91.4 cm (3 ft). Lateral bracing was provided at a distance of 1.07 m (3.5 ft) from each support.

The beams were actually loaded "upside down" with the tension face on top and the compression face on bottom. The actuator is more stable when retracting upwards than when extending downwards. A sketch of the test setup is shown in Figure 3.6.

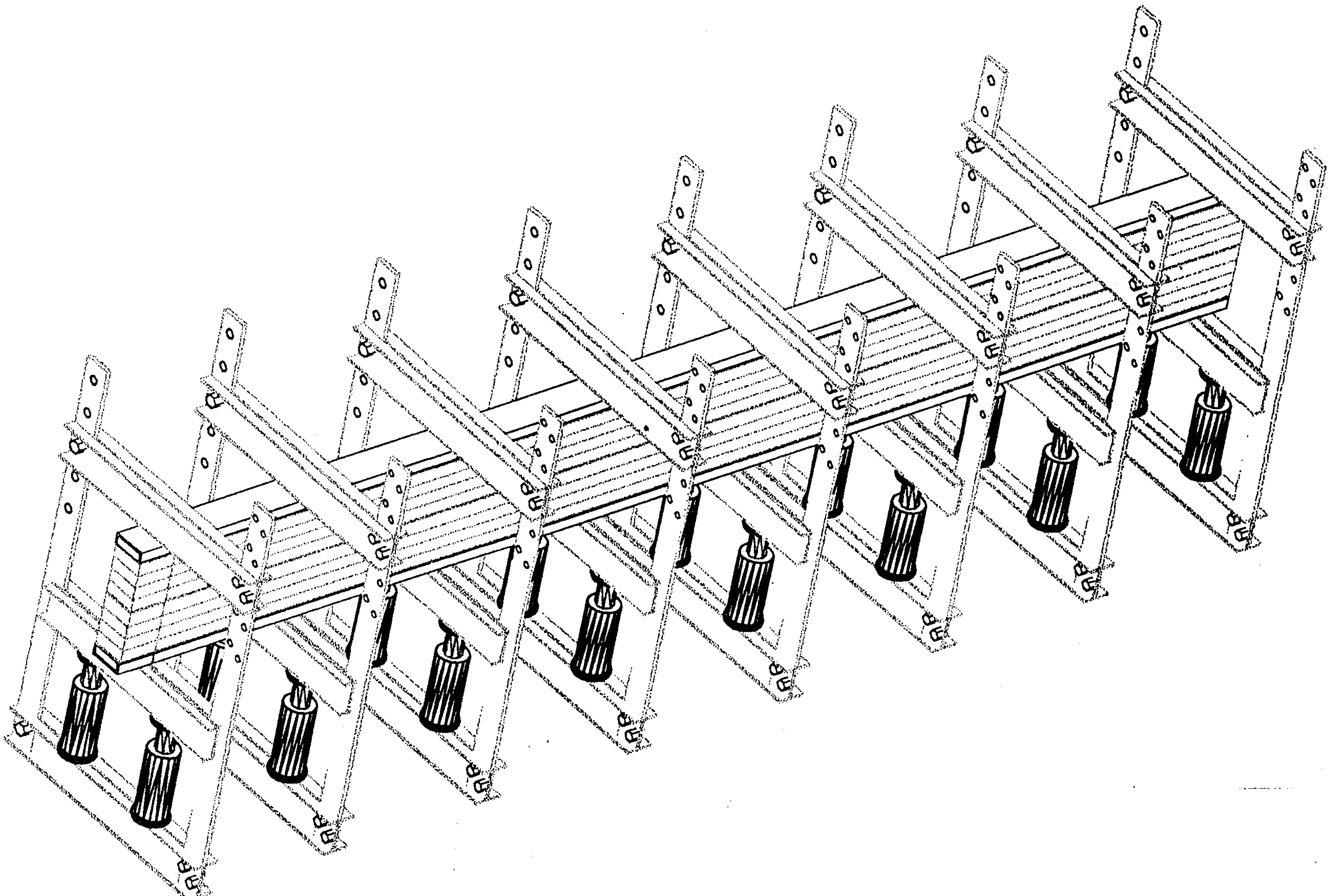


Figure 3.5: Glulam Beam Clamping System at the University of Maine

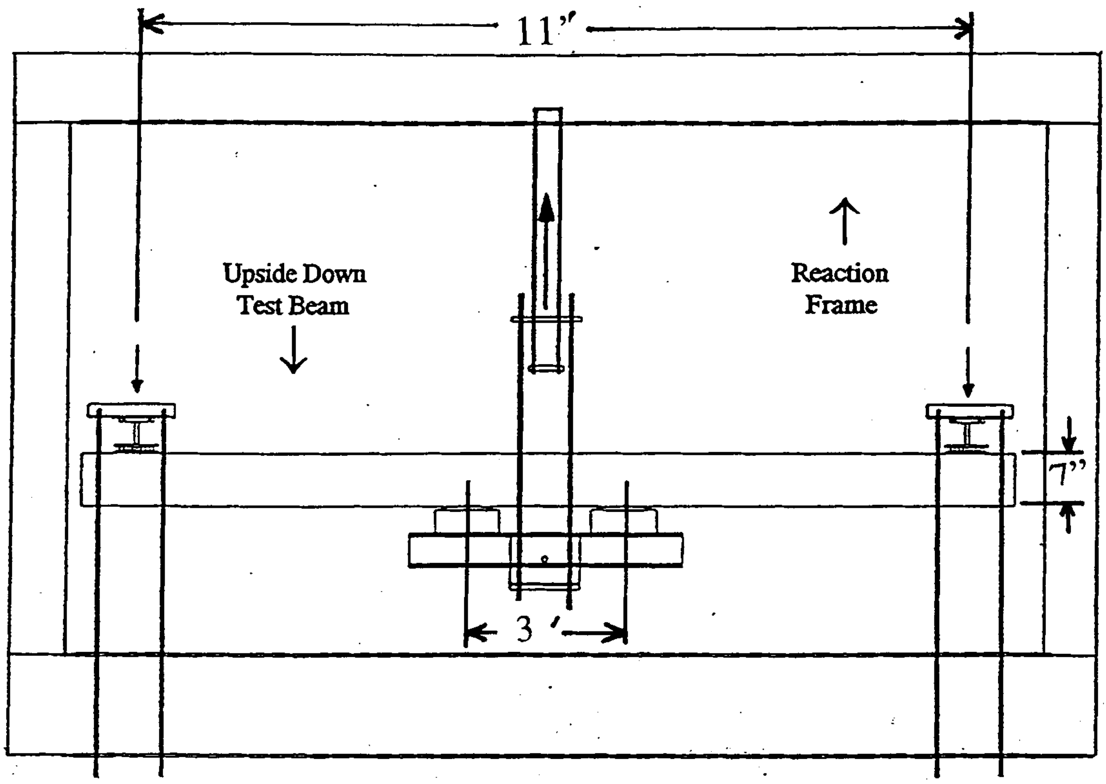


Figure 3.6: Elevation View of Test Setup: Test Beam, Load Head, Supports.

Figure 3.7: Photograph of Test Setup: Test Beam, Supports, Lateral Bracing.

Instrumentation included: 1) external load cell at midspan, 2) external LVDT at midspan, 3) 22 kip MTS actuator with built in displacement transducer and load cell. A photograph of the test setup is given in Figure 3.7.

3.7 Experimental Results

Testing followed ASTM D198-94. The test was conducted in load-control. Load rate was selected such that the expected time to failure was ten minutes, with six and twenty minutes being the lower and upper bounds.

Results of beam testing are presented using data from the load cell, LVDT, and MTS readings. MOE was determined in the elastic region. Full load deflection curves were plotted.

3.7.1 Determination of Initial Beam MOE

The modulus of elasticity (MOE) of the beams was determined by using gross section properties and load deflection data during initial loading. An arbitrary load of about 8.896 kN (2000 lbs) and the corresponding deflection was chosen to determine the MOE. The following equation, from ASTM D198-94 based on four point bending and linear elastic behavior, gives:

$$MOE = [(Pa) / (24\Delta I)] * (3L^2 - 4a^2) \qquad \text{Eq. 3.2}$$

Where MOE = bending modulus of elasticity, based on gross section

P = load (1/2 of the actuator test load)

a = 1/2 of the shear span (48 inches)

Δ = deflection at midspan

L = span length of beam (132 inches)

I = moment of inertia (= $bh^3/12$ for rectangular section)

b = width of the beam (3.4 inches)

h = height of the beam (7.0 inches)

3.7.2 Load Deflection Data

Maximum load, maximum displacement, modulus of rupture (MOR), and initial MOE of the beams are shown in Table 3.2. MOR was based on gross section properties. The moisture content of all beams when tested was 9-11% with a mean of 10%.

Load was determined from an average of the external load cell and MTS load cell data. Deflection was determined from an average of LVDT data and MTS displacement data. Two load cells and LVDTs were used so that the readings of one could be checked against the other to make sure that no erroneous data readings occurred. In all cases, load and deflection readings for the pair of instruments were very similar, so the average was used. Load deflection curves for the beams are given in Figure 3.8.

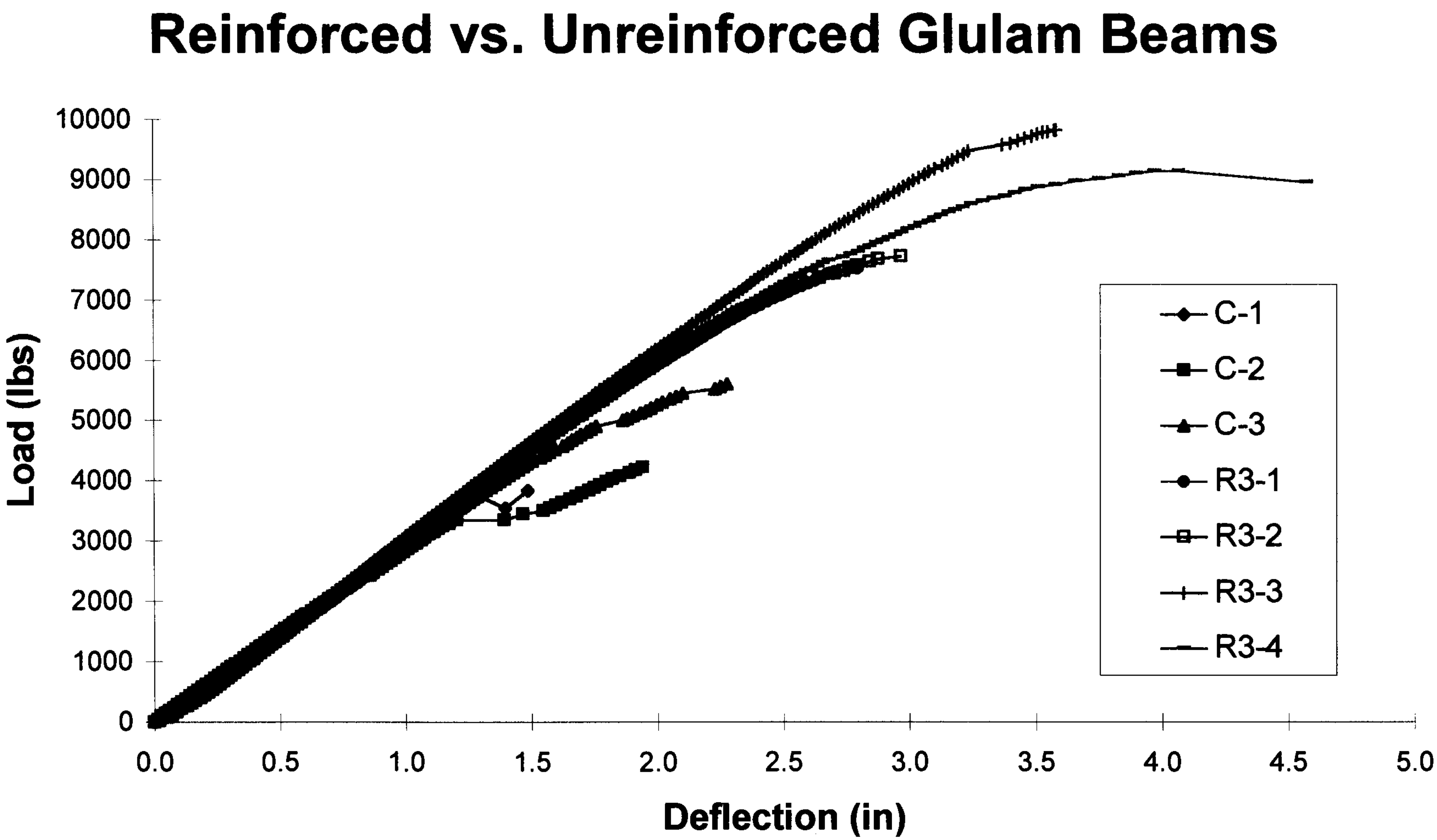


Figure 3.8: Load-Deflection Curves for Control and Wetpreg Reinforced Beams

Table 3.2: Load Deflection Summary

Beam Designation	Max. Load kN	(lbs)	MOR MPa	(psi)	Defl. at Failure cm	(in)	Initial MOE GPa	(Msi)
C-1	17.2	(3860)	23.0	(3340)	3.89	(1.53)	8.62	(1.25)
C-2	18.8	(4230)	25.2	(3660)	4.83	(1.90)	9.17	(1.33)
C-3	24.9	(5600)	33.4	(4840)	5.77	(2.27)	9.03	(1.31)
R3-1	33.5	(7530)*	44.9	(6510)	7.09	(2.79)	8.96	(1.30)
R3-2	34.3	(7720)*	46.0	(6670)	7.54	(2.97)	8.83	(1.28)
R3-3	43.7	(9830)	58.6	(8500)	9.09	(3.58)	9.17	(1.33)
R3-4	40.7	(9150)	54.5	(7910)	11.6	(4.57)	8.83	(1.28)

* Beams failed in lateral-torsional buckling.

Table 3.3 summarizes comparison of wetpreg reinforced beams and control beams, based on average values of the three controls and the four wetpreg beams. Wetpreg reinforced beam MORs were 88% greater than the controls on average, while their MOEs were comparable.

Table 3.3: Summary of Pilot Test Results

	Control	3% FRP Reinforcement	Increase (%)
Number of Samples	3	4	-
Mean Ultimate Load kN (lbs)	20.3 (4560)	38.1 (8560)	88 %
Mean MOR MPa (psi)	27.2 (3940)	51.0 (7400)	88 %
Mean Initial MOE GPa (Msi)	8.96 (1.30)	8.96 (1.30)	0 %
Mean Defl. at Failure cm (in)	4.83 (1.90)	8.84 (3.48)	-

The comparison made in Table 3.3 may not be the best representation of the effect of wetpreg reinforcement since the mean values of the controls were based on one "good" beam and two "bad" beams having offset laminations, while the average values of the reinforced beams were based on two "good" beams and two "bad" beams that had failed in lateral buckling. The best comparison may be to compare the "best" reinforced beam and the "best" control beam. Control beam C-3 failed at 24.9 kN (5.6 kips), and wetpreg reinforced R3-3 failed at 43.7 kN (9.83 kips). This was a mean MOR increase of 79%. MOEs were 9.0 Gpa (1.31 Msi) and 9.1 Gpa (1.33 Msi), which was an increase of 1.5%. See Figure 3.9 for a comparison of load deflection curves for beams C-3 and R3-3.

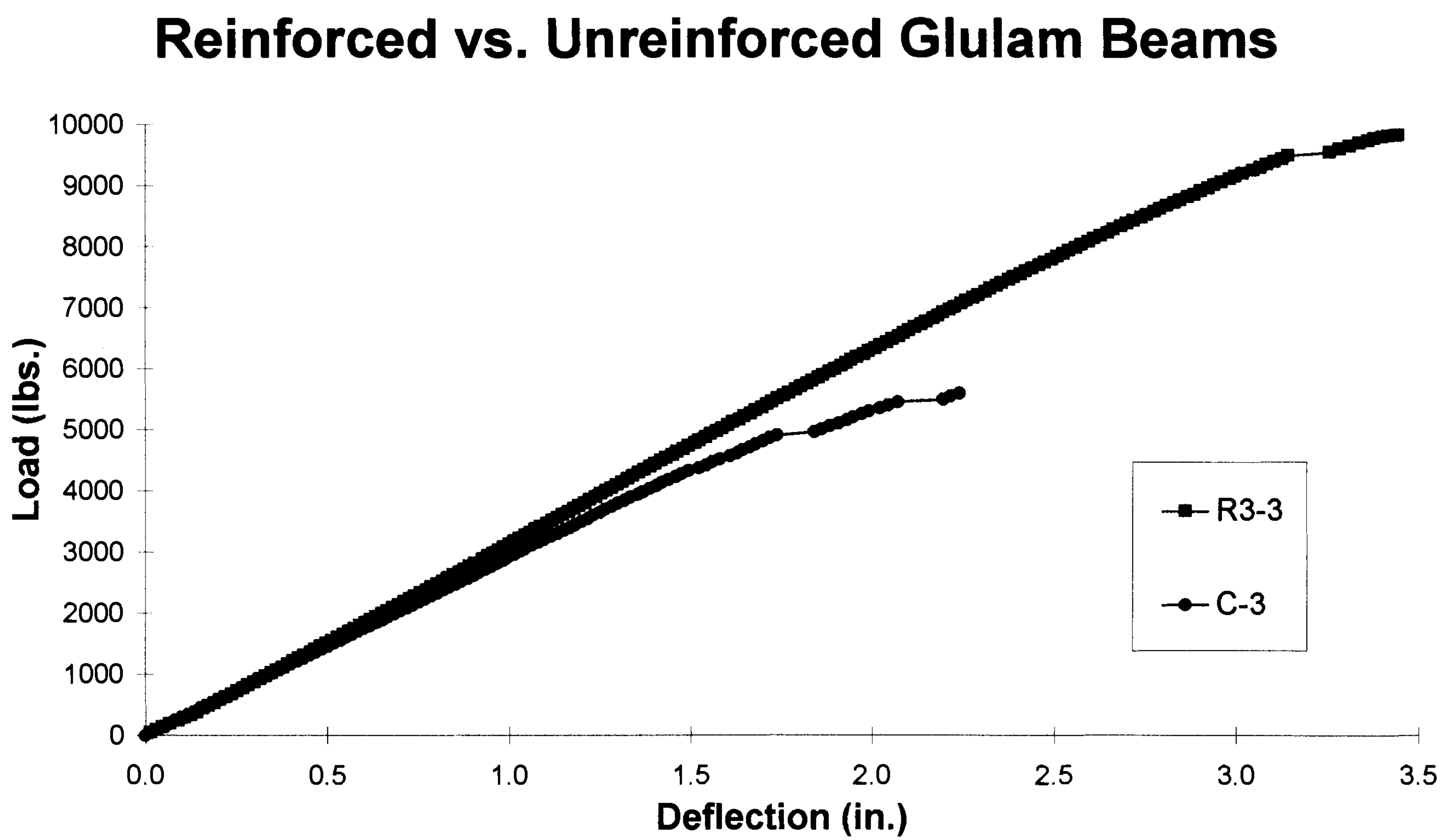


Figure 3.9: Load-Deflection Curves Comparing the "Best" Reinforced and Unreinforced Beams

3.7.3 Lateral Torsional Buckling Failures

Until this pilot test, no glulam beam tested at the University of Maine had failed by lateral torsional buckling. Two of the four reinforced pilot beams failed by lateral torsional buckling. The lateral bracing system had never before been tested, but was found to be insufficient to prevent this type of failure.

It is interesting to note that ASTM D198 states that beams with a depth to width ratio of three or more are "subject to lateral instability" and require lateral bracing. The beams in this test had a depth to width ratio of 2.0. The ASTM D198 is intended for unreinforced glulam, but we assumed that these specifications applied to reinforced glulam as well. The ASTM D198 provision of lateral bracing may need to be modified for reinforced glulam, which have higher compression stresses than unreinforced beams of a given size, thereby increasing the possibility of lateral torsional buckling.

Lateral instability of some beams was affected by the non-uniformity of cross-section caused by a lack of lateral clamping during beam fabrication. This caused off-axis loading on wood fibers in some laminations and enhanced the likelihood of lateral torsional buckling.

4 MATERIAL AND PROCESS REFINEMENT

4.1 Objective

The purpose of conducting material and processes evaluation is to determine the most suitable fiber reinforcement, resin, open time, and clamping pressure for application with glulam.

4.2 Introduction

Six types of E-glass fabrics were evaluated. Two types of resins were evaluated: a phenolic-resorcinol-formaldehyde (PRF) adhesive and an acid-cure phenolic resin. Effects of methanol and caustic additions to the PRF adhesive were also evaluated. Shear testing, cyclic delamination testing, and tension testing were performed.

The minimum shear strength required for wood-wood and for FRP-wood bonds was 7.17 MPa (1040 psi). This is the minimum shear strength allowed by AITC 200-92 for Hem-Fir with a MC of 12% or less. Also, a maximum glue-line failure of 20% was specified by AITC 200-92 for wood-wood bonds, and was extended to FRP-wood and FRP-FRP bonds. Of course, higher shear strengths and lower amounts of glue-line failure were desired.

For cyclic delamination testing, 10% delamination after two cycles is the maximum allowed by AITC 200-92. Since the FRP-wood bond is critical to

reinforced beam performance, the 10% delamination criteria was used but was extended to be the maximum allowable for several cycles. In some tests 3 cycles were performed and in others 5 cycles were performed (after 2 cycles it was noted that practically no change occured in the cyclic delamination samples, as delamination occurred during initial swelling and shrinking).

4.3 Material Selection

4.3.1 Wetpreg Reinforcement

Reinforcement was achieved by creating a fiber reinforced polymer (FRP) composite by a "wetpreg" process. Wetpreg is a more controlled version of hand layup. A fabric is run through a resin bath, between rollers, which impregnate the fabric. The wet fabric is "layed-up" and pressure is applied. The advantages of this process are that the good control of resin/glass content can be achieved, by adjusting the distance between the rollers, and that the resin/glass content is consistent for all reinforcement plies. The wetpreg process is used extensively in the boat industry. See Figure 4.1 for a photograph of the impregnating machine. See Figure 4.2 for a picture of E-glass fabric being run through the impregnator, being wet-out.

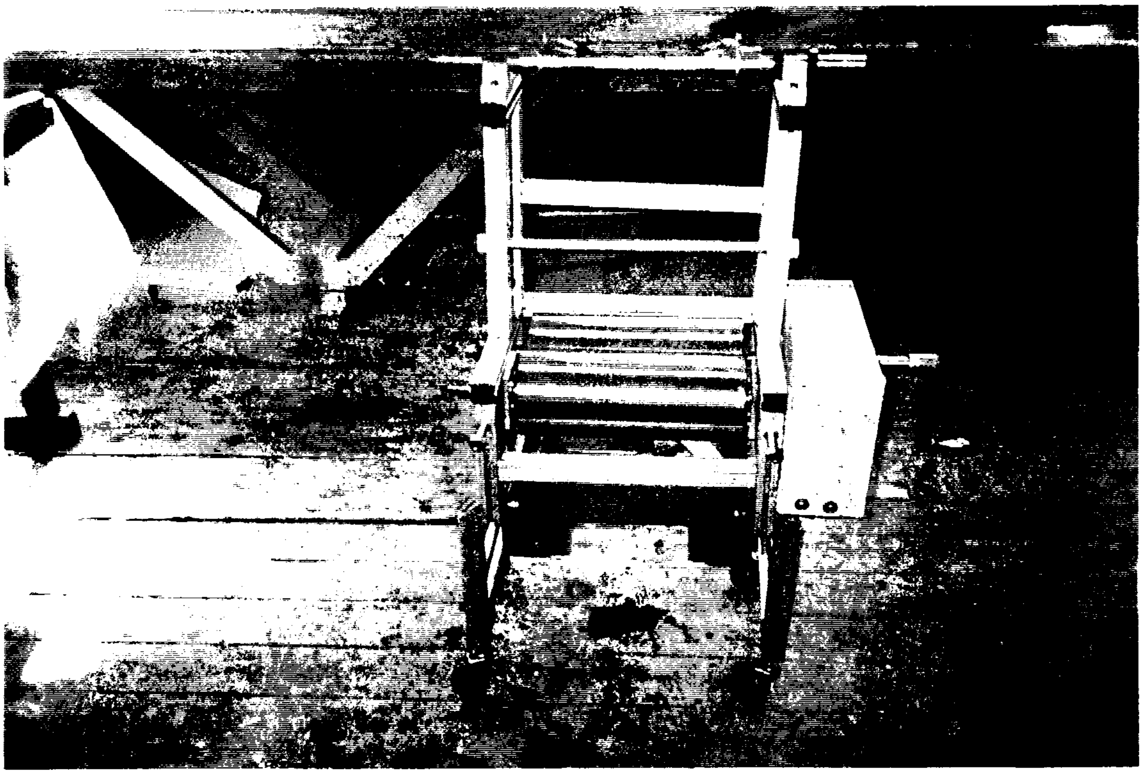


Figure 4.1: Picture of “Impregnator”

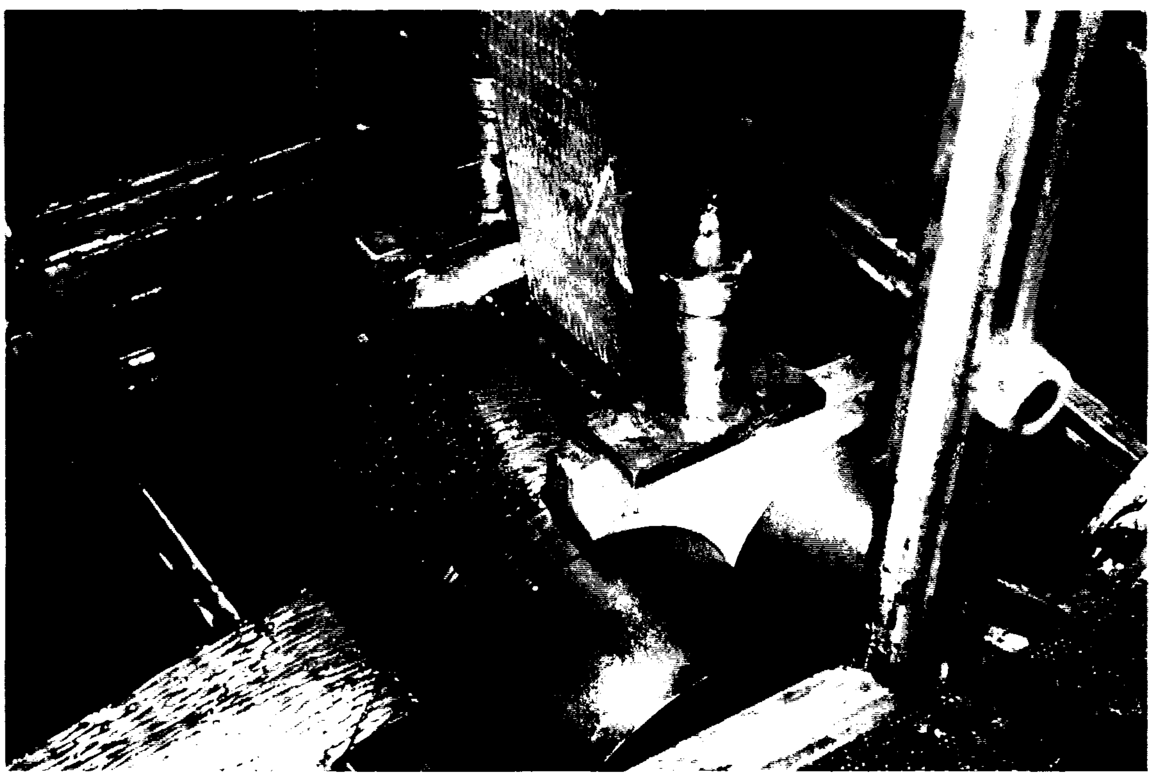


Figure 4.2: Picture of E-glass Fabric Being Wet-Out Through Impregnator

4.3.1.1 Fabric Description

There are two general types of fabrics tested: unidirectional stitched fabrics and unidirectional weave fabrics. Unidirectional means that all the fibers are oriented in the same direction, running the length of the fabric.

For stitched fabrics, the fibers are stitched to a backing piece. Backing pieces used were a thin polyester veil and a heavier chopped glass mat. For the U-72-10 fabric, short, glass fibers were placed in the out-of-plane direction to the fabric, hence called “z” fibers, with the intention of improving fabric shear strength.

For unidirectional weave fabrics, the fibers are woven over transverse fibers. The fibers are then either stitched together, as in the VEW 260 A fabric, or passed over a hot-plate which melts a chemical binder that coats the transverse fibers, thereby binding the fibers together, as in the VEW 260 B and C fabrics. The unidirectional, E-glass fabrics tested are shown in Table 4.1.

Table 4.1: Unidirectional E-glass Fabrics Tested

Fabric Designation	Weight (oz/yd^2)	Backing Type / Additional Comments	Sizing
U 72 - 10	72	10 oz/yd^2 glass chopped fiber mat	Standard
U 72 - 10 Z	72	10 oz/yd^2 glass chopped fiber mat w/some "z" fibers through the thickness	Standard
U 18 - 01	18	1 oz/yd^2 polyester veil	Standard
VEW 260 A	26	None / uni-weave with stitching	Standard
VEW 260 B	26	None / uni-weave with binding	Standard
VEW 260 C	26	None / uni-weave with binding	Phenolic

The "sizing" referred to in Table 4.1 is a chemical coating on the glass fibers. The sizing acts as a lubricant to protect the fibers, especially during handling. The sizing also aids in bonding the polymer matrix to the fibers, by providing active sites for chemical bonding. The chemistry of the sizing can be altered to enhance bonding with specific polymers. The "standard" sizing has active sites for bonding with epoxies and polyesters. The "phenolic" sizing has active sites for bonding with phenolics. Information about sizing chemical formulations is proprietary information.

The stitched fabrics (U 72 -10, U 72 - 10 Z, and U 18 - 01) were obtained from Brunswick Technologies Inc. The unidirectional weave fabrics (VEW 260s) were obtained from Advanced Textiles Inc. See Figure 4.3 for a photograph of the U - 18 - 01 fabric. See Figure 4.4 for a photograph of the U - 72 -10 fabric. See Figure 4.5 for a photograph of the VEW 260 B fabric (which looks the same as the VEW 260 C fabric). See Figure 4.6 for a photograph of the VEW 260 B fabric after wet-out and curing of GP 5022/4822 and GP 4242/4554 resins.

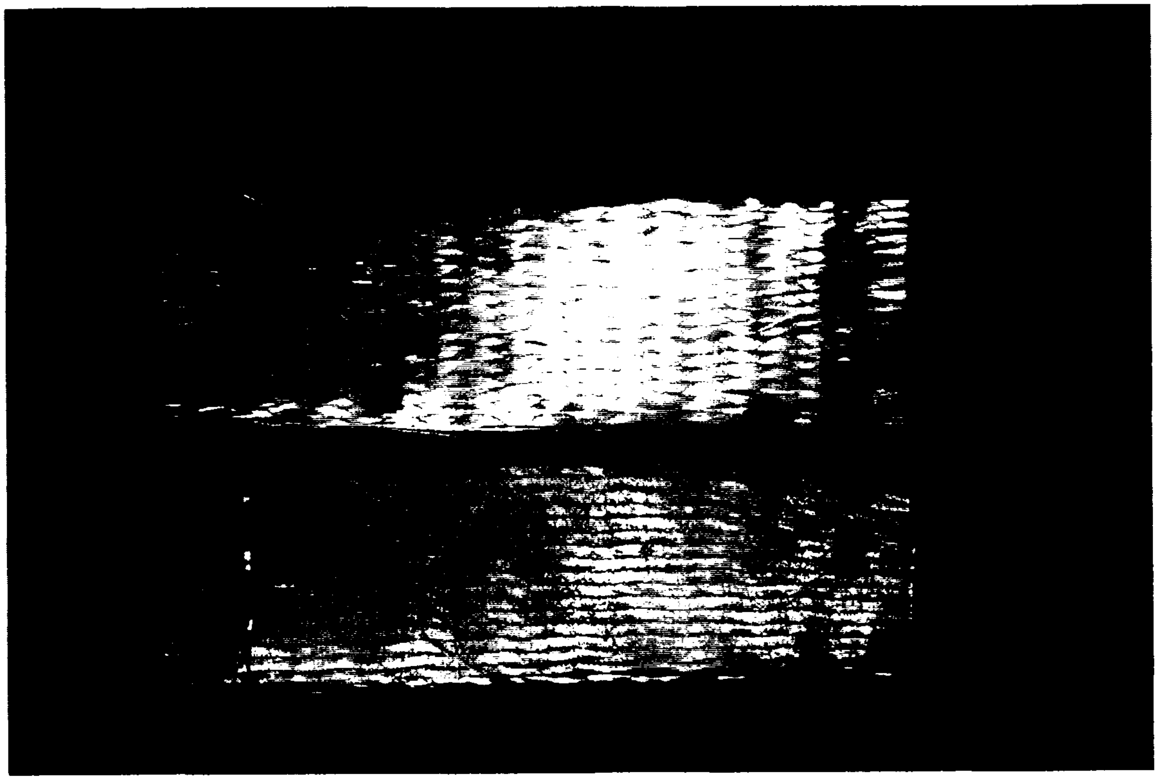


Figure 4.3: U-18-01 Fabric. (top) Fibers (bottom) Polyester Backing.

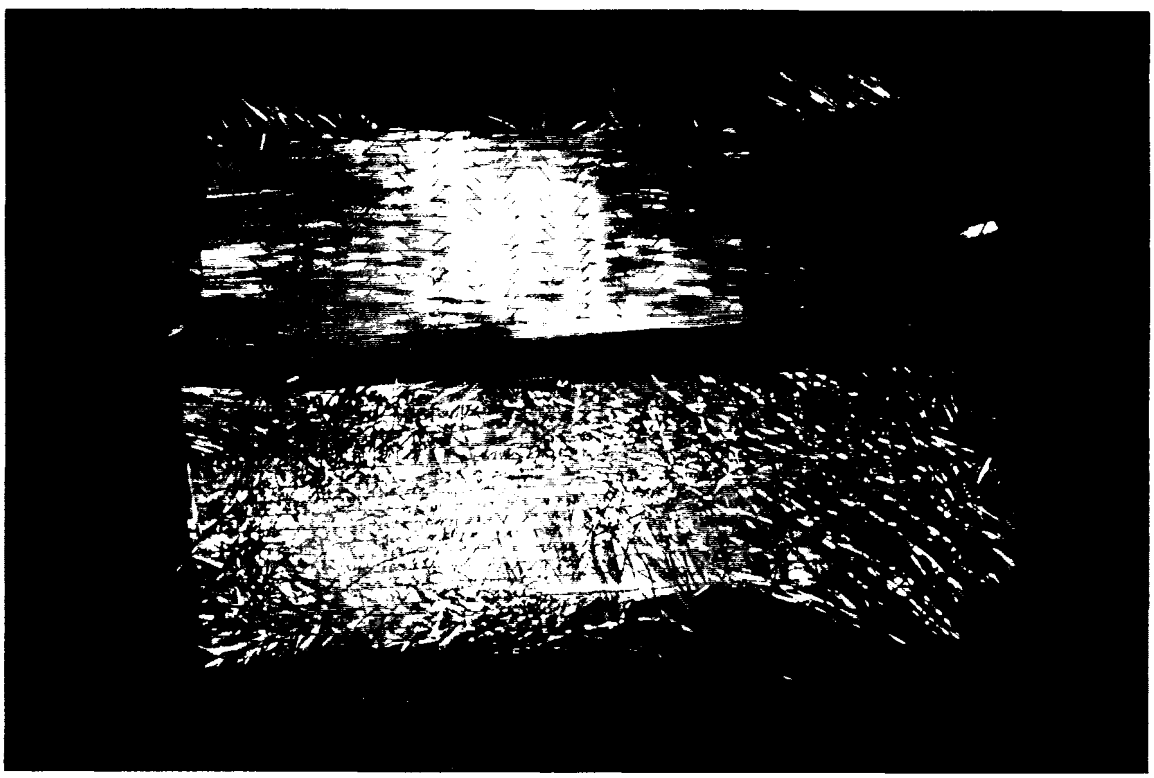


Figure 4.4: U-72-10 Fabric. (top) Fibers (bottom) Chopped Mat Backing.

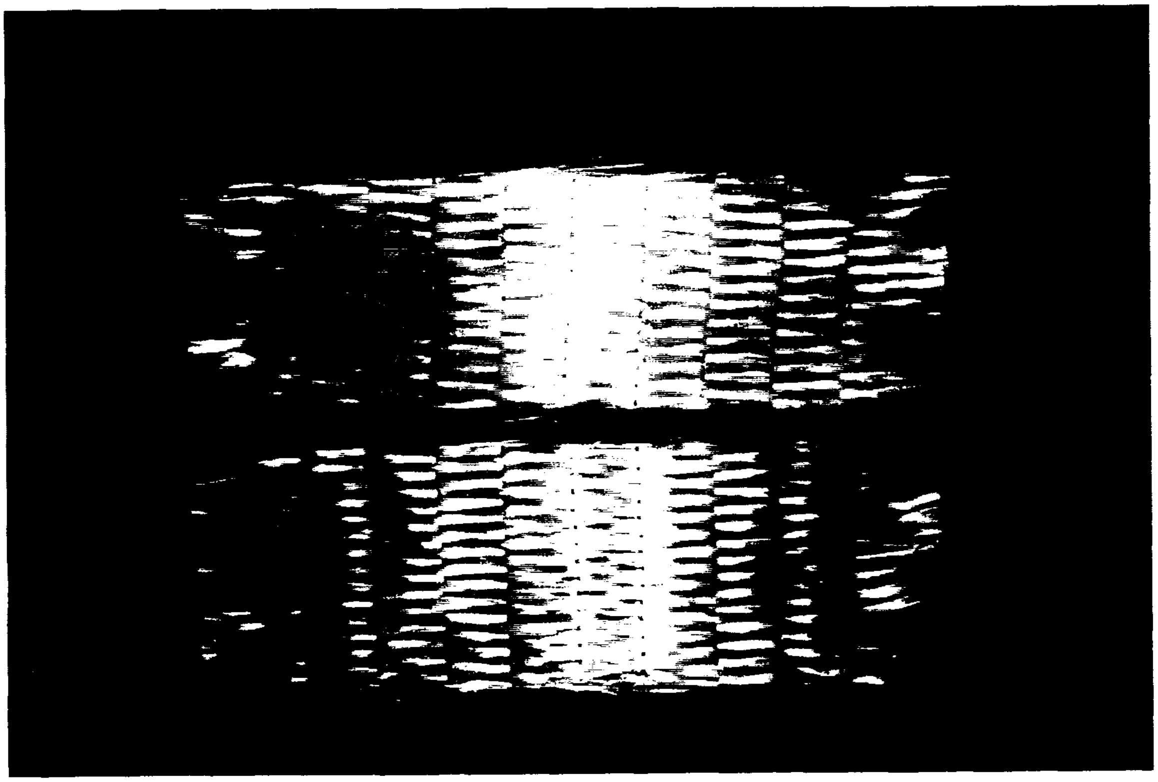


Figure 4.5: Picture of both sides of VEW 260 B Fabric.

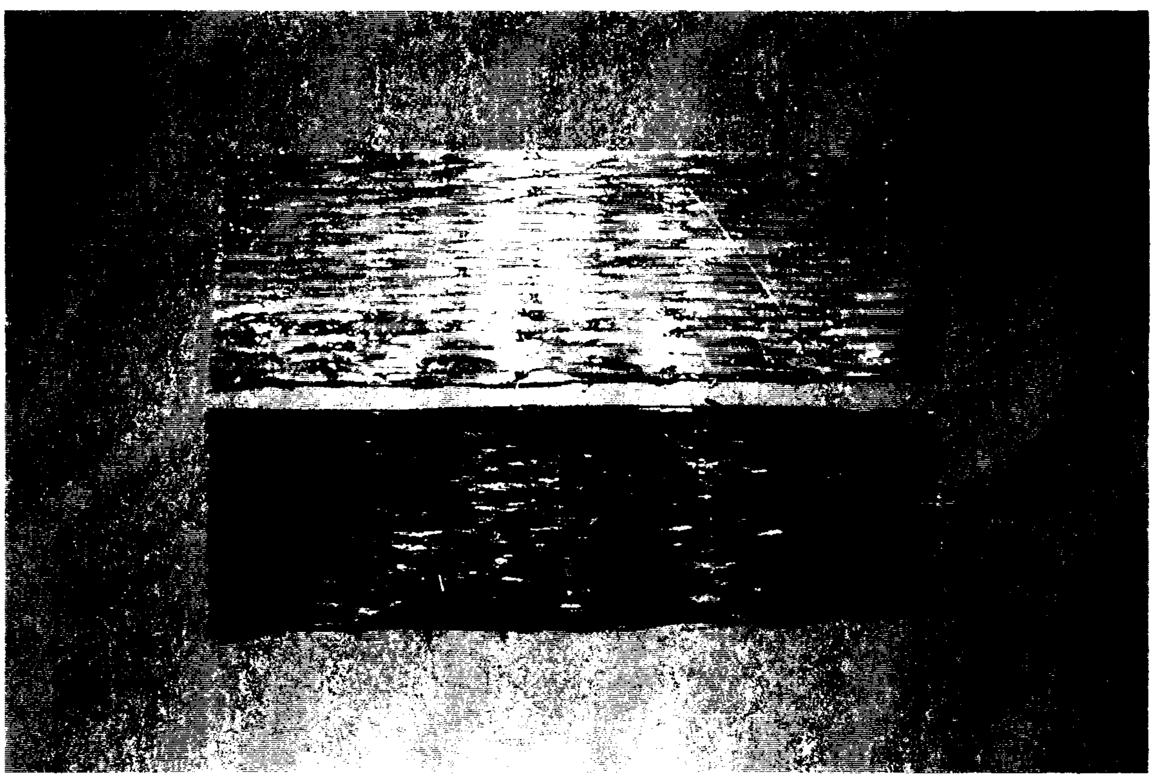


Figure 4.6: Picture of VEW 260 B Fabric with (top) GP 5022/4822 and (bottom) GP 4242/4554

4.3.1.2 Adhesives and Resins

Two types of Georgia Pacific (GP) resins were evaluated. The GP 4242/4554 RESORSABOND® slurry adhesive for laminating softwoods is a phenolic-resorcinol-formaldehyde (PRF). The GP 5022/4822 RESI-SET® Industrial Resin System for fiber reinforced plastics is an acid-cure phenolic resin. Both systems were used as matrix for fiber reinforcement.

The GP 4242/4554 is a standard wood laminating adhesive. It was known to bond wood very well, but it was unknown if it could bond glass to wood or if it could be used as a matrix. The methanol and caustic additions were suggested by GP to reduce adhesive viscosity, to achieve better penetration and fiber wet-out, as well as modifying the curing reactions. The methanol had little effect on the useful pot life (or gel time) of the adhesive, but the caustic reduced the pot life from about 50 to 15 minutes.

The GP 5022/4822 is a "bulk" resin designed specifically for use with glass fibers. It was expected that this resin would perform better than the 4242/4554 as a matrix, but it was unknown if it could bond glass to wood. The 4822 catalyst is comprised of two parts, 4822 A and 4822 B. The 4822 A catalyst is a fast acting curing agent, while the 4822 B catalyst is a slower, long acting agent. The "A and B" catalyst components were combined in equal amounts, and their total was added as 12 parts per hundred by weight to the 5022 resin.

4.3.2 Wood

4.3.2.1 Species and Grade

Eastern Hemlock was determined to be a suitable softwood for use in glulam production in Maine (Lanpher, 1995) and was the only species evaluated and tested in this project. Lumber used was all No. 2 and better visually graded 2x4's, conditioned to 10 - 12% moisture content (MC).

4.3.2.2 Moisture Content

The wood used to fabricate all shear and delamination samples was conditioned at 65% relative humidity and 27°C prior to fabrication. A resistance type moisture meter was used to measure moisture contents of wood used in each test sample. The range of moisture contents was tight, being 9-11%, and being 10% on average. Following fabrication, test samples were placed inside the conditioning chamber to maintain constant moisture content.

4.4 Test Methods

The following tests were conducted to evaluate the suitability of the various fabrics and resins used.

- ASTM D 905 - 94 Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading
- ASTM D 1101 - 92 Standard Test Method for Integrity of Glue Joints in Structural Laminated Wood Products for Exterior Use
- ASTM D 2344 - 84 Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method
- ASTM D 3039 - 93 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
- ASTM D 2584 - 68 Standard Test Method for Ignition Loss of Cured Reinforced Resins.

4.5 Organization of Test Results

Four different ASTM tests were used to evaluate material properties. Shear testing is discussed first and includes evaluation of wood-wood, FRP-wood, and FRP-FRP bonds by following ASTM D 905 as well as evaluation of interlaminar bonds by following ASTM D 2344. Bond durability testing is discussed next and involves cyclic delamination tests following Test Method B of ASTM D 1101-92. Tensile strength and stiffness are discussed last and follows ASTM D 3039.

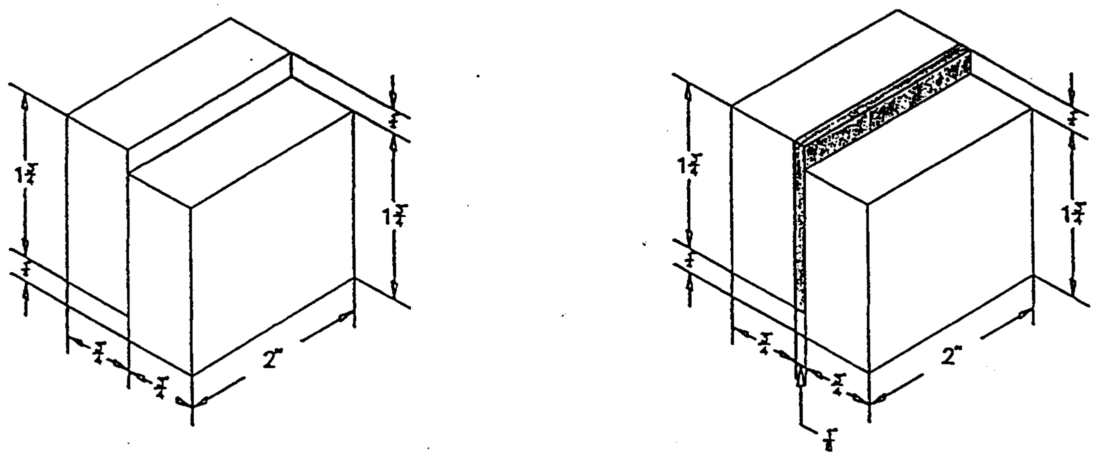
Each section that follows focuses on one of the three types of tests: shear, cyclic delamination, and tensile. In each section test parameters, fabrication details, results, and conclusions will be presented, in that order.

4.6 Shear Testing

4.6.1 Stitched Fabrics - Shear Blocks

Shear testing was conducted according to ASTM D 905 - 94 Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading. See Figure 4.7 for shear block drawings. See Figure 4.8 for a sketch of the shear tool and Figure 4.9 for a photograph of a shear block in the shear tool.

For reinforcement, all fabrics were run between impregnating rollers such that the pre-cured composite had a glass/resin ratio of 50% glass/50% resin by weight or 69% glass/31% resin by volume. The post-cured glass/resin ratio was not determined. It is known, however, that water and solvents are lost during resin curing as well as resin squeeze-out during clamping. The estimated post cured glass/resin content should be about 72% glass/28% resin by weight, or 54% glass/46% resin by volume, based on ignition loss tests performed on similar material.



(a) (b)

Figure 4.7: Sketches of (a) Wood-Wood Shear Specimen and of (b) Wood-FRP Shear Specimen

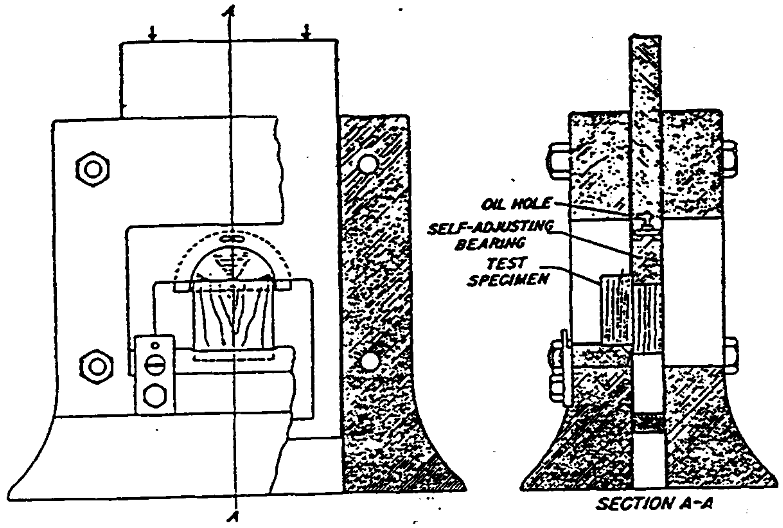


Figure 4.8: Shear Tool (from ASTM D 905)

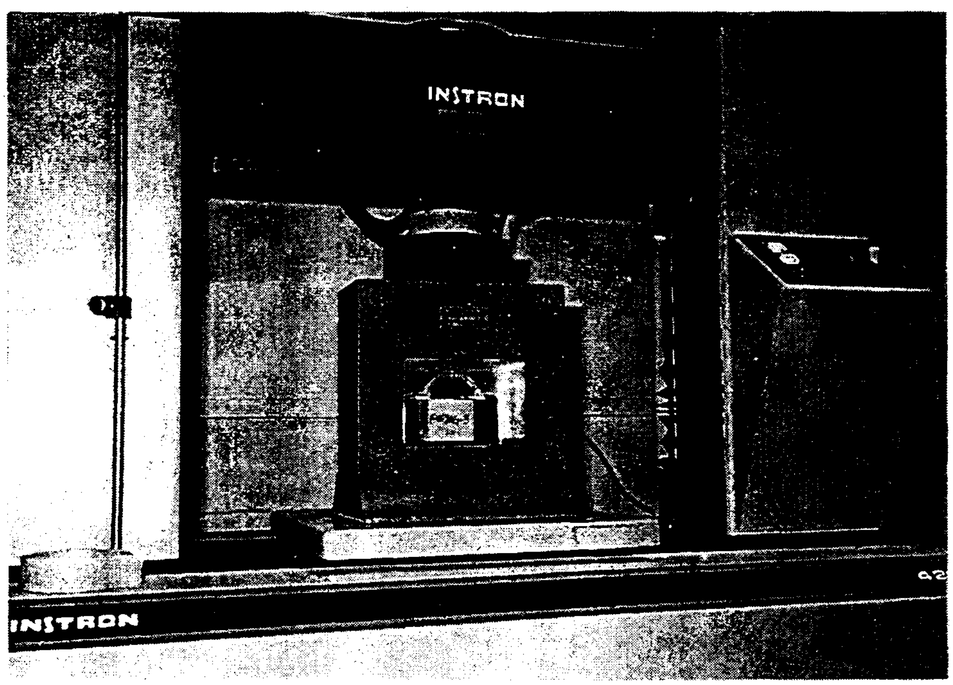


Figure 4.9: Shear Specimen in Shearing Tool

4.6.1.1 Parameters

Shear testing evaluated the bond between the wetpreg reinforcement and the wood. Three stitched fabrics were used: U 72 - 10, U 72 - 10 Z, and U 18 - 01. Testing was conducted to determine how the number of reinforcing plies, "z" fibers, open time, and fabric weight affect FRP-wood shear strengths when using GP 4242/4554 adhesive.

A summary of the test parameters is given in Table 4.2. The first number of the series designation is the number of fabric plies. The second number is the weight of the fabric in ounces per square yard. The third number is the open time in minutes for the samples.

Table 4.2: Summary of Stitched Fabric Test Parameters

Series Designation	Number of Plies	Fabric Type	Open Time (min)
1-72-0	1	U 72 - 10	0
1-72-40	1	U 72 - 10	40
1-72 z-0	1	U 72 - 10 Z	0
1-72 z-40	1	U 72 - 10 Z	40
2-72 z-0	2	U 72 - 10 Z	0
2-72 z-40	2	U 72 - 10 Z	40
4-18-0	4	U 18 -01	0
4-18-40	4	U 18 -01	40

4.6.1.2 Fabrication Details

For each series, three billets were fabricated: one control and two reinforced. A billet is made with two pieces of wood, 45.7 cm (18 in) long, 5.1 cm (2 in) wide and 1.9 cm (3/4 in) thick adhered together. Five 5.1 cm long, shear blocks were cut from the center of each billet. The moisture content of the wood at time of shear billet fabrication was 9-11%, with an average of 10%.

Adhesive spread rate for the wood-wood bond line was 3.8 N/m^2 (80 lb/1000 ft^2). Adhesive spread rate for the wood-FRP bond line was 1.9 N/m^2 (40 lb/1000 ft^2). The closed time, the time between when the adhesive is applied and when clamping is applied, was between 5-10 minutes for all billets. The billets were clamped at 690 kPa (100 psi), for 24 hours. Billets were conditioned at 65% relative humidity and 24°C (75°F) temperature for 7 to 9 days following clamping. Due to large numbers of samples, wood faces were assigned randomly (i.e. unmatched samples).

Four Plies of 18 oz. fabric is equivalent to a single ply of 72 oz. fabric, which is why the number of reinforcement plies were chosen. All reinforcement was oriented such that the FRP backing (veil and mat) faced the wood backing piece; hence, the bond is evaluated between the wood and longitudinal fibers. A loading rate of 0.5 cm/min (0.2 in/min) was used.

4.6.1.3 Results

Shear strength results are given in Table 4.3. Values are expressed as an average of 10 shear blocks, except for the controls that are an average of 40

shear blocks. Average failure modes are given in Table 4.4. See Appendix B for individual shear block results, as well as billet strength statistics.

Table 4.3: Mean Stitched Fabric FRP-Wood Shear Strengths

Series Designation	Number of Samples	Ave. Shear Strength MPa (psi)	COV (%)
Controls	40	9.005 (1306)	14.6
1-72-0	10	10.82 (1569)	9.3
1-72-40	10	10.49 (1522)	14.4
1-72 z-0	10	10.94 (1586)	14.8
1-72 z-40	10	9.177 (1331)	10.7
2-72 z-0	10	9.053 (1313)	13.8
2-72 z-40	10	8.991 (1304)	8.7
4-18-0	10	10.08 (1462)	11.5
4-18-40	10	8.481 (1230)	13.0

Control adhesive spread rate = 3.8 N/m^2 (80 lb/1000 ft^2)
FRP-Wood adhesive spread rate = 1.9 N/m^2 (40 lb/1000 ft^2)
Wood MC = 10%
Clamping pressure = 690 kPa (100 psi) for 24 hours
Temp = 27°C (80°F) Relative Humidity = 30%

Table 4.4: Mean Stitched Fabric Failure Modes

	MATERIAL FAILURE (%)			
Series Designation	Wood	Fabric Backing	Fabric Fibers	Glue-line
Controls	99.4	0	0	0.6
1-72-0	55.0	19.5	25.5	0
1-72-40	65.6	16.0	18.4	0
1-72 z-0	77.4	9.5	13.1	0
1-72 z-40	92.8	3.0	4.2	0
2-72 z-0	78.5	17.0	4.5	0
2-72 z-40	89.2	3.0	7.8	0
4-18-0	82.0	0	18.0	0
4-18-40	92.5	6.0	1.5	0

4.6.1.4 Conclusions

1) Shear strength of the wetpreg FRP-wood bond can be equivalent to that of the wood-wood bond.

2) Shear strength tends to decrease as number of plies increase, as seen by comparing the U 72 - 10 Z series for 1 and 2 plies.

3) Each fabric type showed greater shear strength at zero than at forty minute open time; therefore, shorter open times appear to produce better bonds.

4) All fabric types tested showed greater FRP-wood bond strengths than the minimum wood-wood bond requirement of 7.171 MPa (1040 psi), defined by ANSI/AITC A190.1-1992 for Hem-Fir. The interlaminar, or FRP-FRP, shear strength is evaluated in the next section to better determine which is the better fabric to use.

4.6.2 Stitched Fabrics - Short Beam Shear

Interlaminar bond evaluation was conducted according to ASTM D 2344 - 84 Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method.

4.6.2.1 Parameters

Fabrics U 72 - 10, U 72 -10 Z, and U 18 - 01 were tested. Zero and forty minute open times were tested as well. Five plies were adhered for the 72 oz. fabrics and twelve plies were adhered for the 18 oz. fabric.

4.6.2.2 Fabrication Details

Specimen were 5.1 cm (2 in) long and appoximately 0.64 cm (0.25 in) wide and 0.64 cm (0.25 in) deep. Specimens were cut from a continuous sheet. A closed time of about five minutes resulted during fabrication. A clamping pressure of 690 kPa (100 psi) was used for all samples. Specimens were cured at about 24°C (80°F) and 30% relative humidity for about 20 hours.

Samples were made with the wetpreg process. Fabrics were run between impregnating rollers such that the pre-cured composite had a glass/resin ratio of 50% glass/50% resin by weight, or 69% glass/31% resin by volume. The post-cured glass/resin ratio was not determined. The estimated post cured glass/resin content should be about 72% glass/28% resin by weight, or 54% glass/46% resin by volume, based on ignition loss tests performed on similar material.

unidirectional fibers when passed over a "hot-plate", thus providing fabric integrity.

4.6.3.1.2 Resin Systems

The resins used were GP 4242/4554 and GP 5022/4822 (as described in section 4.3.1.2).

4.6.3.1.3 GP 4242/4554 Modifications

Visual inspection of testing done with the stitched fabrics had shown dry fibers, indicating insufficient wet-out. In order to improve wet-out, it was desired to decrease adhesive viscosity. To this end, GP recommended methanol and caustic modifications in the amounts of 2% and 0.15% additions by weight to the GP 4242/4554 (section 4.3.1.2).

4.6.3.1.4 Clamping Pressure

A clamping pressures of 550 kPa (80 psi) and 275 kPa (40 psi) were used in fabricating shear block specimens with unidirectional weave fabrics. These pressures are lower than the 690 kPa (100 psi) pressure used with the stitched fabrics. It was thought that a reduced pressure would "squeeze-out" less resin from the wetpreg reinforcement, and aid in reducing dry fibers that had been seen with testing done with the stitched fabrics at 690 kPa (100 psi) pressure. Rowlands et. al. (1984) showed that there was little difference in FRP-wood

shear strength of unidirectional glass fabric, bonded with phenolic-resorcinol or phenolic-resorcinol-formaldehyde adhesives to douglas fir, at pressures of 1040 and 690 kPa (150 and 100 psi). It was possible then that shear performance is not sensitive to clamping pressure would not, and reduced pressure could possibly be helpful in improving interlaminar shear strength and bond durability by improving fiber wet-out.

Clamping pressures of 690-1040 kPa (100-150 psi) are typically used to fabricate softwood glulams. If the reinforcement is applied and clamped at the same time as the wood laminations, then the reinforcement would be clamped at 690-1040 kPa (100-150 psi), as dictated by the pressure required to bond the wood laminations. However, if the glulam is fabricated first, and the reinforcement is applied as a second step; then, it is possible to apply any desired pressure to the wetpreg reinforcement. So, clamping pressures of less than 690 kPa (100 psi) can be used to manufacture wetpreg reinforced glulam. Shear strengths of the VEW 260 reinforcement were therefore determined at clamping pressures of 690 kPa (80 psi), and 275 kPa (40 psi) for some specimens.

4.6.3.1.5 Bond Strengths

Shear block tests were conducted to evaluate wood-wood, FRP-wood and FRP-FRP bond lines.

4.6.3.2 Fabrication Details

Closed times of 5-10 minutes resulted during all billet fabrication. Zero minute open times were used throughout. Clamping pressure of 550 kPa (80 psi) was used throughout. Curing conditions were approximately 24°C (80°F) and 30% relative humidity for 20-24 hours. The moisture content of all wood used at time of billet fabrication was 9-11% with an average of 10%. All reinforced billets were fabricated with five plies of fabric. Wetpreg reinforcement was 50% glass/50% resin by weight at time of application.

No adhesive was applied between the FRP and the wood faces, as was done in the stitched fabric testing, because significant "squeeze-out" of adhesive occurred suggesting that there was sufficient adhesive within the wetpreg reinforcement to form a complete bond with the wood. Good results were obtained, so the practice of applying adhesive to the wood of reinforced shear billets was stopped.

4.6.3.3 Results

A summary of the tests conducted can be seen in Table 4.6. Complete test data can be found in Appendix B.

Table 4.6: Summary of Uni-Weave Tests Conducted

	Unmodified 4242/4554		Methanol & 4242/4554		Caustic & 4242/4554		Unmodified 5022/4822	
VEW 260	FRP-Wood	FRP-FRP	FRP-Wood	FRP-FRP	FRP-Wood	FRP-FRP	FRP-Wood	FRP-FRP
A	Table 4.7	-	Table 4.8	-	Table 4.9	-	-	-
B	Table 4.10	Table 4.11	Table 4.12	Table 4.13	Table 4.14	Table 4.15	-	-
C	-	-	-	-	Table 4.16	Table 4.17	Table 4.22	Table 4.23

* All tests listed in Table 4.6 were conducted on specimens fabricated at 550 kPa (80 psi) clamping pressure. In addition, results of specimens fabricated at 275 kPa (40 psi) pressure with VEW 260 C fabric and unmodified 4242/4554 adhesive are shown in Tables 4.19 and 4.20.

4.6.3.3.1 VEW 260 A

Results of unmodified GP 4242/4554 adhesive with VEW 260 A fabric can be found in Table 4.7. Stitching is present on one side of the fabric, so the orientation of the fabric may have an effect on bond performance. It appears that the stitching enhances shear strength, but has an accompanying increase in reinforcement material failure. This effect was not anticipated and specific care to the orientation of the fabric was not done during shear billet layup. Results of the effect of the stitching were inconclusive. In Table 4.7, 4.8, and 4.9, the stitching facing “Front” means the fabric side with stitching faced the front wood shear face (i.e. the stitching was present at the shear bond line), and “Back” means the stitching faced toward the back wood piece.

Table 4.7: Mean FRP-Wood Shear Strengths - VEW 260 A, GP 4242/4554

Specimen Billet Type	# of Samples	Stitching Facing	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Control	5	-	9.453 (1371)	8.6	84	-	16
FRP 1	5	Back	8.777 (1273)	3.6	81	19	0
FRP 2	5	Front	9.791 (1420)	2.2	48	50	2

The effect of adding 2% Methanol by weight to GP 4242/4554 in conjunction with fabric VEW 260 A on FRP-wood shear strength by can be seen in Table 4.8. The methanol addition decreased the shear strength of the FRP-wood bond, but had little effect on the control (wood-wood) strength.

Table 4.8: Mean FRP-Wood Shear Strengths - VEW 260 A, GP 4242/4554 w/Methanol

Specimen Billet Type	# of Samples	Stitching Facing	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue (%)
Control	5	-	9.356 (1357)	4.0	91	-	9
FRP 1	5	Front	7.901 (1146)	7.2	49	45	6
FRP 2	5	Back	8.170 (1185)	11.0	75	8	17

Results of a 0.15% caustic (NaOH) addition by weight to the GP 4242/4554 can be seen in Table 4.9. VEW 260 A fabric was used. The caustic addition greatly increased shear strengths for both the control (wood-wood) and reinforced blocks (FRP-wood). The caustic addition sped up the curing reaction, reducing the pot life of the adhesive from about 50 minutes to about 15 minutes.

Table 4.9: Mean FRP-Wood Shear Strengths - VEW 260 A, GP 4242/4554 w/Caustic

					Mean Material Failure		
Specimen Billet Type	# of Samples	Stitching Facing	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Wood (%)	FRP (%)	Glue-line (%)
Control	5	-	10.45 (1515)	3.9	95	-	5
FRP 1	5	Back	9.977 (1447)	2.7	67	32	1
FRP 2	5	Back	12.25 (1777)	2.9	73	23	4

4.6.3.3.2 VEW 260 B

Results of FRP-wood shear strengths using unmodified GP 4242/4554 adhesive and VEW 260 B fabric is shown in Table 4.10.

Table 4.10: Mean FRP-Wood Shear Strengths - VEW 260 B, GP 4242/4554

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood	5	7.846 (1138)	9.9	97	-	3
FRP-Wood 1	5	8.832 (1281)	15.0	59	38	3
FRP-Wood 2	5	8.522 (1236)	13.5	92	3	5

Results of FRP-FRP shear strengths using unmodified GP 4242/4554 adhesive and VEW 260 B fabric is shown in Table 4.11.

Table 4.11: Mean FRP-FRP Shear Strengths - VEW 260 B, GP 4242/4554

Specimen Billet Type	Number of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood	5	8.812 (1278)	5.4	97	-	3
FRP-FRP 1	5	8.949 (1298)	8.3	-	100	0
FRP-FRP 2	5	10.17 (1475)	2.8	-	100	0

The effect of adding 2% Methanol by weight to GP 4242/4554 in conjunction with fabric VEW 260 B on FRP-wood shear strength can be seen in Table 4.12. The VEW 260 B performed slightly better than the VEW 260 A.

Table 4.12: Mean FRP-Wood Shear Strength - VEW 260 B, GP 4242/4554 w/Methanol

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Average Material Failure Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood	5	8.294 (1203)	7.3	75	-	25
FRP-Wood 1	5	9.515 (1380)	7.5	63	33	4
FRP-Wood 2	5	7.846 (1138)	1.5	97	3	0

The effect of adding 2% methanol to GP 4242/4554 on interlaminar (FRP-FRP) bond strength can be seen in Table 4.13. VEW 260 B fabric was used. Interlaminar shear strengths with methanol addition were low. The FRP-FRP bonds faired as poorly as the FRP-Wood bonds with methanol addition.

Table 4.13: Mean FRP-FRP Shear Strengths - VEW 260 B, GP 4242/4554 w/Methanol

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood 1	5	9.060 (1314)	16.9	79	-	21
FRP-FRP 1	5	7.598 (1102)	9.6	-	100	0
FRP-FRP 2	5	8.246 (1196)	12.0	-	100	0
Wood-Wood 2	5	8.584 (1245)	10.2	73	-	27
FRP-FRP 3	5	7.088 (1028)	13.4	-	100	0
FRP-FRP 4	5	7.508 (1089)	7.9	-	100	0

Results of FRP-Wood shear strengths by caustic addition of GP 4242/4554 with VEW 260 B fabric can be seen in Table 4.14. Wood-wood and FRP-wood bonds showed good strengths.

Table 4.14: Mean FRP-Wood Shear Strengths - VEW 260 B, GP 4242/4554 w/Caustic

				Average Material Failure		
Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood	5	10.42 (1512)	12.5	94	-	6
FRP-FRP 1	5	10.14 (1470)	5.9	21	78	1
FRP-FRP 2	5	9.625 (1396)	6.6	47	37	16

Results of FRP-FRP shear strengths by caustic addition of GP 4242/4554 with VEW 260 B fabric can be seen in Table 4.15. Wood-wood and FRP-FRP bonds showed good strengths.

Table 4.15: Mean FRP-FRP Shear Strengths - VEW 260 B, GP 4242/4554 w/Caustic

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood 1	5	10.37 (1504)	6.1	92	-	8
FRP-FRP 1	5	9.735 (1412)	11.4	-	100	0
FRP-FRP 2	5	10.43 (1513)	5.0	-	100	0
Wood-Wood 2	5	10.25 (1486)	5.2	89	-	11
FRP-FRP 3	5	9.508 (1379)	12.8	-	100	0
FRP-FRP 4	5	10.40 (1509)	3.4	-	100	0

4.6.3.3.3 VEW 260 C

Results of FRP-Wood shear strength by caustic modified GP 4242/4554 with VEW 260 C fabric can be seen in Table 4.16. FRP-wood bonds showed good strengths.

Table 4.16: Mean FRP-Wood Shear Strengths - VEW 260 C, GP 4242/4554 w/Caustic

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood 1	5	12.07 (1751)	4.1	89	-	11
FRP-Wood 1	5	11.26 (1633)	4.2	30	70	0
FRP-Wood 2	5	11.09 (1608)	3.1	36	64	0
Wood-Wood 2	5	12.25 (1776)	9.9	94	-	6
FRP-Wood 3	5	10.91 (1583)	6.7	15	85	0
FRP-Wood 4	5	10.93 (1585)	8.810	31	69	0

Results of FRP-FRP shear strength by caustic modified GP 4242/4554 with VEW 260 C fabric can be seen in Table 4.17. FRP-FRP bonds showed good strengths.

Table 4.17: Mean FRP-FRP Shear Strengths - VEW 260 C, GP 4242/4554 w/Caustic

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood 1	5	11.12 (1613)	10.9	99	-	1
FRP-FRP 1	5	10.29 (1493)	3.8	-	100	0
FRP-FRP 2	5	10.06 (1459)	12.2	-	100	0
Wood-Wood 2	5	11.42 (1657)	8.3	97	-	3
FRP-FRP 3	5	10.65 (1544)	5.8	-	100	0
FRP-FRP 4	5	9.563 (1387)	11.1	-	100	0

4.6.3.3.4 VEW Fabric Comparison

A comparison of the shear strengths obtained with the VEW 260 A, having standard sizing and stitching, the VEW 260 B, having standard sizing and chemical binding, and the VEW 260 C, having phenolic sizing and chemical binding, all with caustic modified GP 4242/4554, can be seen in Table 4.18.

Table 4.18: Comparison of VEW 260 A, B, C Fabrics, GP 4242/4554 w/Caustic

Fabric Type	FRP-Wood Strength MPa (psi)	COV (%)	FRP-FRP Strength MPa (psi)	COV (%)	Wood-Wood Strength MPa (psi)	COV (%)
VEW 260 A	11.11 (1612)	11.1	-	-	10.45 (1515)	3.9
VEW 260 B	9.880 (1433)	6.5	10.02 (1453)	9.1	10.35 (1501)	8.0
VEW 260 C	11.05 (1602)	5.7	10.14 (1471)	9.0	11.71 (1699)	8.9

An analysis of variance was performed for the FRP-FRP bond shear strengths of fabrics B and C. The P-value was high, being 0.671, showing there is no significant difference in the performance of the B and C fabrics. Thus, standard and phenolic sizings are equivalent. The difference in FRP-wood shear strengths for fabric types B and C is attributed to the difference in wood strength.

Testing with fabric A resulted in a greater FRP-wood than wood-wood shear strength, and it is assumed that this was a result of wood variability. It appears that the fabric A performed as well and perhaps slightly better than fabrics B and C; but, without having conducted an FRP-FRP shear test for the A fabric, it is difficult to make a conclusive comparison. It is not however unreasonable to think that the A fabric performs similarly to the B and C fabrics. Therefore, it can be concluded that the VEW 260 A, B, and C fabrics perform equivalently. Also, stitching and chemical binding of the VEW 260 fabrics are equivalent in performance.

4.6.3.3.5 Effect of Adhesive Modifications

Methanol addition to GP 4242/4554 decreased FRP-FRP bond strengths by about 20%. The VEW 260 B fabric showed a mean FRP-FRP shear strength of 9.556 MPa (1386 psi) with unmodified GP 4242/4554 and 7.612 MPa (1104 psi) with methanol modified GP 4242/4554, with COVs of 8.7% and 11.5%, respectively. An analysis of variance was performed, resulting in a P-value of 0.00000283. The P-value was very small, being less than 0.01, showing that the methanol addition did indeed have a significant effect.

The methanol addition did not significantly effect wood-wood bonds. The mean wood-wood strength for VEW 260 B fabric with unmodified GP 4242/4554 was 8.329 MPa (1208 psi) and 8.646 MPa (1254 psi) with methanol modified GP 4242/4554, with COVs of 9.5% and 12.1%, respectively. An analysis of variance was performed, resulting in a P-value of 0.427. The P-value was large, being much greater than 0.01, showing that the methanol addition had no significant effect on wood-wood bond strength.

The methanol addition did not significantly affect FRP-wood bonds. The mean FRP-wood strength for VEW 260 B fabric with unmodified GP 4242/4554 was 8.674 MPa (1258 psi) and 8.674 MPa (1259 psi) with methanol modified GP 4242/4554, with COVs of 13.6% and 11.5%, respectively. An analysis of variance was performed, resulting in a P-value of 0.999. The P-value was very large, being much greater than 0.01, showing that the methanol addition had no significant effect on wood-wood bond strength.

Caustic addition to GP 4242/4554 did not significantly affect FRP-FRP bond strengths. The VEW 260 B fabric showed mean FRP-FRP shear strengths of 9.556 MPa (1386 psi) with unmodified GP 4242/4554 and 10.02 MPa (1453 psi) with caustic modified GP 4242/4554, with COVs of 8.7% and 9.1%, respectively. An analysis of variance was performed, resulting in a P-value of 0.191. The P-value was large, being greater than 0.01, showing that the caustic addition did not have a significant effect on FRP-FRP bond strength.

Caustic addition to GP 4242/4554 increased wood-wood bond strengths by about 24%. The VEW 260 B fabric showed mean wood-wood shear strengths of 8.329 MPa (1208 psi) with unmodified GP 4242/4554 and 10.35 MPa (1501 psi) with caustic modified GP 4242/4554, with COVs of 9.5% and 8.0%, respectively. An analysis of variance was performed, resulting in a P-value of 0.00000351. The P-value was small, being much less than 0.01, showing that the caustic addition did have a significant effect on wood-wood bond strength.

Caustic addition to GP 4242/4554 increased FRP-wood bond strengths by about 14%. The VEW 260 B fabric showed mean wood-wood shear strengths of 8.674 MPa (1258 psi) with unmodified GP 4242/4554 and 9.883 MPa (1433 psi) with caustic modified GP 4242/4554, with COVs of 13.6% and 6.5%, respectively. An analysis of variance was performed, resulting in a P-value of 0.0110. The P-value small, being very close to 0.01, showing that the caustic addition probably did have a significant effect on FRP-wood bond strength.

4.6.3.3.6 Reduced Clamping Pressure

Results of FRP-wood shear strength with unmodified GP 4242/4554, VEW 260 C, and 275 kPa (40 psi) clamping pressure is shown in Table 4.19.

Table 4.19: Mean FRP-Wood Shear Strengths - VEW 260 C, GP 4242/4554, 275 kPa (40 psi) Clamping Pressure

				Mean Material Failure		
Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood1	5	9.977 (1447)	8.7	94	-	6
FRP-Wood 1	5	10.19 (1478)	4.7	30	70	0
FRP-Wood 2	5	11.00 (1596)	6.2	36	64	0
Wood-Wood2	5	10.98 (1592)	3.5	96	-	4
FRP-Wood 3	5	11.18 (1622)	4.9	71	29	0
FRP-Wood 4	5	10.62 (1540)	5.7	44	56	0

Results of FRP-FRP shear strength with unmodified GP 4242/4554, VEW 260 C, and 275 kPa (40 psi) clamping pressure is shown in Table 4.20.

Table 4.20: Mean FRP-FRP Shear Strengths - VEW 260 C, GP 4242/4554, 275 kPa (40 psi) Clamping Pressure

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure		
				Wood (%)	FRP (%)	Glue-line (%)
Wood-Wood1	5	12.05 (1747)	4.0	77	-	23
FRP-Wood 1	5	10.91 (1582)	4.4	-	99	1
FRP-Wood 2	5	11.45 (1660)	7.6	-	100	0
Wood-Wood2	5	9.846 (1428)	8.5	92	-	8
FRP-Wood 3	5	10.52 (1526)	8.3	-	100	0
FRP-Wood 4	5	11.24 (1630)	2.0	-	100	0

4.6.3.3.7 Effect of Clamping Pressure

To determine the effect of reduced pressure, a comparison was made between the results shown in Tables 4.19 and 4.20 (VEW 260 C fabric, unmodified GP 4242/4554 adhesive, 275 kPa (40 psi) clamping pressure), with the results of Tables 4.10 and 4.11 (VEW 260 B fabric, unmodified GP 4242/4554 adhesive, 550 kPa (80 psi) clamping pressure). The comparison between fabric types B and C can be made because it was shown in Table 4.18 that the two fabric types produced equivalent shear strengths.

From Table 4.19 the mean wood-wood shear strength using 275 kPa (40 psi) pressure was 10.48 MPa (1520 psi) with a COV of 7.9%. From Table 4.10 the mean wood-wood shear strength using 550 kPa (80 psi) pressure was 7.847 MPa (1138 psi) with a COV of 9.9%. In both tests wood failure was over 90%, so

the shear strengths were controlled by the wood strength. The strength of the wood used with the 275 kPa (40 psi) specimens was much greater than the strength of the wood used with the 550 kPa (80 psi) specimens. The effect of the change in clamping pressure on the wood-wood shear strengths could not be determined. Likewise, the effect of the change in pressure on FRP-wood shear strengths could not be determined. From Table 4.19 the mean FRP-wood shear strength for 275 kPa (40 psi) pressure was 10.75 MPa (1559 psi) with a COV 6.2%. From Table 4.10 the mean FRP-wood shear strength for 550 kPa (80 psi) pressure was 8.674 MPa (1258 psi) with a COV of 13.6%. It appeared as though the change in pressure had little effect on FRP-wood bonds. This was because the shear strength of the FRP-wood bonds was similar to that of the wood-wood bond for both pressures.

Reducing clamping pressure from 550 kPa (80 psi) to 275 kPa (40 psi) increased mean FRP-FRP shear strengths by about 15%. From Table 4.20 the mean FRP-FRP shear strength for 275 kPa (40 psi) specimens was 11.03 MPa (1600 psi), with a COV of 6.5%. From Table 4.11 the mean FRP-FRP shear strength for 550 kPa (80 psi) specimens was 9.556 MPa (1386 psi), with a COV of 8.7%. An analysis of variance was performed, resulting in a P-value of 0.0002121. The P-value is small, less than 0.01, so it can be concluded that the lower pressure does produce significantly greater FRP-FRP shear strengths.

4.6.3.3.8 GP 5022/4822 Resin

Results of wood-wood shear strengths by GP 5022/4822 acid-cure phenolic can be seen in Table 4.21. The GP 4822 catalyst was added at 12 parts per 100, half of which was a “fast acting” agent and half was a “slow acting” agent. Shear strengths and wood failures were marginally adequate.

Table 4.21: Mean Wood-Wood Shear Strengths - GP 5022/4822

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure	
				Wood (%)	Glue-line (%)
Wood-Wood 1	5	8.025 (1164)	28.8	81	19
Wood-Wood 2	5	7.046 (1022)	19.1	88	12
Wood-Wood 3	5	9.267 (1344)	8.8	88	12
Average	15	8.115 (1177)	21.8	86	14

The FRP-wood bond was evaluated using the GP 5022/4822 and VEW 260 C. See Table 4.22 for results. Solid wood blocks were tested to determine the pure shear strength of the wood. The mean shear strength of FRP-Wood 1 and 2 was 9.226 MPa (1338 psi), while it was 11.83 MPa (1716 psi) for FRP-Wood 3 and 4. The corresponding controls were 9.618 MPa (1398 psi) and 9.115 MPa (1322 psi). The wood-wood specimens in Table 4.22 showed large amounts of glue-line failure, which is not desired, despite the good shear strengths.

Table 4.22: Mean FRP-Wood Shear Strengths - VEW 260 C, GP 5022/4822

Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Mean Material Failure Wood (%)	FRP (%)	Glue-line (%)
Solid Wood 1	5	11.54 (1674)	18.3	100	-	-
Wood-Wood1	5	9.639 (1398)	17.1	52	-	48
FRP-Wood 1	5	8.681 (1259)	15.9	26	60	14
FRP-Wood 2	5	9.763 (1416)	23.0	46	32	22
Solid Wood 2	4	11.53 (1672)	11.7	100	-	-
Wood-Wood2	4	9.115 (1322)	20.6	30	-	70
FRP-Wood 3	5	12.26 (1778)	5.5	6	24	70
FRP-Wood 4	4	11.41 (1655)	18.6	26	34	40

The FRP-FRP bond, using shear blocks cut to the center of the FRP, was evaluated using the GP 5022/4822 acid-cure phenolic and VEW 260 C. See Table 4.23 for results. Solid wood blocks were tested to determine the pure shear strength of the wood. The average shear strength for FRP-FRP 1 and 2 was 8.770 MPa (1272 psi), and 8.977 MPa (1302 psi) for FRP-FRP 3 and 4. The average wood-wood were 7.343 MPa (1065 psi) and 10.33 MPa (1498 psi), and showed significant adhesive failure.

Table 4.23: Mean FRP-FRP Shear Strengths - VEW 260 C, GP 5022/4822

				Mean Material Failure		
Specimen Billet Type	# of Samples	Mean Shear Strength MPa (psi)	Shear Str. COV (%)	Wood (%)	FRP (%)	Glue-line (%)
Solid Wood 1	5	12.21 (1771)	4.3	100	-	-
Wood-Wood1	5	7.343 (1065)	23.6	64	-	36
FRP-FRP 1	5	8.060 (1169)	17.0	-	88	12
FRP-FRP 2	5	9.480 (1375)	22.4	-	100	0
Solid Wood 2	5	11.76 (1706)	2.3	100	-	-
Wood-Wood2	5	10.33 (1498)	22.6	66	-	34
FRP-FRP 3	4	9.301 (1349)	21.3	-	100	0
FRP-FRP 4	5	8.646 (1254)	19.1	-	98	2

A comparison was made between unmodified GP 4242/5022 and GP 5022/4822 shear strengths by an analysis of variance. The mean FRP-FRP shear strength for VEW 260 B and unmodified GP 4242/4554 was 9.556 MPa (1386 psi) with a COV of 8.7% while it was 8.846 MPa (1283 psi) with a COV of 19.6% for VEW 260 C and GP 5022/4822. The P-value was 0.235.

The mean wood-wood shear strength for unmodified GP 4242/4554 was 8.329 MPa (1208 psi) with a COV of 9.5% while it was 9.405 MPa (1364 psi) with a COV of 17.7% for VEW 260 C and GP 5022/4822. The P-value was 0.0845.

The mean FRP-wood shear strength for unmodified GP 4242/4554 was 8.674 MPa (1258 psi) with a COV of 13.6% while it was 10.48 MPa (1520 psi) with a COV of 20.3% for VEW 260 C and GP 5022/4822. The P-value was 0.0197.

The FRP-FRP, FRP-wood, and wood-wood bond shear strengths were not significantly different for the GP 5022/4822 resin and the unmodified GP 4242/4554 adhesive. The P-values were all greater than 0.01, and were 0.235, 0.0845, and 0.0197. It should be noted that for all three bond types, the COV of the GP 5022/4822 shear strength was greater than the COV of the GP 4242/4554 shear strength. Also, the GP 5022/4822 exhibited high glue-line failures, being on average 12% for FRP-FRP bonds, 47% for wood-wood bonds, 36% for FRP-wood bonds.

4.6.3.4 Unidirectional Weave Conclusions

1) VEW 260 B and C fabrics performed equivalently; thus, standard and phenolic sizings perform equivalently.
2) VEW 260 A and C fabrics performed similarly; thus, stitched or chemical bindings perform similarly.
3) VEW 260 A, B, and C fabrics performed similarly.
4) Methanol addition to GP 4242/4554 decreased FRP-FRP bond strengths by about 20.4%. Methanol addition had no significant effect on either wood-wood or FRP-wood bond strengths.
5) Caustic addition to GP 4242/4554 had no significant effect on FRP-FRP bond strength. Caustic addition increased wood-wood bond strengths by about 24% and FRP-wood bond strengths by about 14%. The caustic addition to GP 4242/4554 decreased pot life to about 15 minutes, making application to glulam fabrication difficult.

6) FRP-FRP shear strength was about 15% greater at a clamping pressure of 275 kPa (40 psi) than at 550 kPa (80 psi). It was difficult to determine the effect pressure had on wood-wood and FRP-wood bond strengths, but it was suspected that the effect was small.

7) There was no significant difference in FRP-FRP, wood-wood, or FRP-wood shear strengths for the GP 5022/4822 resin and the unmodified GP 4242/4554 adhesive. The 5022/4822 however exhibited a greater variability in strength and large glue-line failures.

4.7 Cyclic Delamination

Cyclic delamination testing was performed according to Test Method B of ASTM D 1101-92: Standard Test Methods for Integrity of Glue Joints in Structural Laminated Wood Products for Exterior Use. The test is a quality control test and is based on pass/fail criteria. The American National Standard ANSI/AITC A190.1-1992 "Structural Glued Laminated Timber" requires that after one cycle the samples have no more than 5% delamination for softwoods.

There is no criterion for delamination testing involving multiple cycles, so it was decided to use the 5% maximum delamination criteria for any number of cycles. The bond line of particular interest is between the FRP and the adjacent tension lamination, after three cycles.

4.7.1 Stitched Fabrics - Cyclic Delamination Blocks

Blocks with five wood laminations were fabricated. Samples were 17.8 cm (7 in) deep, 8.9 cm (3.5 in) wide, and 7.6 cm (3 in) thick. Three blocks were tested for each of the eight test parameters described in Section 4.6.1.1. Adhesive spread rate for wood-wood bond lines was 3.8 N/m^2 (80 lb/1000 ft^2) . Adhesive spread rate for wood-FRP bond lines was 1.9 N/m^2 (40 lb/1000 ft^2). The resin used for wetout of the wetpreg reinforcement was the GP 4242/4554 PRF adhesive, modified with a 0.15% by weight caustic addition. The FRP ply was located between the bottom lamination (bumperstrip) and the next lamination, the tension lam (see Figure 4.10). Closed time for all billets was between 5 to 10 minutes. Zero open time was used throughout. Billets were clamped at 690 kPa (100 psi), for 24 hours. Billets were conditioned at 65% relative humidity and 24°C (75°F) temperature for about one week following clamping.

Each stitched fabric has one side with a backing piece. Specific care was not taken in the orientation of the FRP plies, thus either the fabric side with backing or the fabric side with unidirectional fibers could have ended-up facing the inner wood lamination or the wood bumperstrip. Extensive failure of backing pieces, which is described below, was not anticipated at the time of specimen fabrication.

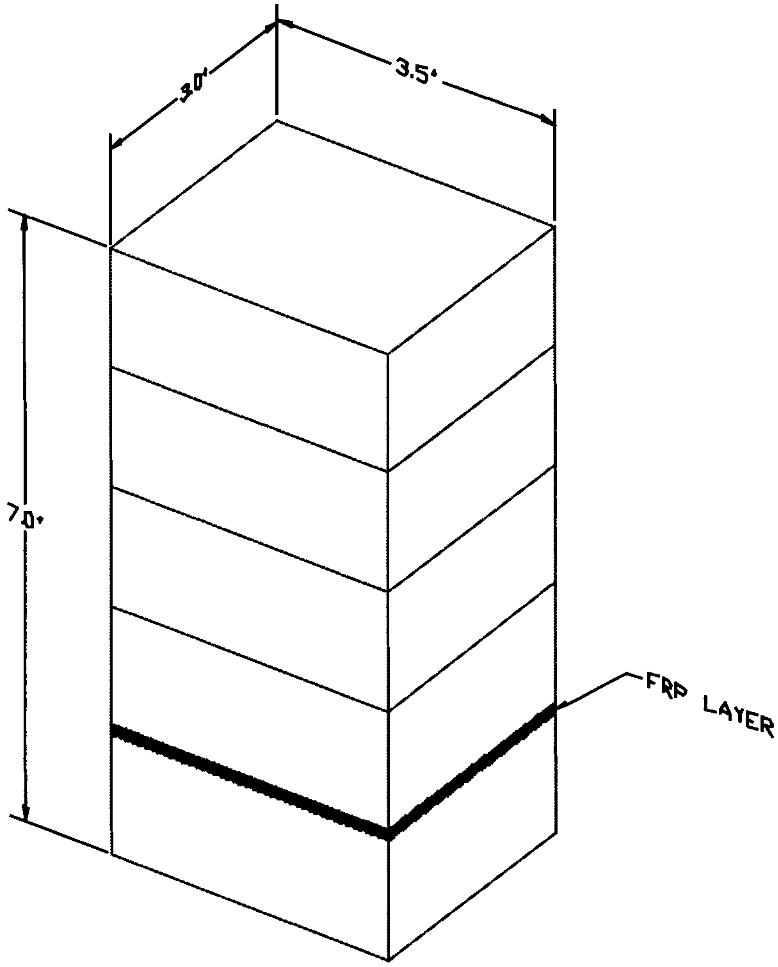


Figure 4.10: Cyclic Delamination Test Specimen

4.7.1.1 Results

Three cycles were run on each test specimen. All of the specimens with 18 oz. fabric, both zero and forty minute open time, passed three delamination cycles, based upon the established criterion. The failure summary of the third cycle showing average values for the three blocks of each combination is shown in Table 4.24.

Table 4.24: Average Delamination Following Three Cycles, GP 4242/4554

Series	Number of Samples	FRP-Tension Lam (%)	FRP-Bumperlam (%)	Backing Interface (%)
1-72-0	3	0	0	50
1-72-40	3	0	0	64
1-72 z-0	3	1	0	23
1-72 z-40	3	3	0	26
2-72 z-0	3	3	0	37
2-72 z-40	3	0	9	37
4-18-0	3	3	34	0
4-18-40	3	0	17	0

The term “backing interface” means a separation or delamination between the backing side of an FRP ply and the surface it is bonded to, whether it be a wood lamination or another ply of FRP. Delamination is described this way because delamination always occurred at the interface of the chopped glass mat backing for the 72 oz/yd^2 fabrics. All specimens with the 72 oz. fabric failed the cyclic delamination test due to the extensive failure at backing interfaces.

The 18 oz. fabric, which had the polyester veil, had little to no FRP - tension lam delamination and had no noticeable backing failure. The 18 oz. fabric passed the test. It should be noted that since the potential problem with backing delamination had not been identified at the time of the test, specific care was not taken with the orientation of FRP plies. It is possible that the polyester veil backing side was bonded to the bumperlam that affected the significant FRP-bumperlam delamination that occurred. Bumperlam delamination is a potential

serviceability and appearance concern. However, delamination between FRP plies did not occur as with the 72 oz. fabrics.

4.7.1.2 Conclusions

1) Fabric plies with chopped fiber backing did not perform well under cyclic delamination testing; therefore, the chopped fiber backing should not be used as part of the glulam reinforcement.
2) Bonds with polyester veil backing did perform well under cyclic delamination testing; therefore, the polyester veil backing is applicable to glulam reinforcement. Failure of the bumperlam bond under cyclic delamination testing did occur however.
3) Zero and forty minute open times showed similar results, so open time has little effect on the ability of bonds, using the materials tested, to perform under cyclic delamination testing.

4.7.2 Unidirectional Weave - Cyclic Delamination Blocks

Four blocks were made with caustic modified GP 4242/4554. Three blocks were made with the GP 5022/4822. Blocks had seven 3.81 cm (1.5 in) wood laminations, 12 plies of VEW 260 B fabric, and a 1.9 cm (0.75 in) thick bumperlam. Samples were 29.5 cm (11.6 in) deep, 8.9 cm (3.5 in) wide, and 7.6 cm (3 in) thick. Adhesive spread rate for wood-wood bond lines was 3.8 N/m^2 (80 $lb/1000\ ft^2$). No adhesive was applied to the wood-FRP interface. It was

located between the bumperstrip and the tension lam. Closed time was about 5 minutes. Zero open time was used. Clamping was 550 MPa (80 psi), for 20 hours. Billets were conditioned at 65% relative humidity and 24°C (75°F) temperature for about one week following clamping.

4.7.2.1 Results

After five delamination cycles on blocks made with GP 4242/4554, three blocks showed no delamination and one block showed 4.6% delamination at the FRP - tension lam bond. The four blocks passed five cycles, based upon the established 5% delamination criterion.

There were several very small cracks between individual FRP plies, which was of concern. The cracks were very small and shallow, and thought to be surface cracking of the matrix. Shear blocks were cut from the blocks that had already undergone five delamination cycles to see how the shear strength of the FRP-FRP bonds was affected.

The average FRP-FRP shear strength, of the four shear blocks cut from the delamination blocks following five delamination cycles, was 14.29 MPa (2073 psi), which is 43% greater than that presented in section 4.6.3.3. It is not apparent why the shear strength increased so dramatically, especially since it was expected to decrease somewhat due to the stress and strain it had undergone during the five delamination cycles. One explanation is that the adhesive was further cured during the drying cycles, which could have created a better cure, adhesion, and material properties.

For the GP 5022/4822 blocks, one block showed 8.8% delamination between the reinforcement and the tension lamination, which was greater than the 5% criterion. The other two blocks did not show any delamination between the reinforcement and the tension lamination; however, the blocks showed 46% and 35% delamination between the reinforcement and the bumperstrip. This excessive delamination was cause for concern, and it was decided that the blocks had failed the test.

4.7.2.2 Conclusions

1) The VEW 260 fabric, when used with GP 4242/4554 adhesive, is resistant to hygro-thermal cycling (specimens passed 5 delamination cycles).

2) Hygro-thermal cycling, for the VEW 260 fabric and GP 4242/4554 adhesive, did not have a detrimental effect on the FRP-FRP bond shear strength.

3) It is likely that application of heat to the wetpreg during curing will increase bond properties.

4) The GP 5022/4822, when used with the VEW 260, did not pass a cycle of the delamination test.

4.8 Reinforcement Tensile Strength

Testing was done according to ASTM D 3039 - 93 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials.

4.8.1 Parameters

4.8.1.1 Resin

Three types of resins were used for matrix material. One was unmodified GP 4242/4554 PRF wood laminating adhesive. Another was GP 4242/4554 with a 0.15% by weight caustic addition. The other was the GP 5022/4822 PRF bulk resin with 12 parts per 100 of the 4822 catalyst added to the 5022 resin.

4.8.1.2 Reinforcing Fabric

Tensile testing was conducted on two fabric types: the U 18 - 01 and the VEW 260. The VEW 260 was tested with two types of sizings: "standard" and "phenolic" sizing.

4.8.1.3 Clamping Pressure

Most of the tensile specimens fabricated and tested were clamped at 550 kPa (80 psi) pressure. Some samples were clamped at 275 kPa (40 psi) pressure, as well.

4.8.1.4 Fabrication

Sheets of approximately 10.2 cm (4 in) wide and 50.8 cm (20 in) long were fabricated. Specimens were cut from the sheet using a diamond saw to 1.3 cm (0.5 in) widths and 25.4 cm (10 in) lengths.

4.8.1.5 Specimen Designation

Test specimens were labeled by the fabric type used, “18” for the U 18 - 01 or “72” for the U - 72 - 10 or “72 Z” for the U - 72 - 10 fabric with z-fibers or “26” for the VEW 260, then by the sizing, “S” for standard or “P” for phenolic, then by the resin used, 4242 or 5022, then by the clamping pressure, 80 or 40, and lastly by the specimen number, 1 through 16.

4.8.1.6 Test Results

A summary of the tensile testing results can be seen in Table 4.25. Data can be seen in Appendix D in Tables D1 through D7.

Table 4.25: Tensile Testing Results Summary

Fabric Type	Sizing	Resin	Clamp Pressure kPa (psi)	# of Samples	Tensile Strength MPa (psi)	MOE GPa (ksi)
U-18-01	Standard	4242	552 (80)	10	407.8 (59150)	42.02 (6095)
U-72-10	Standard	4242	552 (80)	13	267.3 (38774)	37.88 (5494)
U-72-10 Z	Standard	4242	552 (80)	16	204.9 (29715)	35.63 (5168)
VEW 260	Phenolic	4242 w/ caustic	552 (80)	6	409.3 (59361)	39.62 (5747)
VEW 260	Standard	4242 w/ caustic	552 (80)	5	462.4 (67072)	39.42 (5717)
VEW 260	Standard	4242 w/ caustic	276 (40)	5	456.1 (66155)	37.78 (5479)
VEW 260	Phenolic	5022	552 (80)	6	459.8 (66686)	45.36 (6579)

The U-18-01 fabric had good tensile strength and stiffness properties. The U-72-10 and U-72-10 Z had 35% and 50% lower tensile strength and 10% and 15% less stiffness than that of the U-18-01. The VEW 260 fabric showed better tensile strength for standard sizing than phenolic sizing, and was 13% stronger and 6% less stiff than the U-18-01 fabric. The strength and stiffness were similar for clamping pressures of 550 and 275 kPa (80 and 40 psi). The strength of samples made with the 5022 resin and 4242 resin was similar; however, the stiffness of the samples with 5022 resin is 15% greater than the stiffness of the 4242 samples.

In summary, the U-18-01 and the VEW 260 fabrics showed good tensile strength and stiffness, while the U-72-10 and U-72-10 Z fabrics did not. Standard sizing appears to be slightly better than phenolic sizing. Resin 5022 produces the same strength composite as resin 4242, but produces a 15% stiffer composite. Clamping pressures of 550 kPa (80 psi) and 275 kPa (40 psi) produced similar properties.

4.9 System Selection

Two types of fabrics are acceptable for wetpreg reinforcement of glulam beams. The U 18 - 01 fabric and the VEW 260 fabric showed good FRP-wood and FRP-FRP shear strengths, passed cyclic delamination testing, and had good tensile strength and stiffness. The standard sizing and the phenolic sizing of the VEW 260 fabric performed essentially the same. See Table 4.26 for a list of the fabrics tested, from most desirable to least desirable.

Table 4.26: Summary of Fabric Evaluation w/Unmodified GP 4242/4554 Adhesive

Fabric	Summary
U 18-01	FRP-Wood Shear Strength = 10.08 MPa (1462 psi) Short Beam, Interlaminar Shear Strength = 12.79 MPa (1855 psi) Passed Cyclic Delamination Testing (3 cycles)
VEW 260B	FRP-Wood Shear Strength = 8.677 MPa (1258 psi) Shear Block, Interlaminar Shear Strength = 9.559 MPa (1386 psi) Passed Cyclic Delamination Testing (5 cycles)
VEW 260C	Shear testing not performed with unmodified adhesive. Methanol and caustic modified adhesive showed results similar to the VEW 260B. Thus, "phenolic" and "standard" sizings are equivalent.
VEW 260A	FRP-Wood Shear Strength = 9.284 MPa (1346 psi) Interlaminar Shear Strength = test not performed Cyclic Delamination Testing = test not performed
U 72-10	FRP-Wood Shear Strength = 10.82 MPa (1569 psi) Short Beam, Interlaminar Shear Strength = 6.950 MPa (1008 psi) Failed Cyclic Delamination Testing (3 cycles)
U 72-10 Z	FRP-Wood Shear Strength = 10.94 MPa (1586 psi) Short Beam, Interlaminar Shear Strength = 6.674 MPa (968 psi) Failed Cyclic Delamination Testing (3 cycles)

Unmodified GP PRF 4242/4554 adhesive performed well. A 0.15% by weight caustic addition increased shear strengths by 4.8% for FRP-FRP, 13.9% for FRP-wood, and 24.2% for wood-wood bonds with the VEW 260 B fabric. The caustic modification can be used when increased performance is desired and when assembly time can be limited to 15 minutes.

Pilot beams described in chapter 3 were fabricated using the U 18 - 01 fabric with unmodified GP PRF 4242/4554 adhesive. The test beams described in chapter 5 were fabricated using the VEW 260 B fabric with unmodified GP PRF 4242/4554 adhesive. Better bonds could have been achieved by adding caustic, but the limitation of shorter pot life made it impractical for glulam fabrication.

4.10 Conclusions

1) Wetpreg is a suitable process for use in reinforcing glulam beams.

2) Unmodified GP 4242/4554 adhesive bonded E-glass fabric to Eastern Hemlock well. Mean FRP-wood shear strengths for U-18-01 fabric was 10.08 MPa (1462 psi) and 8.677 MPa (1258 psi) for VEW 260 B fabric.

3) Unmodified GP 4242/4554 adhesive can bond plies of E-glass fabric to each other well. Mean short beam interlaminar shear strength of U-18-01 fabric was 12.79 Mpa (1855 psi). Mean shear block interlaminar shear strength of VEW 260 B fabric was 9.559 MPa (1386 psi).

4) Chopped strand mat backing is not desired with stitched fabric. A polyester veil is desirable with stitched fabric.

5) Short open time, 0-5 minutes, produced slightly better bond strengths with unmodified GP 4242/4554 adhesive than for a long open time of forty minutes.

6) Shear strengthening within a ply by “z-fibers” is unwarranted, since U-72 Z-10 short beam shear samples failed between plies. The FRP, therefore, was weaker at the interface between plies than through a ply.

7) There was no significant difference in performance between the unidirectional weave fabric types VEW 260 A, B, and C.

8) There was no significant difference in performance between standard and phenolic sizings.

9) There was no significant difference in performance between stitched and chemical bindings.

10) Methanol addition to GP 4242/4554 decreased FRP-FRP bond strengths by about 20.4%. Methanol addition had no significant effect on either wood-wood or FRP-wood bond strengths.

11) Caustic addition to GP 4242/4554 had no significant effect on FRP-FRP bond strength. Caustic addition increased wood-wood bond strengths by about 24% and FRP-wood bond strengths by about 14%. The caustic addition to GP 4242/4554 decreased pot life to about 15 minutes, making application to glulam fabrication difficult.

12) GP 5022/4822 bulk resin is not applicable for use with wetpreg reinforcing of glulam. The GP 5022/4822 shear strengths were not significantly different from the shear strengths of the unmodified GP 4242/4554. However, large shear strength variability and glue-line failure occurred. Also, GP 5022/4822 cycle delamination specimens failed.

13) FRP-FRP shear strength was about 15% greater at a clamping pressure of 275 kPa (40 psi) than at 550 kPa (80 psi). It was difficult to determine the effect pressure had on wood-wood and FRP-wood bond strengths, but it was suspected that the effect was small.

14) The most desirable combination of fibers and resins tested were: A) U-18-01 fabric with unmodified GP 4242/4554 adhesive, B) VEW 260 B fabric with caustic modified GP 4242/4554 adhesive.

5 BEAM TESTING PROGRAM

5.1 Objective

The purpose of conducting this test program is to obtain quantitative analysis of the performance of wetpreg reinforced glulam beams.

5.2 Introduction

Thirty-one, 3.66 m (12 ft) long glulam beams were fabricated at the University of Maine. Ten beams were unreinforced, or controls. Seven were reinforced with wetpreg at a 2% reinforcement ratio. Seven were reinforced with wetpreg at a 3% reinforcement ratio. Seven were reinforced with wetpreg at a 4% reinforcement ratio. Reinforcement ratio is defined as the cross-sectional area of reinforcement divided by the cross-sectional area of the wood above the reinforcement. Beams were tested in four point bending to ultimate failure. Load and deflection data were collected through failure.

5.3 Materials

5.3.1 Adhesives and Resins

Unmodified GP 4554/4242 phenolic-resorcinol-formaldehyde wood laminating adhesive was used to bond wood laminations and used as the matrix

for the glass reinforcement. A spread rate of 3.8 N/m^2 (80 lb/1000 ft^2) was used between wood laminations.

5.3.2 Reinforcement

Wetpreg reinforcement was a 26 oz/yd^2, E-glass, unidirectional weave, with product designation VEW 260 (produced by Advanced Textiles Inc. and obtained from Brunswick Technologies Inc.). Glass had a "standard" sizing. The beams with 2% reinforcement used five plies of fabric, and actually had a 1.9% reinforcement ratio. The beams with 3% reinforcement used eight plies of fabric, and were very close to 3.0 % reinforcement. The beams with 4% reinforcement used eleven plies of fabric, and actually had a 4.1% reinforcement ratio. The glass/resin content of the wetpreg was 50/50 by weight, or 69/31 by volume, at the time the wetpreg was applied to the glulam.

Material properties of the FRP are expected to be the following (from Chapter 4): ultimate tensile strength of 462.4 MPa (67,070 psi) and modulus of elasticity of 39.42 GPa (5717 ksi). These properties are approximate because they are based on specimens fabricated using caustic modified resin, rather than unmodified resin.

5.3.3 Wood

Eastern Hemlock 2x4's, No.2 and better by NELMA Standards, were used. The lumber was all 3.66 m (12 ft) long and had Moisture Contents of 8-16%, with an average of 12%, prior to gluing. Each piece was planed from 3.81 cm (1.5 in) to 3.56 cm (1.4 in) thick just prior to gluing. Actual lumber width was 8.64 cm (3.4 inches).

The modulus of elasticity (MOE) of the lumber was determined using a Metriguard dynamic MOE tester. There were three zones in each beam (see Figure 5.1): tension, compression, and core. The tension zone had one lamination, as did the compression zone. The core zone had three laminations. The mean MOE of each zone was used for the numerical model. Mean, minimum, and maximum MOE of each zone are given in Table 5.1.

Table 5.1: MOE's of Beam Zones

Zone	Mean MOE		Minimum MOE		Maximum MOE	
	GPa	(Msi)	GPa	(Msi)	GPa	(Msi)
Tension	10.3	(1.50)	9.93	(1.44)	11.0	(1.60)
Compression	9.24	(1.34)	8.96	(1.30)	9.65	(1.40)
Core	7.31	(1.06)	4.48	(0.65)	1.29)	

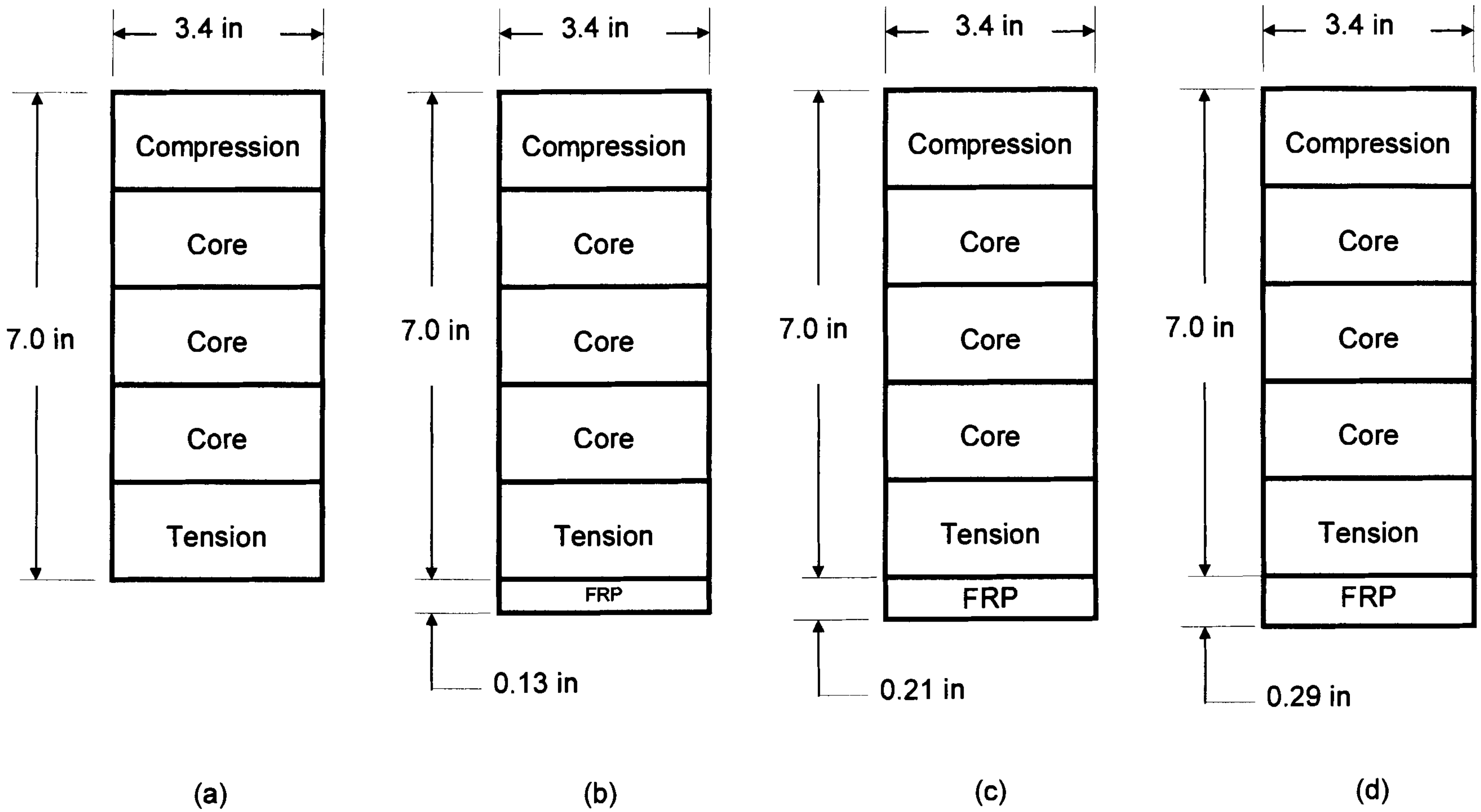


Figure 5.1: Cross-Sections of Test Beams (a) Unreinforced (b) 2% Reinforced (c) 3% Reinforced (d) 4% Reinforced

5.4 Beam Fabrication

Beams were fabricated at the University of Maine. Beams were 3.66 m (12 ft) long and 8.64 cm (3.4 in) wide. Control beams had five, full-length, 3.56 cm (1.4 in) thick laminations (see Figure 5.1). Reinforced beams had five, full-length, 3.56 cm (1.4 in) thick laminations plus the reinforcement. Bumperlams were not used with the reinforced beams. The five laminations of every beam were glued and clamped together. The reinforcement was applied during a second clamping procedure.

The resin in the wetpreg reinforcement served as both matrix for the glass and as adhesive for bonding the FRP and the wood. No adhesive was applied to the face of the tension lamination. Tests (see Chapter 4) have shown that the "squeeze-out" of resin from the wetpreg under glulam clamping pressures provides adequate bonding without having to apply adhesive directly to the wood.

5.4.1 Clamping

The beams were clamped at 550 kPa (80 psi) for 20 to 24 hours. The same system as was used to clamp the Pilot Beams was used (see Chapter 3). Lateral clamping was used, providing uniform cross-sections, which was not done for the Pilot Beams.

5.5 Experimental Test Setup and Test Procedure

The same test setup was used as with testing the Pilot Beams. See Figure 3.6 for a sketch and Figure 3.7 for a photograph of the test setup.

Beams were tested in four point bending. Beams were 3.66 m (12 ft) long with an 3.35 m (11 ft) clear span. The distance between center load heads was 914 cm (3 ft). Lateral bracing was provided 1.07 m (3.5 ft) from each support.

The beams were loaded "upside down" with the tension face on top and the compression face on bottom, because the 97.9 kN (22 kip) MTS actuator was more stable when retracting upwards than when extending downwards. Instrumentation included: 1) external LVDT at midspan, 2) MTS LVDT, and 3) MTS load cell.

Testing followed ASTM D198. Testing was done in load-control. Load rate was selected such that the expected time to failure was ten minutes, with six and twenty minutes being the lower and upper bounds.

5.6 Experimental Results

Results of beam testing are presented using data from an external LVDT, MTS LVDT, and MTS load cell. MOE was determined in the elastic region. Full load deflection curves are plotted.

At time of testing, beams had a mean moisture content (MC) of 10.1% with a standard deviation of 0.7%. Moisture contents ranged from 9.3% to 12.3%, based on an average of three measurements for each beam. Since MCs

were very similar, strength and stiffness results were not adjusted to account for MC variability.

5.6.1 Initial Beam MOE

The modulus of elasticity (MOE) of the beams was determined by using load deflection data during initial loading. An arbitrary load of about 8.9 kN (2000 lbs) and the corresponding deflection was selected to determine the MOE. The results are given in Tables 5.4 through 5.8. The equation used was the same as used for Pilot Beams. See equation 3.2.

5.6.2 Beam Failure Modes

It should be noted that once failure began in a beam, failure progressed very quickly, and often nearly instantaneously. It was difficult to determine the order of events leading to failure. See Table 5.2.

5.6.2.1 Unreinforced Beams

Nine of the ten unreinforced beams failed in tension. Tension failure typically began at a knot on the beam tension side, within 0.9 m (3 ft) of the center span. Beams that failed in this manner were C-1, C-2, C-3, C-5, C-6, C-9, and C-10. Beam C-8 failed in tension, but did not begin at a knot. Beam C-7 exhibited compression failure in two locations before failing in tension at a knot in

Table 5.2: Beam Failure Modes

Beam Designation	Failure Modes
Unreinforced	
C-1	Tension at a Knot
C-2	Tension at a Knot
C-3	Tension at a Knot
C-4	Compression, then Shear
C-5	Tension at a Knot
C-6	Tension at a Knot
C-7	Compression, then Tension at a Knot
C-8	Tension
C-9	Tension at a Knot
C-10	Tension at a Knot
2% Reinforced	
R2-1	Tension at a Knot
R2-2	Compression, then Tension at a Knot
R2-3	Compression, then Tension at a Knot
R2-4	Tension at a Knot
R2-5	Compression, then combo. of Shear and Tension
R2-6	Compression, then Tension at a Knot
R2-7	Compression, then Tension at a Knot
3% Reinforced	
R3-1	Compression, then Tension at a Knot
R3-2	Compression, then Tension at a Knot
R3-3	Tension
R3-4	Tension
R3-5	Compression, then Tension
R3-6	Compression, then Shear and Tension
R3-7	Compression, then Tension at a Knot
4% Reinforced	
R4-1	Compression, then Tension
R4-2	Compression, then Tension
R4-3	Compression, then Tension
R4-4	Combo. of Shear and Tension
R4-5	Shear
R4-6	Compression, max-out actuator before catastrophic failure
R4-7	Compression, the Shear

the second tension lamination. Beam C-4 exhibited compression failure in three locations before failing in shear.

5.6.2.2 2% Reinforced Beams

Five out of seven 2% reinforced beams failed in tension at a knot. Four of those five delaminated between the reinforcement and the wood, from the point of tension failure to the near end of the beam, following tension failure. The other one of the five delaminated between reinforcement plies. The delamination occurred after tension failure began, indicating that delamination initiated due to a redistribution of stress at the location of wood tension failure causing a stress concentration at the bond line. Five of the seven 2% beams exhibited compression failure prior to ultimate failure.

Beams R2-1, R2-3, R2-6, and R2-7 failed in this manner. Beams R2-4 failed in tension and then delaminated between reinforcement plies. Beams R2-3 and R2-4 exhibited a small compression failure prior to tension failure, while beam R2-6 exhibited a large compression failure prior to tension failure.

Beam R2-5 exhibited compression failure in one location, followed by a combination of shear and tension failure and delamination between reinforcement plies. Beam R2-2 exhibited two locations of compression failure, followed by a tension failure at a knot and failure within the tension lamination out to the end of the beam. The reinforcement remained intact for beam R2-2.

5.6.2.3 3% Reinforced Beams

Six of the seven 3% reinforced beams failed in tension. Five of the seven beams exhibited compression failure. Beam R3-1 exhibited compression failure in one location, followed by tension failure at a knot and reinforcement delamination. Beam R3-2 exhibited compression failure in three locations, followed by tension failure and reinforcement delamination. Beam R3-3 failed in tension and delaminated between reinforcement plies. Beam R3-4 failed in tension at a knot in the second tension lamination, and failed to the end of the beam in the second and outer tension laminations. The reinforcement remained intact for beam R3-4. Beam R3-5 exhibited compression failure in four locations, followed by tension failure and reinforcement delamination. Beam R3-6 exhibited compression failure in one location, followed by a combination of shear and tension failure at the end of the beam. Beam R3-7 exhibited compression failure in four locations, followed by tension failure at a knot. The reinforcement remained intact for beam R3-7.

5.6.2.4 4% Reinforced Beams

Five of the seven 4% reinforced beams failed in tension. Six of the seven beams exhibited compression failure prior to ultimate failure. Beam R4-1 and R4-2 both exhibited two large compression failures, followed by tension failure and reinforcement delamination. Beam R4-3 exhibited compression failure in five locations, followed by tension failure. Beam R4-4 failed in a combination of

shear and tension with reinforcement delamination. Beam R4-6 exhibited a large compression failure, followed by a crack in the tension lamination. It deflected very quickly before it maxed out the stroke on the MTS actuator. It was very close to ultimate failure, but did not fail catastrophically because of the deflection restriction.

Beam R4-5 failed in shear. Beam R4-7 exhibited compression failure in two locations before failing in shear. The two beams failed prematurely in shear, and therefore did not reach their ultimate bending capacity. Since determination of the effect of reinforcement addition was based on comparing bending capacities, the two beams were removed from bending strength analysis.

5.6.2.5 Compression Failures

In Chapter 1 it was discussed that compression failure was desirable in a glulam beam. Efficient utilization of material and a ductile failure mode are two primary results of compression failure in glulam. Of the ten unreinforced beams tested only two exhibited compression failure. For the reinforced beams, 5 of the 7 beams with 2% reinforcement, 5 of the 7 beams with 3% reinforcement, and 4 of the 5 beams with 4% reinforcement exhibited compression failure (See Table 5.3 for a list of the beams that exhibited compression failure).

It appears as though 2% reinforcement was enough to induce compression failure. Generally, compression wrinkles for 2% reinforced beams were small and increased in size with increasing amounts of reinforcement. Also, the ductility of the beams increases with an increase in reinforcement, as

can be seen in Figures 5.2 through 5.5. See Appendix E for some photographs of failed beams.

Table 5.3: Beams That Exhibited Compression Failure

Control Beams	2% Beams	3% Beams	4% Beams
C-4	R2-2	R3-1	R4-1
C-7	R2-3	R3-2	R4-2
	R2-4	R3-5	R4-3
	R2-5	R3-6	R4-6
	R2-6	R3-7	

5.6.3 MOR, Max Load, and Max Displacements

Maximum load, maximum displacement, modulus of rupture (MOR), and initial MOE of the beams are shown in Tables 5.3 through 5.6 for each reinforcement level, respectively. MOR was determined based on gross section properties and ultimate moment. Load deflection curves for the beams are given in Figures 5.2 through 5.5.

It is interesting to note increased ductility as reinforcement increases. The test was performed in load control, so toughness could unfortunately not be measured. It is suspected however that glulam beams become much tougher with increasing reinforcement.

It should be noted that beams R2-4, R3-2, R3-5, R3-6, R4-1, and R4-3 experienced lateral torsional buckling when approaching their maximum capacity. These beams showed either large "jumps" in deflection when buckling occurred, or large increases in deflection with little change in load following buckling. It

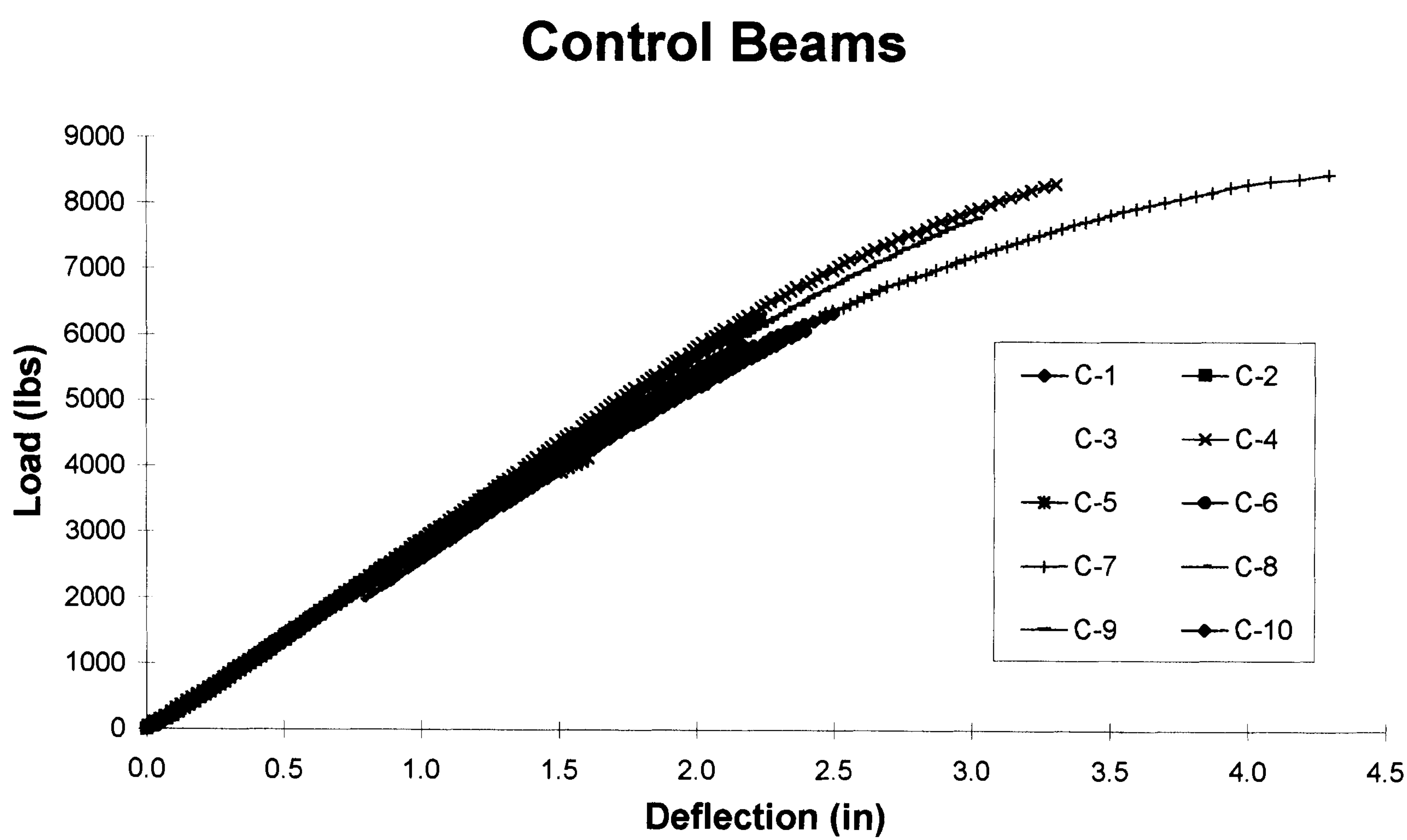


Figure 5.2: Control Beam Load-Deflection Curves

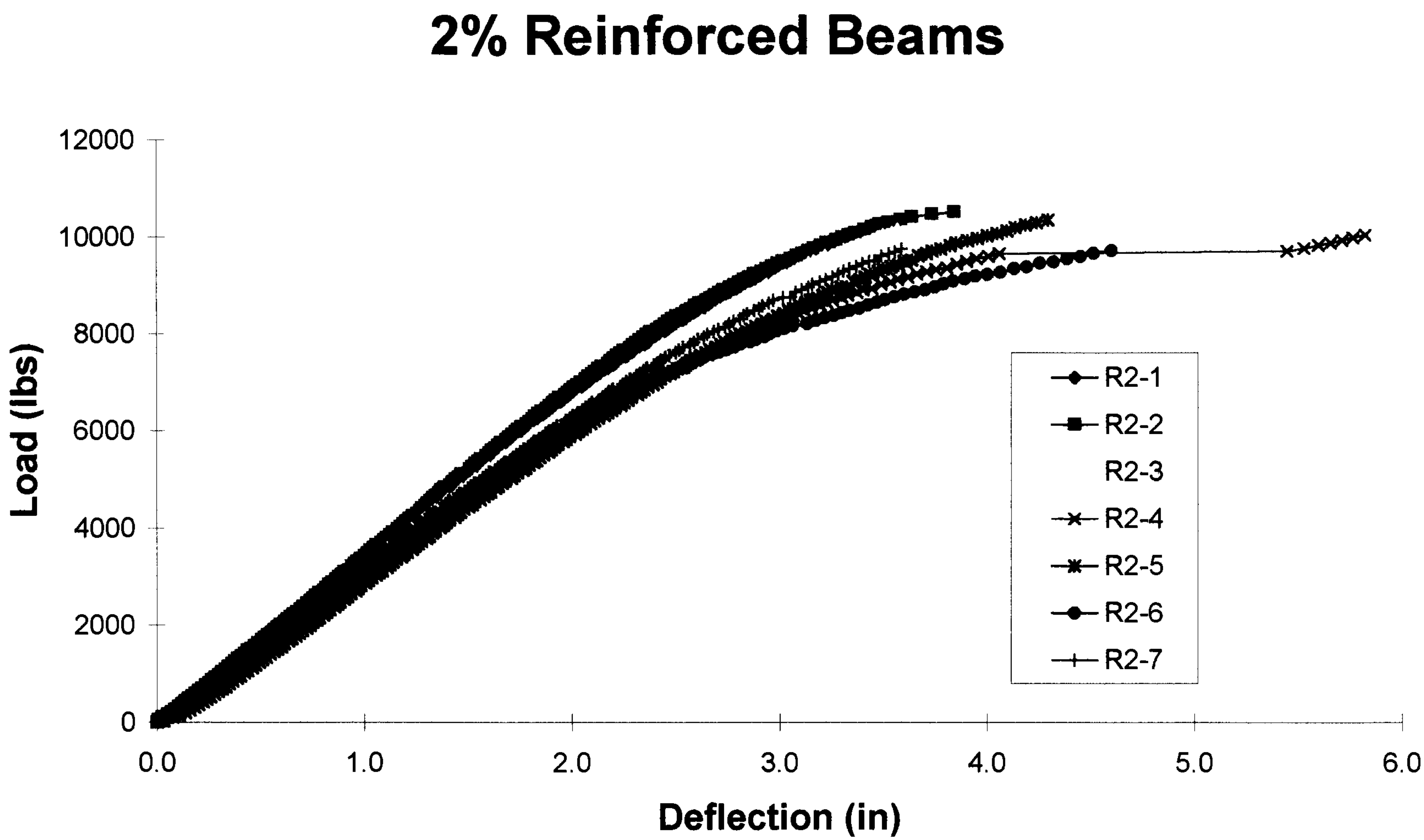


Figure 5.3: 2% Reinforced Beam Load-Deflection Curves

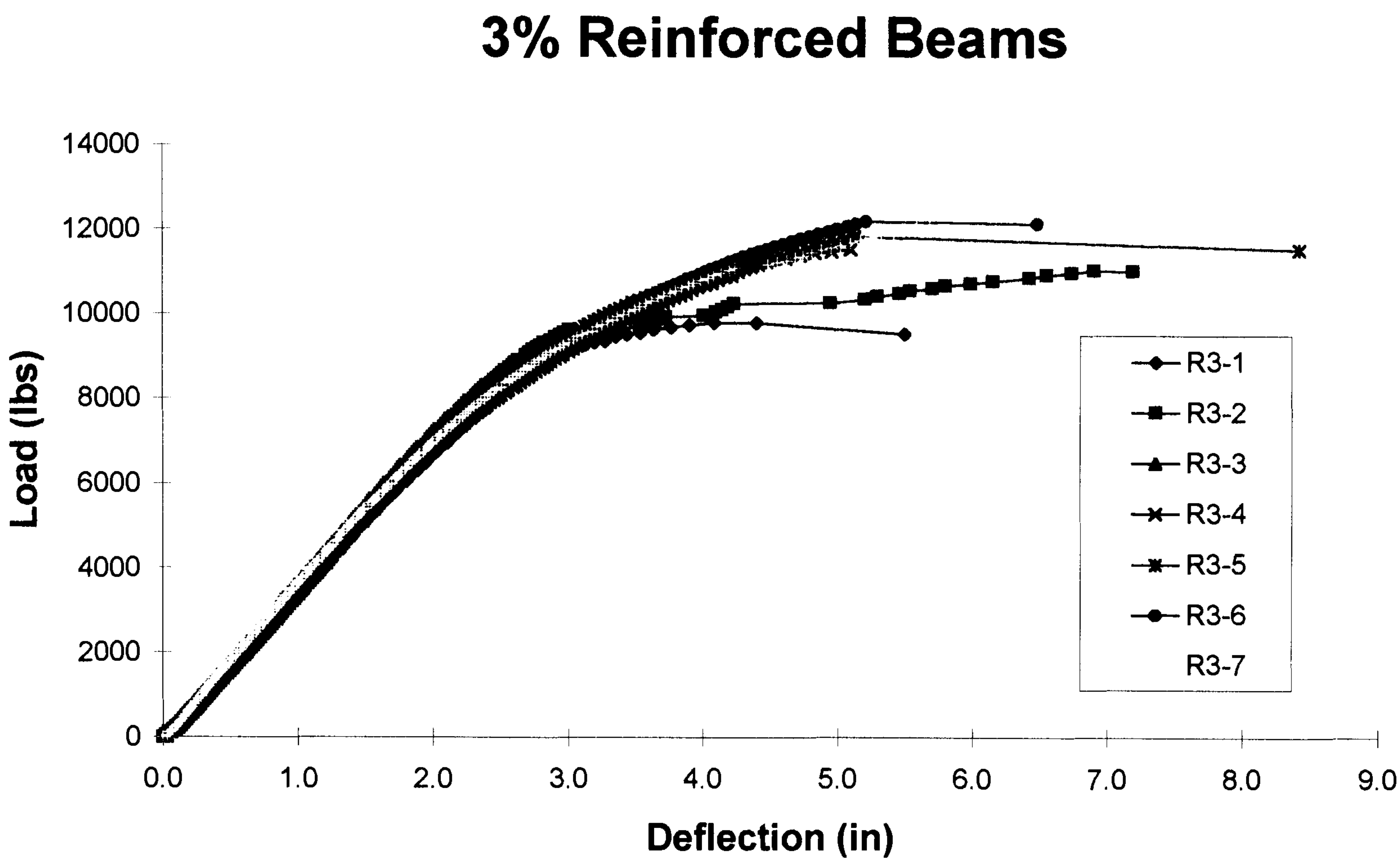


Figure 5.4: 3% Reinforced Beam Load-Deflection Curves

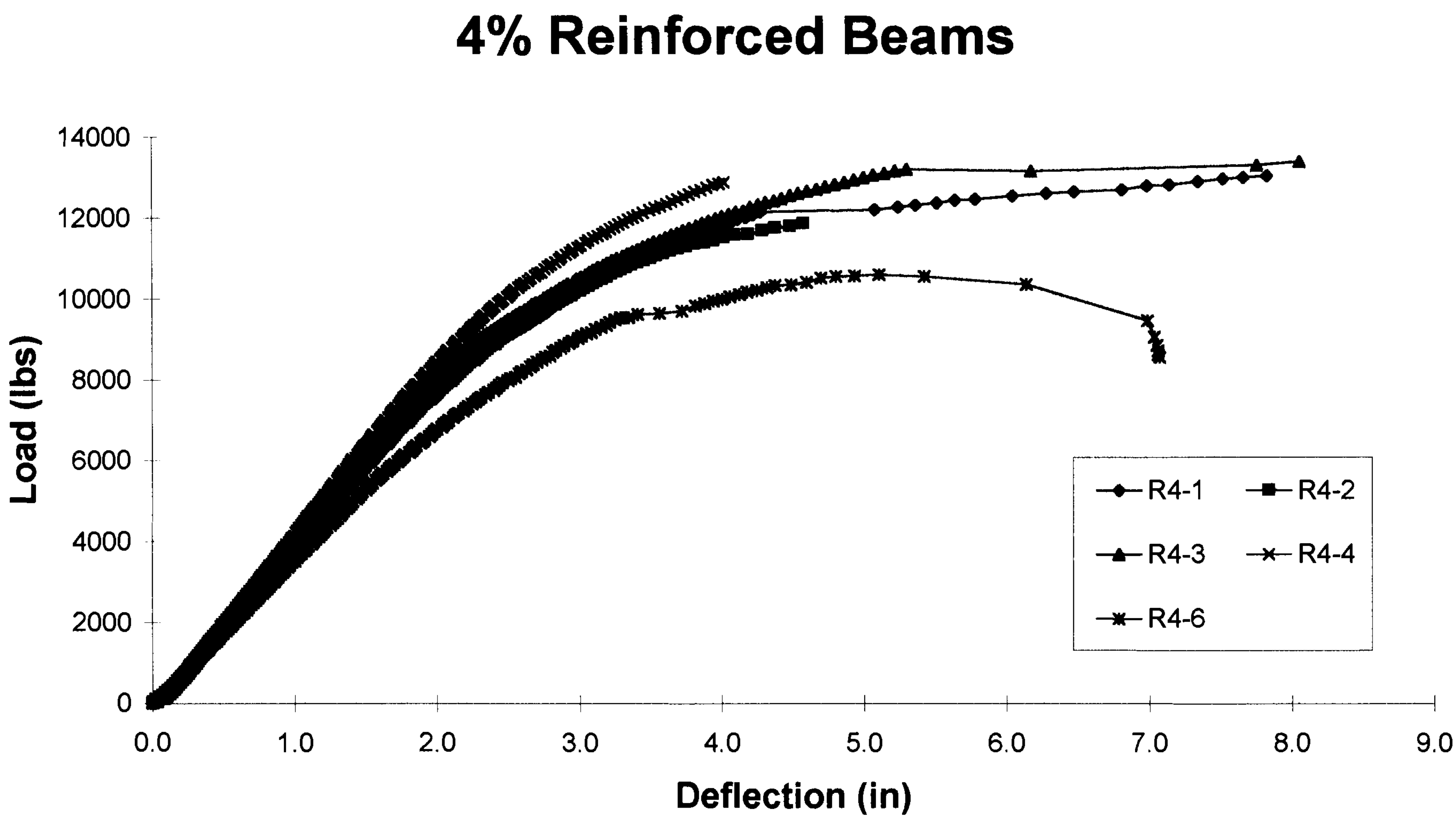


Figure 5.5: 4% Reinforced Beam Load-Deflection Curves

was hoped that buckling would not occur as it had with the pilot beams, since lateral clamping was provided.

Table 5.4: Load-Deflection Summary of Control Beams

Beam Designation	Max. Load kN	(lbs)	MOR MPa	(psi)	Max. Deflect. cm	(in)	Initial MOE GPa	(Msi)
C-1	27.0	(6070)	36.2	(5250)	6.07	(2.39)	7.79	(1.13)
C-2	27.8	(6250)	37.2	(5400)	5.66	(2.23)	8.55	(1.24)
C-3	29.0	(6520)	38.9	(5640)	6.27	(2.47)	8.34	(1.21)
C-4	37.1	(8330)	49.6	(7200)	8.38	(3.30)	8.62	(1.25)
C-5	18.5	(4150)	24.7	(3580)	4.09	(1.61)	8.76	(1.27)
C-6	26.0	(5840)	34.8	(5050)	5.49	(2.16)	8.69	(1.26)
C-7	37.7	(8480)	50.5	(7320)	10.9	(4.29)	8.27	(1.20)
C-8	34.6	(7790)	46.5	(6740)	7.65	(3.01)	8.55	(1.24)
C-9	26.5	(5960)	35.5	(5150)	5.84	(2.30)	8.27	(1.20)
C-10	28.2	(6340)	37.8	(5480)	6.32	(2.49)	8.41	(1.22)
Mean	29.2	(6573)	39.2	(5681)	6.65	(2.62)	8.41	(1.22)
COV	19.9 %		19.9 %		28.4 %		3.3 %	

Table 5.5: Load-Deflection Summary of 2% Reinforced Beams

Beam Designation	Max. Load kN	(lbs)	MOR MPa	(psi)	Max. Deflect. cm	(in)	Initial MOE GPa	(Msi)
R2-1	45.6	(10250)	58.9	(8540)	8.76	(3.45)	9.72	(1.41)
R2-2	46.8	(10520)	60.5	(8770)	9.75	(3.84)	9.79	(1.42)
R2-3	45.3	(10180)	58.5	(8480)	9.07	(3.57)	8.89	(1.29)
R2-4	44.7	(10050)*	57.8	(8380)	14.8	(5.82)	9.03	(1.31)
R2-5	46.1	(10360)	59.5	(8630)	10.9	(4.29)	7.86	(1.14)
R2-6	43.3	(9730)	55.9	(8110)	11.7	(4.60)	8.96	(1.30)
R2-7	43.5	(9770)	56.1	(8140)	9.12	(3.59)	8.83	(1.28)
Mean	45.0	(10124)	58.2	(8435)	10.6	(4.16)	9.03	(1.31)
COV	2.9 %		2.9 %		20.2 %		7.3 %	

*Lateral buckling just prior to failure.

Table 5.6: Load-Deflection Summary of 3% Reinforced Beams

Beam Designation	Max. Load kN	(lbs)	MOR MPa	(psi)	Max. Deflect. cm	(in)	Initial MOE GPa	(Msi)
R3-1	43.6	(9800)	55.0	(7980)	14.0	(5.50)	9.58	(1.39)
R3-2	49.1	(11030)*	62.0	(8990)	18.3	(7.19)	9.24	(1.34)
R3-3	45.5	(10240)	57.5	(8340)	8.86	(3.49)	9.52	(1.38)
R3-4	51.3	(11540)	64.8	(9400)	13.0	(5.10)	9.03	(1.31)
R3-5	52.7	(11840)*	66.5	(9650)	21.4	(8.42)	9.31	(1.35)
R3-6	54.3	(12210)*	68.5	(9940)	16.5	(6.48)	9.65	(1.40)
R3-7	53.9	(12120)	68.1	(9880)	14.4	(5.68)	10.1	(1.46)
Mean	50.1	(11254)	63.2	(9169)	15.2	(5.98)	9.52	(1.38)
COV	8.3 %		8.3 %		26.4 %		3.4 %	

* Lateral buckling just prior to failure.

Table 5.7: Load-Deflection Summary of 4% Reinforced Beams

Beam Designation	Max. Load kN (lbs)	MOR MPa (psi)	Max. Deflect. cm (in)	Initial MOE GPa (Msi)
R4-1	58.1 (13060)*	71.8 (10410)	19.9 (7.82)	10.8 (1.56)
R4-2	52.8 (11870)	65.2 (9460)	11.6 (4.57)	9.65 (1.40)
R4-3	58.7 (13420)*	73.8 (10700)	20.4 (8.04)	10.5 (1.52)
R4-4	57.4 (12900)	70.9 (10280)	10.2 (4.01)	10.7 (1.55)
R4-5	31.9 (7180)**	-	16.9 (6.65)	10.8 (1.56)
R4-6	47.2 (10620)	58.3 (8460)	18.0 (7.07)	9.45 (1.37)
R4-7	55.6(12510)**	-	9.58 (3.77)	11.1 (1.61)
Mean	55.0 (12374)	68.0 (9862)	16.0 (6.30)	10.4 (1.51)
COV	9.2 %	9.2 %	29.9 %	5.9 %

*Lateral buckling just prior to failure.
**Beams R4-5 and R4-7 failed in shear, so they will be excluded from the set for purposes of ultimate strength, but not for initial stiffness.

Table 5.8 summarizes MOR and MOE statistics. The coefficient of variation (COV) of the MOR was 19.9% for unreinforced beam strengths, but dropped to 2.9%, 8.3%, and 9.2% for 2%, 3%, and 4% reinforced beams, respectively. Addition of reinforcement reduces strength variability dramatically. According to ASTM D 2915, standard deviations of 2.104, 2.251, and 2.464 are to be subtracted from the mean to obtain the 5% lower tolerance limit (LTL) with a 75% confidence level from sample sizes of 10, 7, and 5, respectively. According to ASTM D3737, the allowable strength is obtained by dividing the 5% LTL by a factor of 2.1.

Table 5.8: Summary of MOR and MOE Statistics

Beam Type	# of Samples	MOR Mean MPa(psi)	MOR COV (%)	MOR 5% LTL * MPa(psi)	MOR Allowable Stress** MPa(psi)	MOE Mean MPa(psi)	MOE COV (%)
Control	10	39.17 (5681)	19.9	22.77 (3303)	10.85 (1573)	8.41 (1.22)	3.3
2% Rein-forced	7	58.16 (8435)	2.9	54.35 (7882)	25.88 (3753)	9.03 (1.31)	7.3
3% Rein-forced	7	63.22 (9169)	8.3	51.35 (7448)	24.46 (3547)	9.52 (1.38)	3.4
4% Rein-forced	5	68.00 (9862)	9.2	52.60 (7629)	25.05 (3633)	10.4 (1.51)	5.9

* LTL = Lower Tolerance Limit
** Allowable Stress = 5% LTL / 2.1 as per ASTM D3737

Table 5.9 compares the strengths and MOEs of the reinforced beams to that of the controls, based on mean values.

Table 5.9: Comparison of Reinforced Beams to Unreinforced Beams

Beam Type	Mean Load Increase (%)	Mean MOR Increase (%)	Allow. Strength Increase (%)	Initial MOE Increase (%)
2% Reinforced	54.0	50.2	139	7.0
3% Reinforced	71.2	61.4	126	12.5
4% Reinforced	88.3	73.6	131	23.7

The mean ultimate load carrying capacity of a glulam beam can be increased by 54% with only a 2% reinforcement ratio, or by 88% with a 4% reinforcement ratio. Even better, however, is the increase in allowable strength. The 5% LTL is reduced less for reinforced beams because of smaller COVs. This, in addition to increased ultimate strength, causes allowable strengths of reinforced beams to be over twice that of unreinforced beams. A beam with only 2% reinforcement has an allowable strength that is 139% greater than an unreinforced beam. It should be noted that the largest allowable strength increase occurred for the 2% beams, rather than for the 3% or 4% beams, because the COV was very low, being only 2.9%.

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Summary

6.1.1 Overview

The objective of this project was to create an inexpensive, high strength, reinforced glulam beam. Research was divided into three parts: 1) pilot beam testing, 2) material and process refinement, and 3) experimental beam testing. Seven glulam pilot beams, 4 reinforced and 3 unreinforced, were tested in four point bending to ultimate failure. Extensive shear, cyclic delamination, and tensile testing was performed with six E-glass fabrics and two resin systems. Thirty-one experimental glulam beams, 21 reinforced and 10 unreinforced, were tested in four point bending to ultimate failure.

6.1.2 Literature Review

Research on reinforced wood has been on-going since World War 2. Attempts have been made to bond both steel and aluminum plates and bars to wood beams. The focus of current research, however, is the application of fiber reinforced polymers.

6.1.3 Pilot Beam Testing

Seven, 3.66 m (12 ft) long, 17.8 cm (7 in) deep, 8.64 cm (3.4 in) wide glulam beams were fabricated using Eastern Hemlock at the University of Maine. Four glulam beams were wetpreg reinforced at a 3.3% reinforcement ratio using unidirectional E-glass fabric. The beams were tested in bending to ultimate failure, and compared against the results of three unreinforced beams.

6.1.4 Materials and Process Refinement

The materials evaluated were three unidirectional stitched E-glass fabrics, three unidirectional weave E-glass fabrics, a phenolic-resorcinol-formaldehyde (PRF) adhesive, and an acid-cure phenolic resin. Open times of zero and forty minutes and clamping pressures of 690 MPa (100 psi), 550 MPa (80 psi), and 275 MPa (40 psi) were used. Testing was conducted through shear block, short beam shear, cyclic delamination, and tensile tests. Shear testing evaluated the strength of wood-wood, FRP-wood, and FRP-FRP bonds. Cyclic delamination evaluated bond durability. Tensile strengths and stiffnesses were obtained through tensile testing.

6.1.5 Experimental Program

Thirty-one Eastern Hemlock beams were fabricated and tested in bending to ultimate failure. Ten beams were unreinforced and seven beams were

reinforced with each 2%, 3%, and 4% reinforcement ratios using unidirectional E-glass fabric and PRF resin.

6.2 Conclusions

6.2.1 Pilot Beam Testing

Wetpreg reinforcement of glulam using unidirectional E-glass fabric and PRF resin is feasible. Adding only 3% reinforcement increased mean beam strength by 88%, but did not change stiffness.

6.2.2 Materials and Process Refinement

GP 4242/4554 PRF adhesive and U 18 - 01 E-glass stitched fabric was the best system, among those tested, to use as wetpreg reinforcement of eastern hemlock. Unmodified GP 4242/4554 created strong FRP-wood bonds, being 10.08 MPa (1462 psi) for FRP-wood with U-18-01 fabric and 8.677 MPa (1258 psi) for FRP-wood with VEW 260 B fabric. Unmodified GP 4242/4554 also created strong interlaminar (FRP-FRP) bonds, being 12.79 Mpa (1855 psi) for short beam shear with U-18-01 fabric and 9.559 MPa (1386 psi) for shear block strength with VEW 260 B fabric.

Methanol addition to GP 4242/4554 adhesive decreased bond strength by 20.4% for FRP-FRP bonds. The methanol addition had no significant effect on either FRP-wood or wood-wood bond strengths. Caustic addition to GP 4242/4554 had no significant effect on FRP-FRP bond strengths, but increased

FRP-wood bond strengths by 13.9% and wood-wood bond strengths by 24.2%. The caustic addition decreased pot life to about 15 minutes, making application to glulam fabrication difficult.

GP 5022/4822 resin was not suitable for use with E-glass in wetpreg reinforcement of glulam. The GP 5022/4822 produced good bond strengths of 8.682 MPa (1259 psi) for wood-wood, 10.53 MPa (1527 psi) for FRP-wood, and 8.874 MPa (1287 psi) FRP-FRP shear strengths. However, large amounts of glue-line failure occurred, being 47% for wood-wood and 36% for FRP-wood bonds. Also, cycle delamination specimens failed with GP 5022/4822.

For stitched fabrics, chopped mat backing was not desirable, whereas a polyester veil backing was. Short open times produced slightly better bond strengths. "Z" fibers were not needed.

Unidirectional weave fabrics perform well. The VEW 260 A, B, and C fabrics performed similarly. There was no significant difference in performance of standard and phenolic sizings or of stitched and chemical bindings.

6.2.3 Experimental Program

Reinforced beams showed mean load capacity increases over the unreinforced controls of 54%, 71%, and 88% for 2%, 3%, and 4% reinforced beams, respectively. Reinforced beams showed allowable strength increases of 139%, 126%, and 131% for 2%, 3%, and 4% reinforced beams, respectively, because of both increased strength and decreased variability.

6.2.4 Optimum Reinforcement

The increased allowable strength was similar for the three levels of reinforcement, despite the increased mean ultimate strength for increased amounts of reinforcement. Beams with different reinforcement ratios were considered to be of equivalent strength, since allowable stress design is currently used with glulam. Beams with the smaller amounts of reinforcement was less expensive and equivalent in strength to the 3% and 4% reinforced beams; therefore, 2% reinforcement was most effective under the test conditions used.

6.2.5 Reinforced Beam Cost Estimate

A material's cost estimate was conducted (see Appendix F) for beams based on allowable stress design. The assumed costs of materials were the following: $0.35/board foot for No. 2 and better eastern hemlock lumber, $1.30/lb for VEW 260 E-glass fabric, and $0.80/lb for GP 4242/4554 adhesive. A 2% reinforced beam resulted in a decreased wood volume of 58.2%, and a cost savings of 8.5%. The cost savings would likely improve in the future, as the trend in the past has been increasing lumber costs and decreasing reinforcement costs.

6.3 Recommendations for Future Research

6.3.1 Materials

The best fabric tested was the U-18-01, which was a unidirectional E-glass fabric stitched to a thin polyester veil. It could be beneficial to use the same fabric type, but increase its weight to reduce the number of plies needed. Shear, cyclic delamination, and tensile testing would need testing for the new weight fabric.

The GP 4242/4554 adhesive performed well for both bond strength and durability. There was, however, concern for its performance when used in thick layups, on the order of an inch, because of water and solvent byproducts of curing. The byproducts have no means of escape from the center of a thick laminate, and may create points of weak bonding.

Testing of bond lines was primarily done through shear block testing. Some work was done with a short beam shear test, which is thought to be a better method of evaluating the interlaminar shear strength of the FRP. More of the short beam shear test should be performed in the future. Also, Mode 1 fracture testing should be implemented to evaluate interlaminar bond strength and toughness.

It was important to be able to produce reinforcing fabric that does not have loose fibers on the edges. Loose tows of fibers on the fabric edge resulted from the cutting of a wide roll of fabric into smaller rolls. The cut edge fibers tended to wrap around the rollers of the impregnator and get caught, slowing down

production, as the impregnation had to be stopped until the caught fibers could be cut away from the rollers.

6.3.2 Processes

Even though the GP 4242/4554 is a room temperature cure adhesive, it was thought that applied heat would produce a stronger bond. The reinforcement would be the primary beneficiary of the additional heat, as it had a large amount of resin that needed curing. A possible method to provide the extra heat would be to apply the reinforcement to a preheated tension lamination. The latent heat within the wood could improve bonding.

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Appendix A:

Resin and Adhesive Product Information

Georgia-Pacific

Georgia-Pacific Resins, Inc.

2883 Miller Road • Decatur, Georgia 30035 • Tel: (770) 593-6800 • Fax: (770) 322-9973

Technical Bulletin - PUB 151B

Laminating Softwoods with Resorsabond® 4242/4554 Slurry Adhesive

Introduction

Resorsabond® 4242/4554 slurry adhesive is a room temperature-curing phenol-resorcinol adhesive system specifically designed for laminating and general assembly gluing of western softwoods and southern yellow pine. This slurry adhesive is a two-component (liquid/liquid) exterior (wet-use) adhesive developed for use with liquid/liquid meter-mixing direct application equipment. With proper adhesive application and upon final curing, the slurry adhesive will produce a waterproof glue bond which meets the specifications for exterior exposure conditions.

Laminates which may be subjected to severe use conditions are often post-treated with wood preservatives. The bond obtained from a properly metered, mixed, applied and cured slurry adhesive will not be affected by this post-treatment. Lumber which has been pretreated for improved decay resistance or fire retardancy can present gluing problems and must be thoroughly evaluated before any gluing production is scheduled.

Resorsabond® 4242/4554 slurry adhesive is faster curing than the Resorsabond® 4242/4553 system. Although this faster curing characteristic results in shorter glue working life and assembly times, it is advantageous for cold weather gluing conditions.

Description

Resorsabond® 4242/4554 slurry adhesive is supplied in two components:

1. Resorsabond® 4242 - liquid phenol-resorcinol resin; and
2. Resorsabond® 4554 - powder hardener that is mixed with a prescribed amount of water prior to use to produce a liquid slurry hardener.

Resorsabond® 4242 liquid resin and slurried Resorsabond® 4554 hardener are mixed in predetermined proportions to produce the finished adhesive system. This two-component adhesive system with the intermediate step of preparing the slurry hardener is designed for mixing with a continuous liquid/liquid proportionating meter mixer where short mixing time requires rapid viscosity buildup. This slurry adhesive is especially adapted for extruder spreading and vertical lay-up procedures. When properly mixed, the finished adhesive gives an excellent extruder glue bead pattern which strongly resists sagging or run-off when lumber is standing on edge prior to and during assembly before pressure is applied to the total assembly.

Georgia-Pacific

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Product Information - PUB 151

Resorsabond® Product Information

Resorsabond® 4242 Resin

Typical Properties

Type	phenol-resorcinol-formaldehyde
Appearance	red/purple liquid
Non-volatiles, %	53.5 - 54.5
Density, lbs./gal. @ 25°C	9.58 - 9.66
Viscosity, cps @ 25°C	1200 - 2000
pH	8.8 - 9.8
Flash Point, °F	> 200
Free Formaldehyde, %	< 0.1
Free Phenol, %	9.0 - 9.5
Storage Life at 25°C	3 months

Resorsabond® 4554 Hardener

Typical Properties

Appearance	brown/gray powder
Density, lbs./cu. ft. @ 25°C	25 - 27
Free Formaldehyde, %	< 2.0
Storage Life at 20°C	3 months

Resorsabond® 4242/4554 slurry adhesive system meets the requirements of the following standards:

- **ASTM, D-2559-92, "Standard Specification for Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet-Use) Exposure Conditions;" and**
- **ANSI / AITC, A190.1-1992, "American National Standard for Wood Products - Structural Glued Laminated Timber."**

Handling

Whenever Resorsabond 4242 resin, Resorsabond 4554 hardener or Resorsabond 4242/4554 slurry adhesive are handled, personal protective equipment - rubber gloves, rubber aprons and protective glasses or goggles - should be worn. In case of skin contact, immediately wash skin thoroughly with soap and water. For eye contact, flush eyes with large quantities of water for at least 15 minutes and contact a physician. Avoid breathing dust and vapors. Use with adequate ventilation.

Resorsabond 4242/4554 - Properly mixed and stored, Resorsabond 4242/4554 adhesive contains less than 1% free formaldehyde.

Resorsabond 4242 Resin - Contains phenol. Prolonged skin contact may cause dermatitis in some individuals.

Resorsabond 4554 Hardener - Contains formaldehyde. Formaldehyde is irritating to mucous membranes and may cause dermatitis. The dust is potentially explosive if dispersed in air and exposed to flames, sparks or static electricity.

Storage

Resorsabond 4242 resin is supplied in nonreturnable 5-gallon pails, nonreturnable 55-gallon drums, tote bins and tank trucks. Storage life is four months at 70°F and may be extended by storing at lower temperatures. Resorsabond 4242 may be stored under refrigeration at temperatures as low as 40°F.

Resorsabond 4554 hardener is supplied in 50-pound bags, 200-pound returnable open-top poly drums, and 1000- to 1500-pound super sacks. Containers must be kept tightly closed during storage. Storage life is four months when kept in closed containers in a cool, dry place. Prolonged aging may cause minor changes in the efficiency of the hardener. Therefore, containers are marked to indicate the end of recommended usable life and outdated hardeners must be retested prior to use.

Mixing Instructions

Resorsabond 4242/4554 slurry adhesive can be adapted for use with most of the current continuous liquid/liquid meter-mixing equipment.

Prior to use, Resorsabond 4554 hardener is slurried with tap water in a ratio of 40 parts hardener to 60 parts water with the hardener added to the water for best results. Continuous slow agitation of this slurry is required for continuous in-line liquid/liquid meter-mixing equipment. Agitation is recommended to minimize any settling of the hardener components. The recommended use life of the hardener slurry is 72 hours. It is recommended that the hardener slurry be kept cool. Resorsabond 4242 liquid resin is proportionately metered with slurried Resorsabond 4554 hardener at a ratio of 70 parts resin to 30 parts slurried hardener.

Please refer to the attachment entitled "Resorsabond® 4242/4554 Slurry Adhesive Mixing Instructions and Handling Precautions" for detailed preparation instructions and material handling precautions. Copies of the document should be posted in your mixing and gluing areas.

Conditions of Wood

The wood surface to be bonded should be clean, freshly prepared, knife-planed smooth, and carefully fitted. IMPORTANT: Wood moisture content should not exceed 16%. For optimum bond quality, the moisture content should be within the 8% - 12% range. The moisture content of the wood to be bonded should not be considered as an average, but rather all moisture values should fall within the range specified above.

Spreading

The recommended spread weight range for this slurry adhesive is 60 to 95 pounds per 1,000 square feet of single glue line. The heavier spread weights are required for longer assembly times and higher lumber temperatures. With lay-up procedures where spread lumber is placed on edge, it is recommended that frequent inspections be made to ensure that the applied adhesive has the required anti-sag property and is not running off.

Assembly Time

The following table of maximum allowable assembly times is given for range of lumber temperatures and spread weights in pounds of glue per 1,000 square feet of single glue line. Gluing lumber having temperatures above or below the specified range is not recommended due to the adverse effects on assembly time and cure conditions.

Maximum Total Assembly Time

Lumber Temperature	Spread Weight, lbs. of glue/1000 sq. ft. of single glue line			
	60 lbs.	75 lbs.	85 lbs.	95 lbs.
	Total Assembly Time, minutes			
55° F	80	90	100	120
65° F	55	65	80	95
75° F	40	50	55	70
80° F	35	40	45	55

NOTE: The maximum total assembly time in minutes comprises the sum of both the open and closed assembly times. The open assembly time should not exceed 1/3 of the total assembly time. For example, with a glue spread of 75 lbs. and a lumber temperature of 65°F, the maximum total assembly time is 65 minutes with a maximum open assembly time of 22 minutes.

IMPORTANT: The entire assembly should be placed under full pressure before the first glue lines have lost tackiness to the touch and appear dry.

Open Assembly = the time interval between first spreading the surfaces and placing them in close proximity with each other. During this period, the glue spread surfaces are exposed to air and are subject to evaporation losses.
Closed Assembly = the time the surfaces are in contact until the application of pressure. During this period, the spread surfaces are protected from evaporation.
Total Assembly = the time interval between spreading the first surface to application of full pressure. It is the sum of both the open and closed assembly times.

Pressure

Clamping pressure of 100-150 psi is recommended for Western softwoods and Southern pine. High density wood and highly cambered beams will require higher pressures. In all cases, the assembly conditions and clamping pressure should produce a uniform glue squeeze-out along the entire length of the glue lines.

Curing

For laminated lumber gluing, the following table shows the *ABSOLUTE MINIMUM clamp time at the given inner glue line temperatures.* When using lumber having temperatures lower than 65°F, it will be necessary to apply heat to the packaged lay-up to raise the temperature of the innermost glue line to 75°F and higher, if possible. The glue line temperature should be carefully measured with a thermocouple at the point farthest from the heat source.

Inner Glue Line Temperatures, °F	Absolute Minimum Clamp Curing Times, hours
65	10
75	7
85	5
95	3

The clamp curing times are measured from the time the innermost glue line reaches the desired temperature and therefore, the total clamp times may be longer than indicated in the table. As an example, the clamped innermost glue line temperature is initially measured at 55°F. Heating of the clamped beam commences, and the innermost glue line temperature is subsequently measured at 75°F. ***ABSOLUTE MINIMUM*** clamp time is measured from this point. Referring to the above table, this temperature must be maintained for 7 hours or longer before pressure is released.

Laminated arches or other constructions where stress is imparted to the package should be clamped 50% longer than the minimum times given in the above table. This added clamp time will minimize effects resulting from "spring back" at the time of unclamping. After proper curing and aging for a few days, the bonded wood members will meet the requirements of the specifications previously noted.

Clean Up

Resorsabond® 4242/4554 slurry adhesive is readily miscible with water. Mixing and application equipment can be cleaned with warm water or a dilute caustic solution. After initial cleaning, follow with a thorough rinse using fresh water. In order to minimize the amount of wash water generated and reduce the disposal problem, remove as much of the mixed glue as possible prior to washing. The undiluted waste glue can be placed in a suitable container and allowed to harden and cure into an insoluble material. In some instances, solid waste disposal sites have accepted this solid material. Consult with the solid waste disposal personnel for acceptance.

Precautions for Proper Use

The preceding recommendations for stock conditions, assembly times, cure times, temperatures, pressures, and mixing should be followed closely for best results. The information presented in this bulletin is based on gluing experience with untreated Southern pine, Douglas fir, and Hem fir. Please contact your Georgia-Pacific Resins, Inc. sales or technical representative at the numbers below for additional information. Specific application questions should be referred to a GP technical representative:

Eugene, OR	(541) 688-5221	Albany, OR	(541) 928-4171
Decatur, GA	(770) 593-6800	Tacoma, WA	(206) 572-8181

IMPORTANT: The technical data herein is believed to be accurate. It is offered for your consideration, investigation, and verification. Buyer assumes all risk of use, storage, and handling of the product. NO WARRANTY, EXPRESS OR IMPLIED, IS MADE INCLUDING, BUT NOT LIMITED TO, IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE WHICH ARE SPECIFICALLY EXCLUDED. Nothing contained herein shall be construed as a license to operate under, or recommendation to infringe, any patents.

Adhesive Ratio Determination

Mix ratio is 100 parts Resorsabond® 4242 resin to 43 parts Resorsabond® 4554 hardener slurry or 2.33 parts resin to 1.0 parts hardener. Allowable adhesive mix ratio is 2.28 to 2.40.

Resin, lbs.	Pounds of Slurried Hardener Required for Adhesive Mix Ratios of		
	2.28	2.33	2.40
5.0	2.2	2.1	2.1
5.1	2.2	2.2	2.1
5.2	2.3	2.2	2.2
5.3	2.3	2.3	2.2
5.4	2.4	2.3	2.2
5.5	2.4	2.4	2.3
5.6	2.5	2.4	2.3
5.7	2.5	2.4	2.4
5.8	2.5	2.5	2.4
5.9	2.6	2.5	2.5
6.0	2.6	2.6	2.5
6.1	2.7	2.6	2.5
6.2	2.7	2.7	2.6
6.3	2.8	2.7	2.6
6.4	2.8	2.7	2.7
6.5	2.9	2.8	2.7
6.6	2.9	2.8	2.7
6.7	2.9	2.9	2.8
6.8	3.0	2.9	2.8
6.9	3.0	3.0	2.9
7.0	3.1	3.0	2.9
7.1	3.1	3.0	3.0
7.2	3.2	3.1	3.0
7.3	3.2	3.1	3.0
7.4	3.2	3.2	3.1
7.5	3.3	3.2	3.1
7.6	3.3	3.3	3.2
7.7	3.4	3.3	3.2
7.8	3.4	3.3	3.2
7.9	3.5	3.4	3.3
8.0	3.5	3.4	3.3
8.1	3.6	3.5	3.4
8.2	3.6	3.5	3.4

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Adhesive Ratio Determination

Resin, lbs.	Pounds of Slurried Hardener Required for Adhesive Mix Ratios of 2.28	2.33	2.40
8.3	3.6	3.6	3.5
8.4	3.7	3.6	3.5
8.5	3.7	3.6	3.5
8.6	3.8	3.7	3.6
8.7	3.8	3.7	3.6
8.8	3.9	3.8	3.7
8.9	3.9	3.8	3.7
9.0	3.9	3.9	3.8
9.1	4.0	3.9	3.8
9.2	4.0	3.9	3.8
9.3	4.1	4.0	3.9
9.4	4.1	4.0	3.9
9.5	4.2	4.1	4.0
9.6	4.2	4.1	4.0
9.7	4.3	4.2	4.0
9.8	4.3	4.2	4.1
9.9	4.3	4.2	4.1
10.0	4.4	4.3	4.2
10.1	4.4	4.3	4.2
10.2	4.5	4.4	4.2
10.3	4.5	4.4	4.3
10.4	4.6	4.5	4.3
10.5	4.6	4.5	4.4
10.6	4.6	4.5	4.4
10.7	4.7	4.6	4.5
10.8	4.7	4.6	4.5
10.9	4.8	4.7	4.5
11.1	4.8	4.7	4.6
11.1	4.9	4.8	4.6
11.2	4.9	4.8	4.7
11.3	5.0	4.8	4.7
11.4	5.0	4.9	4.7
11.5	5.0	4.9	4.8
11.6	5.1	5.0	4.8
11.7	5.1	5.0	4.9
11.8	5.2	5.1	4.9
11.9	5.2	5.1	5.0
12.0	5.3	5.2	5.0
12.1	5.3	5.2	5.0

Adhesive Ratio Determination

Resin, lbs.	Pounds of Slurried Hardener Required for Adhesive Mix Ratios of 2.28	2.33	2.40
12.2	5.4	5.2	5.1
12.3	5.4	5.3	5.1
12.4	5.4	5.3	5.2
12.5	5.5	5.4	5.2
12.6	5.5	5.4	5.2
12.7	5.6	5.5	5.3
12.8	5.6	5.5	5.3
12.9	5.7	5.5	5.4
13.0	5.7	5.6	5.4
13.1	5.7	5.6	5.5
13.2	5.8	5.7	5.5
13.3	5.8	5.7	5.5
13.4	5.9	5.8	5.6
13.5	5.9	5.8	5.6
13.6	6.0	5.8	5.7
13.7	6.0	5.9	5.7
13.8	6.1	5.9	5.7
13.9	6.1	6.0	5.8
14.0	6.1	6.0	5.8
14.1	6.2	6.1	5.9
14.2	6.2	6.1	5.9
14.3	6.3	6.1	6.0
14.4	6.3	6.2	6.0
14.5	6.4	6.2	6.0
14.6	6.4	6.3	6.1
14.7	6.4	6.3	6.1
14.8	6.5	6.4	6.2
14.9	6.5	6.4	6.2
15.0	6.6	6.4	6.2
15.1	6.6	6.5	6.3

Georgia·Pacific

Georgia-Pacific Resins, Inc.

2883 Miller Road • Decatur, Georgia 30035 • Tel: (770) 593-6800 • Fax: (770) 322-9973

Resorsabond® 4242/4554 Slurry Adhesive
Mixing Instructions and Handling Precautions

Mixing Instructions

Resorsabond® 4554 Hardener Slurry

	Parts by Weight	1 Bag	2 Bags	3 Bags
Water	60	75 lbs.	150 lbs.	225 lbs.
Resorsabond® 4554 Hardener	40	50 lbs.	100 lbs.	150 lbs.
- Add hardener slowly to water and mix until smooth -				
TOTAL	100	125 lbs.	250 lbs.	375 lbs.
Continuous slow agitation or mixing prior to use is recommended.				

Final Adhesive Mix

Resorsabond® 4242 resin	70 parts by weight
Resorsabond® 4554 hardener slurry	30 parts by weight

Handling Precautions

Whenever Resorsabond® 4242 resin, Resorsabond® 4554 hardener or Resorsabond® 4242/4554 slurry adhesive are handled, personal protective equipment - rubber gloves, rubber aprons and protective glasses or goggles - should be worn. In case of skin contact, immediately wash skin thoroughly with soap and water. For eye contact, flush eyes with large quantities of water for at least 15 minutes and contact a physician. Avoid breathing dust and vapors. Use with adequate ventilation.

Resorsabond® 4242/4554 - Properly mixed and stored Resorsabond 4242/4554 adhesives contain less than 1% free formaldehyde.

Resorsabond® 4242 Resin - Contains phenol. Prolonged skin contact may cause dermatitis in some individuals.

Resorsabond® 4554 Hardener - Contains formaldehyde. Formaldehyde is irritating to mucous membranes and may cause dermatitis. The dust is potentially explosive if dispersed in air and exposed to flames, sparks, or static electricity.

Resorsabond® 4554 Hardener Slurry

Typical Properties

Appearance	dark brown/gray slurry
Mix Ratio; parts by weight	60 water : 40 hardener
Density, lbs./gal. @ 25°C	9.6 - 9.8
pH	5.5 - 6.5
Free Formaldehyde, % (stored at 25°C)	< 2.0
Storage Life at 25°C	48 hours

Resorsabond® 4242/4554 Adhesive Mix

Typical Properties

Appearance	red/brown slurry
Mix Ratio; parts by weight	70 resin : 30 hardener slurry
Density, lbs./gal. @ 25°C	9.5 - 9.7
Viscosity, cps @ 25°C	3000 - 6000
pH	8.7 - 9.0
Free Formaldehyde, %	< 1.0
Gelation Time at 25°C	1.58 - 2.25 hours

NOTE: Details of adhesive use parameters can be found in PUB 151B - "Laminating Softwoods with Resorsabond® 4242/4554 Slurry Adhesive."

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2883 Miller Road • Decatur, Georgia 30035 • Tel: (770) 593-6800 • Fax: (770) 322-9973

Product Information - PUB 151

Resorsabond® Product Information

Resorsabond® 4242 Resin

Typical Properties

Type	phenol-resorcinol-formaldehyde
Appearance	red/purple liquid
Non-volatiles, %	53.5 - 54.5
Density, lbs./gal. @ 25°C	9.58 - 9.66
Viscosity, cps @ 25°C	1200 - 2000
pH	8.8 - 9.8
Flash Point, °F	> 200
Free Formaldehyde, %	< 0.1
Free Phenol, %	9.0 - 9.5
Storage Life at 25°C	3 months

Resorsabond® 4554 Hardener

Typical Properties

Appearance	brown/gray powder
Density, lbs./cu. ft. @ 25°C	25 - 27
Free Formaldehyde, %	< 2.0
Storage Life at 20°C	3 months

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Resorsabond® 4554 Hardener Slurry

Typical Properties

Appearance	dark brown/gray slurry
Mix Ratio; parts by weight	60 water : 40 hardener
Density, lbs./gal. @ 25°C	9.6 - 9.8
pH	5.5 - 6.5
Free Formaldehyde, % (stored at 25°C)	< 2.0
Storage Life at 25°C	48 hours

Resorsabond® 4242/4554 Adhesive Mix

Typical Properties

Appearance	red/brown slurry
Mix Ratio; parts by weight	70 resin : 30 hardener slurry
Density, lbs./gal. @ 25°C	9.5 - 9.7
Viscosity, cps @ 25°C	3000 - 6000
pH	8.7 - 9.0
Free Formaldehyde, %	< 1.0
Gelation Time at 25°C	1.58 - 2.25 hours

NOTE: Details of adhesive use parameters can be found in PUB 151B - "Laminating Softwoods with Resorsabond® 4242/4554 Slurry Adhesive."

Appendix B:

Shear Block Data and Analysis of Variance

Specimen Number	Failure Mode (%)				Specimen Stress (psi)
	Wood	Mat Layer	FRP Layer	Glueline	
72-0-C1-1	100	0	0	0	1183
72-0-C1-2	100	0	0	0	1438
72-0-C1-3	100	0	0	0	1206
72-0-C1-4	100	0	0	0	1263
72-0-C1-5	100	0	0	0	1774
72-40-C1-1	100	0	0	0	1169
72-40-C1-2	100	0	0	0	1213
72-40-C1-3	100	0	0	0	1267
72-40-C1-4	100	0	0	0	1337
72-40-C1-5	100	0	0	0	1321
Z-0-C1-1	100	0	0	0	1271
Z-0-C1-2	100	0	0	0	1308
Z-0-C1-3	-	-	-	-	-
Z-0-C1-4	100		0	0	1362
Z-0-C1-5	100	0	0	0	1530
Z-40-C1-1	100	0	0	0	1219
Z-40-C1-2	100	0	0	0	1594
Z-40-C1-3	100	0	0	0	1656
Z-40-C1-4	100	0	0	0	1408
Z-40-C1-5	100	0	0	0	1135
2Z-0-C1-1	95	0	0	5	1270
2Z-0-C1-2	95	0	0	5	1103
2Z-0-C1-3	100	0	0	0	1261
2Z-0-C1-4	100	0	0	0	1321
2Z-0-C1-5	100	0	0	0	1626
2Z-40-C1-1	100	0	0	0	1489
2Z-40-C1-2	100	0	0	0	1409
2Z-40-C1-3	100	0	0	0	1416
2Z-40-C1-4	100	0	0	0	1483
2Z-40-C1-5	100	0	0	0	1535
18-0-C1-1	100	0	0	0	1171
18-0-C1-2	100	0	0	0	1333
18-0-C1-3	100	0	0	0	1168
18-0-C1-4	95	0	0	5	1154
18-0-C1-5	100	0	0	0	1081
18-40-C1-1	100	0	0	0	1008
18-40-C1-2	100	0	0	0	867
18-40-C1-3	95	0	0	5	1380
18-40-C1-4	100	0	0	0	1042
18-40-C1-5	100	0	0	0	1159
Averages	99.5	0	0	0.5	1306

Data For
Tables 4.3 and 4.4

Control Strength Stats	
Mean	1306
Stnd Deviation	190
COV	14.6
Minimum	867
Maximum	1774

Specimen Number	Failure Mode (%)				Specimen Stress (psi)
	Wood	Mat Layer	FRP Layer	Glueline	
72-0-1-1	10	10	80	0	1783
72-0-1-2	80	0	20	0	1532
72-0-1-3	20	75	5	0	1731
72-0-1-4	0	0	100	0	1757
72-0-1-5	0	60	40	0	1518
72-0-2-1	100	0	0	0	1573
72-0-2-2	40	50	10	0	1555
72-0-2-3	100	0	0	0	1411
72-0-2-4	100	0	0	0	1351
72-0-2-5	100	0	0	0	1482
Averages	55.0	19.5	25.5	0	1569

Data For
Tables 4.3 and 4.4

1-72-0 Strength Stats	
Mean	1569
Stnd Deviation	146
COV	9.3
Minimum	1351
Maximum	1783

72-40-1-1	95	0	5	0	1421
72-40-1-2	100	0	0	0	1162
72-40-1-3	100	0	0	0	1237
72-40-1-4	100	0	0	0	1419
72-40-1-5	96	0	4	0	1497
72-40-2-1	10	0	90	0	1712
72-40-2-2	0	90	10	0	1544
72-40-2-3	50	0	50	0	1846
72-40-2-4	10	70	20	0	1715
72-40-2-5	95	0	5	0	1667
Averages	65.6	16.0	18.4	0	1522

1-72-40 Strength Stats	
Mean	1522
Stnd Deviation	219
COV	14.4
Minimum	1162
Maximum	1846

Z-0-1-1	100	0	0	0	1540
Z-0-1-2	100	0	0	0	1477
Z-0-1-3	99	1	0	0	1589
Z-0-1-4	70	30	0	0	1609
Z-0-1-5	100	0	0	0	1883
Z-0-2-1	90	4	6	0	1345
Z-0-2-2	90	5	5	0	1384
Z-0-2-3	60	0	40	0	1712
Z-0-2-4	50	50	0	0	1294
Z-0-2-5	15	5	80	0	2023
Averages	77.4	9.5	13.1	0	1586

1-72Z-0 Strength Stats	
Mean	1586
Stnd Deviation	234
COV	14.8
Minimum	1294
Maximum	2023

Specimen Number	Failure Mode (%)				Specimen Stress (psi)
	Wood	Mat Layer	FRP Layer	Glueline	
Z-40-1-1	90	10	0	0	1426
Z-40-1-2	70	0	30	0	1302
Z-40-1-3	95	5	0	0	1345
Z-40-1-4	95	5	0	0	1428
Z-40-1-5	93	0	7	0	1643
Z-40-2-1	90	10	0	0	1250
Z-40-2-2	100	0	0	0	1117
Z-40-2-3	100	0	0	0	1245
Z-40-2-4	95	0	5	0	1263
Z-40-2-5	100	0	0	0	1289
Averages	92.8	3.0	4.2	0	1331

Data For
Tables 4.3 and 4.4

1-72Z-40 Strength Stats	
Mean	1331
Stnd Deviation	143
COV	10.7
Minimum	1117
Maximum	1643

2Z-0-1-1	0	100	0	0	1290
2Z-0-1-2	95	0	5	0	1506
2Z-0-1-3	50	50	0	0	1457
2Z-0-1-4	100	0	0	0	1550
2Z-0-1-5	100	0	0	0	1474
2Z-0-2-1	95	5	0	0	1128
2Z-0-2-2	60	0	40	0	1375
2Z-0-2-3	100	0	0	0	1116
2Z-0-2-4	100	0	0	0	1146
2Z-0-2-5	85	15	0	0	1087
Averages	78.5	17.0	4.5	0	1313

2-72Z-0 Strength Stats	
Mean	1313
Stnd Deviation	182
COV	13.8
Minimum	1087
Maximum	1550

2Z-40-1-1	100	0	0	0	1149
2Z-40-1-2	100	0	0	0	1305
2Z-40-1-3	100	0	0	0	1125
2Z-40-1-4	0	30	70	0	1451
2Z-40-1-5	100	0	0	0	1194
2Z-40-2-1	97	0	3	0	1375
2Z-40-2-2	95	0	5	0	1403
2Z-40-2-3	100	0	0	0	1300
2Z-40-2-4	100	0	0	0	1410
2Z-40-2-5	100	0	0	0	1332
Averages	89.2	3.0	7.8	0	1304

2-72Z-40 Strength Stats	
Mean	1304
Stnd Deviation	114
COV	8.7
Minimum	1125
Maximum	1451

Specimen Number	Failure Mode (%)				Specimen Stress (psi)
	Wood	Mat Layer	FRP Layer	Glueline	
18-0-1-1	100	0	0	0	1369
18-0-1-2	100	0	0	0	1555
18-0-1-3	100	0	0	0	1725
18-0-1-4	100	0	0	0	1550
18-0-1-5	100	0	0	0	1100
18-0-2-1	60	0	40	0	1585
18-0-2-2	80	0	20	0	1389
18-0-2-3	90	0	10	0	1399
18-0-2-4	60	0	40	0	1428
18-0-2-5	30	0	70	0	1523
Averages	82.0	0.0	18.0	0	1462

Data For
Tables 4.3 and 4.4

4-18-0 Strength Stats	
Mean	1462
Stnd Deviation	168
COV	11.5
Minimum	1100
Maximum	1725

18-40-1-1	100	0	0	0	1259
18-40-1-2	90	0	10	0	1131
18-40-1-3	100	0	0	0	1021
18-40-1-4	95	0	5	0	1091
18-40-1-5	100	0	0	0	1129
18-40-2-1	100	0	0	0	1555
18-40-2-2	100	0	0	0	1163
18-40-2-3	100	0	0	0	1290
18-40-2-4	100	0	0	0	1247
18-40-2-5	40	60	0	0	1410
Averages	92.5	6.0	1.5	0	1230

4-18-40 Strength Stats	
Mean	1230
Stnd Deviation	160
COV	13.0
Minimum	1021
Maximum	1555

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
GP 26-C-1	70	-	30	1398
GP 26-C-2	100	-	0	1184
GP 26-C-3	80	-	20	1355
GP 26-C-4	80	-	20	1412
GP 26-C-5	90	-	10	1505
Averages	84	-	16	1371
GP 26-1-1	80	20	0	1343
GP 26-1-2	95	5	0	1250
GP 26-1-3	100	0	0	1243
GP 26-1-4	100	0	0	1232
GP 26-1-5	30	70	0	1296
Averages	81	19	0	1273
GP 26-2-1	50	50	0	1428
GP 26-2-2	40	60	0	1427
GP 26-2-3	40	60	0	1429
GP 26-2-4	50	40	10	1449
GP 26-2-5	60	40	0	1368
Averages	48	50	2	1420

Data For Table 4.7

Control Strength Stats	
Mean	1371
Stnd Deviation	118
COV	8.6
Minimum	1184
Maximum	1505

FRP Billet 1 Strength Stats	
Mean	1273
Stnd Deviation	46
COV	3.6
Minimum	1232
Maximum	1343

FRP Billet 2 Strength Stats	
Mean	1420
Stnd Deviation	31
COV	2.2
Minimum	1368
Maximum	1449

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
MC1	95	-	5	1296
MC2	100	-	0	1303
MC3	75	-	25	1421
MC4	95	-	5	1379
MC5	90	-	10	1384
Averages	91	-	9	1357
M11	65	30	5	1178
M12	65	30	5	1193
M13	70	25	5	1230
M14	25	65	10	1024
M15	20	75	5	1104
Averages	49	45	6	1146
M21	95	5	0	1021
M22	90	5	5	1196
M23	85	5	10	1095
M24	75	10	15	1348
M25	30	15	55	1264
Averages	75	8	17	1185

Data For Table 4.8

Control Strength Stats	
Mean	1357
Stnd Deviation	55
COV	4.0
Minimum	1296
Maximum	1421

FRP Billet 1 Strength Stats	
Mean	1146
Stnd Deviation	82
COV	7.2
Minimum	1024
Maximum	1230

FRP Billet 2 Strength Stats	
Mean	1185
Stnd Deviation	130
COV	11.0
Minimum	1021
Maximum	1348

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	Thin FRP Layer	Glueline	
KC1	95	-	5	1439
KC2	95	-	5	1590
KC3	95	-	5	1495
KC4	100	-	0	1497
KC5	90	-	10	1554
Averages	95	0	5	1515

Data For Table 4.9

Wood-Wood Strength Stats	
Mean	1515
Stnd Deviation	58
COV	3.9
Minimum	1439
Maximum	1590

K11	75	20	5	1484
K12	65	35	0	1459
K13	50	50	0	1393
K14	95	5	0	1420
K15	50	50	0	1477
Averages	67	32	1	1447

FRP-Wood 1 Strength Stats	
Mean	1447
Stnd Deviation	39
COV	2.7
Minimum	1393
Maximum	1484

K21	70	30	0	1799
K22	75	20	5	1818
K23	95	0	5	1688
K24	75	20	5	1804
K25	50	45	5	1774
Averages	73	23	4	1777

FRP-Wood 2 Strength Stats	
Mean	1777
Stnd Deviation	52
COV	2.9
Minimum	1688
Maximum	1818

Specimen Number	Specimen Stress
K11	1484
K12	1459
K13	1393
K14	1420
K15	1477
K21	1799
K22	1818
K23	1688
K24	1804
K25	1774

Data For Table 4.18

VEW 260 A; FRP-Wood	
Mean	1612
Stnd Deviation	179
COV	11.1
Minimum	1393
Maximum	1818

Specimen Number	Failure Mode (%) Wood	FRP Layer	Glueline	Specimen Stress (psi)
U-WC-1	95	-	5	1123
U-WC-2	95	-	5	1278
U-WC-3	100	-	0	1051
U-WC-4	100	-	0	1012
U-WC-5	95	-	5	1223
Averages	97	0	3	1138

Data For Table 4.10

Wood-Wood Strength Stats	
Mean	1138
Stnd Deviation	112
COV	9.9
Minimum	1012
Maximum	1278

U-W1-1	25	70	5	1496
U-W1-2	0	100	0	1109
U-W1-3	95	0	5	1115
U-W1-4	85	10	5	1478
U-W1-5	90	10	0	1208
Averages	59	38	3	1281

FRP-Wood 1 Strength Stats	
Mean	1281
Stnd Deviation	192
COV	15.0
Minimum	1109
Maximum	1496

U-W2-1	90	5	5	1220
U-W2-2	90	5	5	1348
U-W2-3	95	0	5	956
U-W2-4	90	5	5	1285
U-W2-5	95	0	5	1370
Averages	92	3	5	1236

FRP-Wood 1 Strength Stats	
Mean	1236
Stnd Deviation	167
COV	13.5
Minimum	956
Maximum	1370

U-FC-1	100	-	0	1182
U-FC-2	95	-	5	1258
U-FC-3	95	-	5	1269
U-FC-4	95	-	5	1316
U-FC-5	100	-	0	1367
Averages	97	0	3	1278

Data For Table 4.11

Wood-Wood Strength Stats	
Mean	1278
Stnd Deviation	69
COV	5.4
Minimum	1182
Maximum	1367

U-F1-1	-	100	0	1325
U-F1-2	-	100	0	1336
U-F1-3	-	100	0	1395
U-F1-4	-	100	0	1112
U-F1-5	-	100	0	1320
Averages	0	100	0	1298

FRP-FRP 1 Strength Stats	
Mean	1298
Stnd Deviation	108
COV	8.3
Minimum	1112
Maximum	1395

U-F2-1	-	100	0	1512
U-F2-2	-	100	0	1418
U-F2-3	-	100	0	1511
U-F2-4	-	100	0	1482
U-F2-5	-	100	0	1451
Averages	0	100	0	1475

FRP-FRP 2 Strength Stats	
Mean	1475
Stnd Deviation	41
COV	2.8
Minimum	1418
Maximum	1512

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
MCC1W	80	-	20	1338
MCC2W	65	-	35	1211
MCC3W	60	-	40	1093
MCC4W	80	-	20	1180
MCC5W	90	-	10	1193
Averages	75	-	25	1203

Data For Table 4.12

Wood-Wood Strength Stats	
Mean	1203
Stnd Deviation	88
COV	7.3
Minimum	1093
Maximum	1338

MC11W	50	50	0	1301
MC12W	90	5	5	1449
MC13W	85	5	10	1374
MC14W	65	35	0	1512
MC15W	25	70	5	1262
Averages	63	33	4	1380

FRP-Wood 1 Strength Stats	
Mean	1380
Standard Deviation	103
COV	7.5
Minimum	1262
Maximum	1512

MC21W	100	0	0	1154
MC22W	100	0	0	1116
MC23W	100	0	0	1130
MC24W	95	5	0	1155
MC25W	90	10	0	1132
Averages	97	3	0	1138

FRP-Wood 2 Strength Stats	
Mean	1138
Standard Deviation	17
COV	1.5
Minimum	1116
Maximum	1155

Specimen Number	Failure Mode (%) Wood	FRP Layer	Glueline	Specimen Stress (psi)
MAC1F	75	-	25	1467
MAC2F	75	-	25	1023
MAC3F	85	-	15	1164
MAC4F	85	-	15	1570
MAC5F	75	-	25	1344
Averages	79	-	21	1314

Data For Tabe 4.13

Wood-Wood 1 Strength Stats	
Mean	1314
Standard Deviation	222
COV	16.9
Minimum	1023
Maximum	1570

MA11F	-	100	0	1203
MA12F	-	100	0	1231
MA13F	-	100	0	1027
MA14F	-	100	0	1024
MA15F	-	100	0	1026
Averages	-	100	0	1102

FRP-FRP 1 Strength Stats	
Mean	1102
Standard Deviation	105
COV	9.6
Minimum	1024
Maximum	1231

MA21F	-	100	0	1364
MA22F	-	100	0	1248
MA23F	-	100	0	1067
MA24F	-	100	0	1276
MA25F	-	100	0	1025
Averages	-	100	0	1196

FRP-FRP 2 Strength Stats	
Mean	1196
Standard Deviation	144
COV	12.0
Minimum	1025
Maximum	1364

MBC1F	60	-	40	1096
MBC2F	75	-	25	1276
MBC3F	75	-	25	1440
MBC4F	75	-	25	1205
MBC5F	80	-	20	1206
Averages	73	-	27	1245

Wood-Wood 2 Strength Stats	
Mean	1245
Standard Deviation	127
COV	10.2
Minimum	1096
Maximum	1440

MB11F	-	100	0	1005
MB12F	-	100	0	1222
MB13F	-	100	0	919
MB14F	-	100	0	1107
MB15F	-	100	0	887
Averages	-	100	0	1028

FRP-FRP 3 Strength Stats	
Mean	1028
Standard Deviation	138
COV	13.4
Minimum	887
Maximum	1222

MB21F	-	100	0	979
MB22F	-	100	0	1082
MB23F	-	100	0	1127
MB24F	-	100	0	1210
MB25F	-	100	0	1048
Averages	-	100	0	1089

FRP-FRP 4 Strength Stats	
Mean	1089
Standard Deviation	86
COV	7.9
Minimum	979
Maximum	1210

Specimen Number	Specimen Stress (psi)
MCC1W	1338
MCC2W	1211
MCC3W	1093
MCC4W	1180
MCC5W	1193

Wood-Wood Strength Stats	
Mean	1203
Stnd Deviation	88
COV	7.3
Minimum	1093
Maximum	1338

MC11W	1301
MC12W	1449
MC13W	1374
MC14W	1512
MC15W	1262
MC21W	1154
MC22W	1116
MC23W	1130
MC24W	1155
MC25W	1132

FRP-Wood Strength Stats	
Mean	1259
Stnd Deviation	145
COV	11.5
Minimum	1116
Maximum	1512

Specimen Number	Specimen Stress (psi)
MAC1F	1467
MAC2F	1023
MAC3F	1164
MAC4F	1570
MAC5F	1344
MBC1F	1096
MBC2F	1276
MBC3F	1440
MBC4F	1205
MBC5F	1206

Wood-Wood Strength Stats	
Mean	1279
Stnd Deviation	174
COV	13.6
Minimum	1023
Maximum	1570

MA11F	1203
MA12F	1231
MA13F	1027
MA14F	1024
MA15F	1026
MA21F	1364
MA22F	1248
MA23F	1067
MA24F	1276
MA25F	1025
MB11F	1005
MB12F	1222
MB13F	919
MB14F	1107
MB15F	887
MB21F	979
MB22F	1082
MB23F	1127
MB24F	1210
MB25F	1048

FRP-FRP Strength Stats	
Mean	1104
Standard Deviati	127
COV	11.5
Minimum	887
Maximum	1364

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
KDC1W	90	-	10	1568
KDC2W	95	-	5	1510
KDC3W	95	-	5	1787
KDC4W	95	-	5	1277
KDC5W	95	-	5	1416
Averages	94	-	6	1512

KD11W	20	80	0	1525
KD12W	5	95	0	1376
KD13W	45	55	0	1431
KD14W	0	100	0	1426
KD15W	35	60	5	1593
Averages	21	78	1	1470

KD21W	70	10	20	1377
KD22W	50	25	25	1266
KD23W	15	75	10	1519
KD24W	55	30	15	1431
KD25W	45	45	10	1389
Averages	47	37	16	1396

Data For Table 4.14

Wood-Wood Strength Stats	
Mean	1512
Stnd Deviation	189
COV	12.5
Minimum	1277
Maximum	1787

FRP-Wood 1 Strength Stats	
Mean	1470
Stnd Deviation	87
COV	5.9
Minimum	1376
Maximum	1593

FRP-Wood 2 Strength Stats	
Mean	1396
Stnd Deviation	92
COV	6.6
Minimum	1266
Maximum	1519

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
KEC1F	90	-	10	1517
KEC2F	95	-	5	1418
KEC3F	95	-	5	1440
KEC4F	90	-	10	1496
KEC5F	90	-	10	1651
Averages	92	-	8	1504
KE11F	-	100	0	1224
KE12F	-	100	0	1521
KE13F	-	100	0	1626
KE14F	-	100	0	1322
KE15F	-	100	0	1369
Averages	-	100	0	1412
KE21F	-	100	0	1413
KE22F	-	100	0	1577
KE23F	-	100	0	1565
KE24F	-	100	0	1448
KE25F	-	100	0	1560
Averages	-	100	0	1513
KFC1F	95	-	5	1599
KFC2F	80	-	20	1487
KFC3F	95	-	5	1516
KFC4F	80	-	20	1402
KFC5F	95	-	5	1426
Averages	89	-	11	1486
KF11F	-	100	0	1288
KF12F	-	100	0	1364
KF13F	-	100	0	1609
KF14F	-	100	0	1483
KF15F	-	100	0	1149
Averages	-	100	0	1379
KF21F	-	100	0	1497
KF22F	-	100	0	1590
KF23F	-	100	0	1513
KF24F	-	100	0	1494
KF25F	-	100	0	1450
Averages	-	100	0	1509

Data For Table 4.15

Wood-Wood 1 Strength Stats	
Mean	1504
Stnd Deviation	91
COV	6.1
Minimum	1418
Maximum	1651

FRP-FRP 1 Strength Stats	
Mean	1412
Stnd Deviation	160
COV	11.4
Minimum	1224
Maximum	1626

FRP-FRP 2 Strength Stats	
Mean	1513
Stnd Deviation	76
COV	5.0
Minimum	1413
Maximum	1577

Wood-Wood 2 Strength Stats	
Mean	1486
Stnd Deviation	78
COV	5.2
Minimum	1402
Maximum	1599

FRP-FRP 3 Strength Stats	
Mean	1379
Stnd Deviation	177
COV	12.8
Minimum	1149
Maximum	1609

FRP-FRP 4 Strength Stats	
Mean	1509
Stnd Deviation	51
COV	3.4
Minimum	1450
Maximum	1590

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
L5-C-1	75	-	25	1848
L5-C-2	95	-	5	1718
L5-C-3	90	-	10	1668
L5-C-4	95	-	5	1720
L5-C-5	90	-	10	1798
Averages	89	-	11	1751
L5-1-1	50	50	0	1740
L5-1-2	10	90	0	1615
L5-1-3	20	80	0	1551
L5-1-4	35	65	0	1637
L5-1-5	35	65	0	1620
Averages	30	70	0	1633
L5-2-1	5	95	0	1557
L5-2-2	35	65	0	1613
L5-2-3	40	60	0	1648
L5-2-4	50	50	0	1559
L5-2-5	50	50	0	1663
Averages	36	64	0	1608
L6-C-1	98	2	2	1859
L6-C-2	100	0	0	1919
L6-C-3	90	0	10	1844
L6-C-4	100	0	0	1785
L6-C-5	80	0	20	1472
Averages	94	0	6	1776
L6-1-1	15	85	0	1749
L6-1-2	0	100	0	1477
L6-1-3	5	95	0	1509
L6-1-4	50	50	0	1581
L6-1-5	55	45	0	1596
Averages	25	75	0	1583
L6-2-1	5	95	0	1623
L6-2-2	10	90	0	1752
L6-2-3	40	60	0	1371
L6-2-4	50	50	0	1550
L6-2-5	50	50	0	1629
Averages	31	69	0	1585

Data For Table 4.16

Wood-Wood 1 Strength Stats	
Mean	1751
Stnd Deviation	72
COV	4.1
Minimum	1668
Maximum	1848

FRP-Wood 1 Strength Stats	
Mean	1633
Stnd Deviation	69
COV	4.2
Minimum	1551
Maximum	1740

FRP-Wood 2 Strength Stats	
Mean	1608
Stnd Deviation	49
COV	3.1
Minimum	1557
Maximum	1663

Wood-Wood 2 Strength Stats	
Mean	1776
Stnd Deviation	176
COV	9.9
Minimum	1472
Maximum	1919

FRP-Wood 3 Strength Stats	
Mean	1583
Stnd Deviation	105
COV	6.7
Minimum	1477
Maximum	1749

FRP-Wood 4 Strength Stats	
Mean	1585
Stnd Deviation	140
COV	8.8
Minimum	1371
Maximum	1752

Specimen Number	Failure Mode (%) Wood	FRP Layer	Glueline	Specimen Stress (psi)
L3-C-1	95	-	5	1471
L3-C-2	100	-	0	1479
L3-C-3	100	-	0	1531
L3-C-4	100	-	0	1879
L3-C-5	100	-	0	1705
Averages	99	-	1	1613
L3-1-1	-	100	0	1521
L3-1-2	-	100	0	1557
L3-1-3	-	100	0	1453
L3-1-4	-	100	0	1515
L3-1-5	-	100	0	1418
Averages	-	100	0	1493
L3-2-1	-	100	0	1569
L3-2-2	-	100	0	1259
L3-2-3	-	100	0	1689
L3-2-4	-	100	0	1468
L3-2-5	-	100	0	1310
Averages	-	100	0	1459
L4-C-1	95	-	5	1768
L4-C-2	95	-	5	1779
L4-C-3	100	-	-	1642
L4-C-4	95	-	5	1661
L4-C-5	100	-	-	1438
Averages	97	-	5	1657
L4-1-1	-	100	0	1601
L4-1-2	-	100	0	1623
L4-1-3	-	100	0	1586
L4-1-4	-	100	0	1404
L4-1-5	-	100	0	1508
Averages	-	100	0	1544
L4-2-1	-	100	0	1607
L4-2-2	-	100	0	1204
L4-2-3	-	100	0	1415
L4-2-4	-	100	0	1285
L4-2-5	-	100	0	1426
Averages	-	100	0	1387

Data For Table 4.17

Wood-Wood 1 Strength Stats	
Mean	1613
Stnd Deviation	176
COV	10.9
Minimum	1471
Maximum	1879

FRP-FRP 1 Strength Stats	
Mean	1493
Stnd Deviation	56
COV	3.8
Minimum	1418
Maximum	1557

FRP-FRP 2 Strength Stats	
Mean	1459
Stnd Deviation	179
COV	12.2
Minimum	1259
Maximum	1689

Wood-Wood 2 Strength Stats	
Mean	1657
Stnd Deviation	137
COV	8.3
Minimum	1438
Maximum	1779

FRP-FRP 3 Strength Stats	
Mean	1544
Stnd Deviation	90
COV	5.8
Minimum	1404
Maximum	1623

FRP-FRP 4 Strength Stats	
Mean	1387
Stnd Deviation	154
COV	11.1
Minimum	1204
Maximum	1607

Specimen Number	Failure Mode (%)		Specimen Stress (psi)
	Wood	Glueline	
C-C1-1	90	10	1416
C-C1-2	80	20	1242
C-C1-3	60	40	1516
C-C1-4	90	10	939
C-C1-5	85	15	709
Averages	81	19	1164

Data For Table 4.18

Wood-Wood 1 Strength Stats	
Mean	1164
Standard Deviation	336
COV	28.8
Minimum	709
Maximum	1516

C-C2-1	85	15	1254
C-C2-2	80	20	775
C-C2-3	95	5	1185
C-C2-4	90	10	952
C-C2-5	90	10	942
Averages	88	12	1022

Wood-Wood 2 Strength Stats	
Mean	1022
Standard Deviation	195
COV	19.1
Minimum	775
Maximum	1254

C-C3-1	95	5	1172
C-C3-2	75	25	1484
C-C3-3	90	10	1299
C-C3-4	95	5	1355
C-C3-5	85	15	1411
Averages	88	12	1344

Wood-Wood 3 Strength Stats	
Mean	1344
Standard Deviation	118
COV	8.8
Minimum	1172
Maximum	1484

Specimen Number	Specimen Stress
C-C1-1	1416
C-C1-2	1242
C-C1-3	1516
C-C1-4	939
C-C1-5	709
C-C2-1	1254
C-C2-2	775
C-C2-3	1185
C-C2-4	952
C-C2-5	942
C-C3-1	1172
C-C3-2	1484
C-C3-3	1299
C-C3-4	1355
C-C3-5	1411

Stats for ALL Together	
Mean	1177
Standard Deviati	256
COV	21.8
Minimum	709
Maximum	1516

Specimen Number	Specimen Stress (psi)
KD11W	1525
KD12W	1376
KD13W	1431
KD14W	1426
KD15W	1593
KD21W	1377
KD22W	1266
KD23W	1519
KD24W	1431
KD25W	1389

Data for Table 4.18

VEW 260 B; FRP-Wood	
Mean	1433
Stnd Deviation	93
COV	6.5
Minimum	1266
Maximum	1593

Specimen Number	Specimen Stress (psi)
KDC1W	1568
KDC2W	1510
KDC3W	1787
KDC4W	1277
KDC5W	1416
KEC1F	1517
KEC2F	1418
KEC3F	1440
KEC4F	1496
KEC5F	1651
KFC1F	1599
KFC2F	1487
KFC3F	1516
KFC4F	1402
KFC5F	1426

Data For Table 4.18

VEW 260 B; Wood-Wood	
Mean	1501
Stnd Deviation	120
COV	8.0
Minimum	1277
Maximum	1787

Specimen Number	Specimen Stress (psi)
KE11F	1224
KE12F	1521
KE13F	1626
KE14F	1322
KE15F	1369
KE21F	1413
KE22F	1577
KE23F	1565
KE24F	1448
KE25F	1560
KF11F	1288
KF12F	1364
KF13F	1609
KF14F	1483
KF15F	1149
KF21F	1497
KF22F	1590
KF23F	1513
KF24F	1494
KF25F	1450

Data For Table 4.18

VEW 260 B; FRP-FRP	
Mean	1453
Stnd Deviation	132
COV	9.1
Minimum	1149
Maximum	1626

Specimen Number	Specimen Stress (psi)
L5-C-1	1848
L5-C-2	1718
L5-C-3	1668
L5-C-4	1720
L5-C-5	1798
L6-C-1	1859
L6-C-2	1919
L6-C-3	1844
L6-C-4	1785
L6-C-5	1472
L3-C-1	1471
L3-C-2	1479
L3-C-3	1531
L3-C-4	1879
L3-C-5	1705
L4-C-1	1768
L4-C-2	1779
L4-C-3	1642
L4-C-4	1661
L4-C-5	1438

Data For Table 4.18

VEW 260 C; Wood-Wood	
Mean	1699
Stnd Deviation	151
COV	8.9
Minimum	1438
Maximum	1919

Specimen Number	Specimen Stress (psi)
L3-1-1	1521
L3-1-2	1557
L3-1-3	1453
L3-1-4	1515
L3-1-5	1418
L3-2-1	1569
L3-2-2	1259
L3-2-3	1689
L3-2-4	1468
L3-2-5	1310
L4-1-1	1601
L4-1-2	1623
L4-1-3	1586
L4-1-4	1404
L4-1-5	1508
L4-2-1	1607
L4-2-2	1204
L4-2-3	1415
L4-2-4	1285
L4-2-5	1426

Data For Table 4.18

VEW 260 C; FRP-FRP	
Mean	1471
Stnd Deviation	132
COV	9.0
Minimum	1204
Maximum	1689

Specimen Number	Specimen Stress (psi)
L5-1-1	1740
L5-1-2	1615
L5-1-3	1551
L5-1-4	1637
L5-1-5	1620
L5-2-1	1557
L5-2-2	1613
L5-2-3	1648
L5-2-4	1559
L5-2-5	1663
L6-1-1	1749
L6-1-2	1477
L6-1-3	1509
L6-1-4	1581
L6-1-5	1596
L6-2-1	1623
L6-2-2	1752
L6-2-3	1371
L6-2-4	1550
L6-2-5	1629

Data For Table 4.18

VEW 260 C; FRP-Wood	
Mean	1602
Stnd Deviation	92
COV	5.7
Minimum	1371
Maximum	1752

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
B3-C-1	95	-	5	1461
B3-C-2	95	-	5	1470
B3-C-3	95	-	5	1515
B3-C-4	95	-	5	1559
B3-C-5	90	-	10	1232
Averages	94	-	6	1447
B3-1-1	30	70	0	1540
B3-1-2	70	30	0	1360
B3-1-3	15	85	0	1508
B3-1-4	20	80	0	1477
B3-1-5	15	85	0	1506
Averages	30	70	0	1478
B3-2-1	30	70	0	1590
B3-2-2	20	80	0	1481
B3-2-3	0	100	0	1643
B3-2-4	60	40	0	1737
B3-2-5	70	30	0	1529
Averages	36	64	0	1596
B4-C-1	95	-	5	1588
B4-C-2	95	-	5	1584
B4-C-3	95	-	5	1625
B4-C-4	100	-	0	1657
B4-C-5	95	-	10	1508
Averages	96	-	5	1592
B4-1-1	60	40	0	1714
B4-1-2	75	25	0	1509
B4-1-3	60	40	0	1675
B4-1-4	85	15	0	1587
B4-1-5	75	25	0	1623
Averages	71	29	0	1622
B4-2-1	60	40	0	1411
B4-2-2	50	50	0	1525
B4-2-3	40	60	0	1639
B4-2-4	40	60	0	1604
B4-2-5	30	70	0	1523
Averages	44	56	0	1540

Data For Table 4.19

Wood-Wood 1 Strength Stats	
Mean	1447
Stnd Deviation	126
COV	8.7
Minimum	1232
Maximum	1559

FRP-Wood 1 Strength Stats	
Mean	1478
Stnd Deviation	70
COV	4.7
Minimum	1360
Maximum	1540

FRP-Wood 2 Strength Stats	
Mean	1596
Stnd Deviation	100
Range	256
Minimum	1481
Maximum	1737

Wood-Wood 2 Strength Stats	
Mean	1592
Stnd Deviation	56
COV	3.5
Minimum	1508
Maximum	1657

FRP-Wood 3 Strength Stats	
Mean	1622
Stnd Deviation	79
COV	4.9
Minimum	1509
Maximum	1714

FRP-Wood 4 Strength Stats	
Mean	1540
Stnd Deviation	88
COV	5.7
Minimum	1411
Maximum	1639

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
C1-W-1	100	-	-	1482
C1-W-2	100	-	-	1273
C1-W-3	100	-	-	1680
C1-W-4	100	-	-	2017
C1-W-5	100	-	-	1918
Averages	100	-	-	1674

Data For Table 4.20

Solid Wood 1 Strength Stats	
Mean	1674
Standard Deviation	306
COV	18.3
Minimum	1273
Maximum	2017

C1-C-1	40	-	60	1074
C1-C-2	60	-	40	1603
C1-C-3	70	-	30	1222
C1-C-4	30	-	70	1483
C1-C-5	60	-	40	1608
Averages	52	-	48	1398

Control 1 Strength Stats	
Mean	1398
Standard Deviation	240
COV	17.1
Minimum	1074
Maximum	1608

C1-1-1	10	90	0	927
C1-1-2	0	100	0	1268
C1-1-3	60	20	20	1346
C1-1-4	10	70	20	1296
C1-1-5	50	20	30	1460
Averages	26	60	14	1259

FRP-Wood 1 Strength Stats	
Mean	1259
Standard Deviation	200
COV	15.9
Minimum	927
Maximum	1460

C1-2-1	40	60	0	880
C1-2-2	30	30	40	1338
C1-2-3	90	0	10	1574
C1-2-4	70	0	30	1602
C1-2-5	0	70	30	1687
Averages	46	32	22	1416

FRP-Wood 2 Strength Stats	
Mean	1416
Standard Deviation	326
COV	23.0
Minimum	880
Maximum	1687

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
C2-W-1	100	-	-	1740
C2-W-2	100	-	-	1917
C2-W-3	100	-	-	1486
C2-W-4	100	-	-	1546
C2-W-5	100	-	-	-
Averages	100	-	-	1672

Data For Table 4.20

Solid Wood 2 Strength Stats	
Mean	1672
Standard Deviation	196
COV	11.7
Minimum	1486
Maximum	1917

C2-C-1	40	-	60	914
C2-C-2	10	-	90	1451
C2-C-3	-	-	-	-
C2-C-4	20	-	80	1443
C2-C-5	50	-	50	1479
Averages	30	-	70	1322

Control 2 Strength Stats	
Mean	1322
Standard Deviation	272
COV	20.6
Minimum	914
Maximum	1479

C2-1-1	20	10	70	1634
C2-1-2	10	20	70	1905
C2-1-3	0	30	70	1755
C2-1-4	0	40	60	1802
C2-1-5	0	20	80	1792
Averages	6	24	70	1778

FRP-Wood 3 Strength Stats	
Mean	1778
Standard Deviation	97
COV	5.5
Minimum	1634
Maximum	1905

C2-2-1	10	30	60	1699
C2-2-2	5	65	30	1211
C2-2-3	50	10	40	1909
C2-2-4	40	30	30	1802
C2-2-5	-	-	-	-
Averages	26	34	40	1655

FRP-Wood 4 Strength Stats	
Mean	1655
Standard Deviation	308
COV	18.6
Minimum	1211
Maximum	1909

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
B1-C-1	60	-	40	1784
B1-C-2	70	-	30	1680
B1-C-3	90	-	10	1684
B1-C-4	95	-	5	1844
B1-C-5	70	-	30	1743
Averages	77	-	23	1747

Data For Table 4.20

Wood-Wood 1 Strength Stats	
Mean	1747
Stnd Deviation	69
COV	4.0
Minimum	1680
Maximum	1844

B1-1-1	-	95	5	1581
B1-1-2	-	100	0	1523
B1-1-3	-	100	0	1535
B1-1-4	-	100	0	1699
B1-1-5	-	100	0	1571
Averages	-	99	1	1582

FRP-FRP 1 Strength Stats	
Mean	1582
Stnd Deviation	70
COV	4.4
Minimum	1523
Maximum	1699

B1-2-1	-	100	0	1582
B1-2-2	-	100	0	1653
B1-2-3	-	100	0	1590
B1-2-4	-	100	0	1880
B1-2-5	-	100	0	1593
Averages	-	100	0	1660

FRP-FRP 2 Strength Stats	
Mean	1660
Stnd Deviation	126
COV	7.6
Minimum	1582
Maximum	1880

B2-C-1	100	-	0	1420
B2-C-2	80	-	20	1452
B2-C-3	85	-	15	1518
B2-C-4	100	-	0	1526
B2-C-5	95	-	5	1227
Averages	92	-	8	1428

Wood-Wood 2 Strength Stats	
Mean	1428
Stnd Deviation	121
COV	8.5
Minimum	1227
Maximum	1526

B2-1-1	-	100	0	1381
B2-1-2	-	100	0	1578
B2-1-3	-	100	0	1510
B2-1-4	-	100	0	1447
B2-1-5	-	100	0	1712
Averages	-	100	0	1526

FRP-FRP 3 Strength Stats	
Mean	1526
Stnd Deviation	127
COV	8.3
Minimum	1381
Maximum	1712

B2-2-1	-	100	0	1653
B2-2-2	-	100	0	1611
B2-2-3	-	100	0	1674
B2-2-4	-	100	0	1595
B2-2-5	-	100	0	1619
Averages	-	100	0	1630

FRP-FRP 4 Strength Stats	
Mean	1630
Stnd Deviation	32
COV	2.0
Minimum	1595
Maximum	1674

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
C3-W-1	100	-	-	1802
C3-W-2	100	-	-	1745
C3-W-3	100	-	-	1676
C3-W-4	100	-	-	1881
C3-W-5	100	-	-	1750
Averages	100	-	-	1771

Data For Table 4.21

Solid Wood 1 Strength Stats	
Mean	1771
Standard Deviation	76
COV	4.3
Minimum	1676
Maximum	1881

C3-C-1	60	-	40	1000
C3-C-2	70	-	30	1291
C3-C-3	50	-	50	1083
C3-C-4	80	-	20	1277
C3-C-5	60	-	40	676
Averages	64	-	36	1065

Control 1 Strength Stats	
Mean	1065
Standard Deviation	251
COV	23.6
Minimum	676
Maximum	1291

C3-1-1	-	100	0	1102
C3-1-2	-	100	0	886
C3-1-3	-	100	0	1138
C3-1-4	-	80	20	1339
C3-1-5	-	60	40	1378
Averages	-	88	12	1169

FRP-FRP 1 Strength Stats	
Mean	1169
Standard Deviation	199
COV	17.0
Minimum	886
Maximum	1378

C3-2-1	-	100	0	864
C3-2-2	-	100	0	1444
C3-2-3	-	100	0	1572
C3-2-4	-	100	0	1647
C3-2-5	-	100	0	1348
Averages	-	100	0	1375

FRP-FRP 2 Strength Stats	
Mean	1375
Standard Deviation	308
COV	22.4
Minimum	864
Maximum	1647

Specimen Number	Failure Mode (%)			Specimen Stress (psi)
	Wood	FRP Layer	Glueline	
C4-W-1	100	-	-	1698
C4-W-2	100	-	-	1705
C4-W-3	100	-	-	1662
C4-W-4	100	-	-	1694
C4-W-5	100	-	-	1770
Averages	100	-	-	1706

Data For Table 4.21

Solid Wood 2 Strength Stats	
Mean	1706
Standard Deviation	40
COV	2.3
Minimum	1662
Maximum	1770

C4-C-1	50	-	50	1056
C4-C-2	70	-	30	1575
C4-C-3	80	-	20	1862
C4-C-4	60	-	40	1747
C4-C-5	70	-	30	1248
Averages	66	-	34	1498

Control 2 Strength Stats	
Mean	1498
Standard Deviation	339
COV	22.6
Minimum	1056
Maximum	1862

C4-1-1	-	100	0	1124
C4-1-2	-	100	0	1554
C4-1-3	-	-	-	-
C4-1-4	-	100	0	1080
C4-1-5	-	100	0	1636
Averages	-	100	0	1349

FRP-FRP 3 Strength Stats	
Mean	1349
Standard Deviation	287
COV	21.3
Minimum	1080
Maximum	1636

C4-2-1	-	100	0	1067
C4-2-2	-	100	0	982
C4-2-3	-	100	0	1280
C4-2-4	-	100	0	1354
C4-2-5	-	90	10	1585
Averages	-	98	2	1254

FRP-FRP 4 Strength Stats	
Mean	1254
Standard Deviation	240
COV	19.1
Minimum	982
Maximum	1585

FRP-FRP Bond
40 psi and 80 psi Pressure
VEW 260 B, GP 4242/4554

Samples	40 psi	80 psi	Samples
B3-1-1	1540	1325	U-F1-1
B3-1-2	1360	1336	U-F1-2
B3-1-3	1508	1395	U-F1-3
B3-1-4	1477	1112	U-F1-4
B3-1-5	1506	1320	U-F1-5
B3-2-1	1590	1512	U-F2-1
B3-2-2	1481	1418	U-F2-2
B3-2-3	1643	1511	U-F2-3
B3-2-4	1737	1482	U-F2-4
B3-2-5	1529	1451	U-F2-5
B4-1-1	1714		
B4-1-2	1509		
B4-1-3	1675		
B4-1-4	1587		
B4-1-5	1623		
B4-2-1	1411		
B4-2-2	1525		
B4-2-3	1639		
B4-2-4	1604		
B4-2-5	1523		

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
40 psi	20	31182.1	1559.1	9293.1
80 psi	10	13862.9	1386.3	14613.6

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	199094.5	1	199094.5	18.09	0.0002121	4.1960
Within Groups	308091.3	28	11003.3			
Total	507185.8	29				

FRP-FRP Shear Strengths
VEW 260 B and C Fabrics,
GP 4242/4554 w/Caustic, 80 psi Pressure

Sample	VEW260B	VEW260C	Sample
KE11F	1224	1521	L3-1-1
KE12F	1521	1557	L3-1-2
KE13F	1626	1453	L3-1-3
KE14F	1322	1515	L3-1-4
KE15F	1369	1418	L3-1-5
KE21F	1413	1569	L3-2-1
KE22F	1577	1259	L3-2-2
KE23F	1565	1689	L3-2-3
KE24F	1448	1468	L3-2-4
KE25F	1560	1310	L3-2-5
KF11F	1288	1601	L4-1-1
KF12F	1364	1623	L4-1-2
KF13F	1609	1586	L4-1-3
KF14F	1483	1404	L4-1-4
KF15F	1149	1508	L4-1-5
KF21F	1497	1607	L4-2-1
KF22F	1590	1204	L4-2-2
KF23F	1513	1415	L4-2-3
KF24F	1494	1285	L4-2-4
KF25F	1450	1426	L4-2-5

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
VEW260B	20	29059.9	1453.0	17420.2
VEW260C	20	29417.5	1470.9	17476.0

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3196.2	1	3196.2	0.1832	0.67107	4.0982
Within Groups	663027.9	38	17448.1			
Total	666224.1	39				

FRP-FRP Bond
Unmodified and Methanol Modified GP 4242/4554
VEW 260 B, 80 psi Pressure

Sample	Unmodified	Methanol	Sample
U-F1-1	1325	1203	MA11F
U-F1-2	1336	1231	MA12F
U-F1-3	1395	1027	MA13F
U-F1-4	1112	1024	MA14F
U-F1-5	1320	1026	MA15F
U-F2-1	1512	1364	MA21F
U-F2-2	1418	1248	MA22F
U-F2-3	1511	1067	MA23F
U-F2-4	1482	1276	MA24F
U-F2-5	1451	1025	MA25F
		1005	MB11F
		1222	MB12F
		919	MB13F
		1107	MB14F
		887	MB15F
		979	MB21F
		1082	MB22F
		1127	MB23F
		1210	MB24F
		1048	MB25F

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Unmodified	10	13862.9	1386.3	14613.6
Methanol	20	22075.2	1103.8	16088.2

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	532176.5	1	532176.5	34.083	0.00000283	4.196
Within Groups	437198.8	28	15614.2			
Total	969375.4	29				

Wood-Wood Bond
Unmodified and Methanol Modified GP 4242/4554
from VEW 260 B Series Testing, 80 psi Pressure

Sample	Unmodified	Methanol	Sample
U-WC-1	1123	1338	MCC1W
U-WC-2	1278	1211	MCC2W
U-WC-3	1051	1093	MCC3W
U-WC-4	1012	1180	MCC4W
U-WC-5	1223	1193	MCC5W
U-FC-1	1182	1467	MAC1F
U-FC-2	1258	1023	MAC2F
U-FC-3	1269	1164	MAC3F
U-FC-4	1316	1570	MAC4F
U-FC-5	1367	1344	MAC5F
		1096	MBC1F
		1276	MBC2F
		1440	MBC3F
		1205	MBC4F
		1206	MBC5F

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Unmodified	10	12079.9	1208.0	13209.5
Methanol	15	18807.0	1253.8	23110.4

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	12593.1	1	12593.1	0.65466	0.42674	4.2793
Within Groups	442431.1	23	19236.1			
Total	455024.2	24				

FRP-Wood
Unmodified and Methanol Modified GP 4242/4554
VEW 260 B, 80 psi Pressure

Sample	Unmodified	Methanol	Sample
U-W1-1	1496	1301	MC11W
U-W1-2	1109	1449	MC12W
U-W1-3	1115	1374	MC13W
U-W1-4	1478	1512	MC14W
U-W1-5	1208	1262	MC15W
U-W2-1	1220	1154	MC21W
U-W2-2	1348	1116	MC22W
U-W2-3	956	1130	MC23W
U-W2-4	1285	1155	MC24W
U-W2-5	1370	1132	MC25W

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Unmodified	10	12584.9	1258.5	29386.4
Caustic	10	12586.1	1258.6	21124.9

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.07186	1	0.07186	0.00000285	0.99867	4.4139
Within Groups	454602.0	18	25255.7			
Total	454602.1	19				

FRP-FRP Bond
Unmodified and Caustic Modified GP 4242/4554
VEW 260 B, 80 psi Pressure

Sample	Unmodified	Caustic	Sample
U-F1-1	1325	1224	KE11F
U-F1-2	1336	1521	KE12F
U-F1-3	1395	1626	KE13F
U-F1-4	1112	1322	KE14F
U-F1-5	1320	1369	KE15F
U-F2-1	1512	1413	KE21F
U-F2-2	1418	1577	KE22F
U-F2-3	1511	1565	KE23F
U-F2-4	1482	1448	KE24F
U-F2-5	1451	1560	KE25F
		1288	KF11F
		1364	KF12F
		1609	KF13F
		1483	KF14F
		1149	KF15F
		1497	KF21F
		1590	KF22F
		1513	KF23F
		1494	KF24F
		1450	KF25F

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Unmodified	10	13862.9	1386.3	14613.6
Caustic	20	29059.9	1453.0	17420.2

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	29660.1	1	29660.1	1.7956	0.19102	4.1960
Within Groups	462506.6	28	16518.1			
Total	492166.7	29				

Wood-Wood Bond
Unmodified and Caustic Modified GP 4242/4554
from VEW 260 B Series Testing, 80 psi Pressure

Sample	Unmodified	Caustic	Sample
U-WC-1	1123	1568	KDC1W
U-WC-2	1278	1510	KDC2W
U-WC-3	1051	1787	KDC3W
U-WC-4	1012	1277	KDC4W
U-WC-5	1223	1416	KDC5W
U-FC-1	1182	1517	KEC1F
U-FC-2	1258	1418	KEC2F
U-FC-3	1269	1440	KEC3F
U-FC-4	1316	1496	KEC4F
U-FC-5	1367	1651	KEC5F
		1599	KFC1F
		1487	KFC2F
		1516	KFC3F
		1402	KFC4F
		1426	KFC5F

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Unmodified	10	12079.9	1208.0	13209.5
Caustic	15	22509.6	1500.6	14492.6

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	513869.8	1	513869.8	36.730	0.00000351	4.2793
Within Groups	321782.7	23	13990.6			
Total	835652.5	24				

FRP-Wood
Unmodified and Caustic Modified GP 4242/4554
VEW 260 B, 80 psi Pressure

Sample	Unmodified	Caustic	Sample
U-W1-1	1496	1525	KD11W
U-W1-2	1109	1376	KD12W
U-W1-3	1115	1431	KD13W
U-W1-4	1478	1426	KD14W
U-W1-5	1208	1593	KD15W
U-W2-1	1220	1377	KD21W
U-W2-2	1348	1266	KD22W
U-W2-3	956	1519	KD23W
U-W2-4	1285	1431	KD24W
U-W2-5	1370	1389	KD25W

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Unmodified	10	12584.9	1258.5	29386.4
Caustic	10	14333.0	1433.3	8627.5

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	152803.9	1	152803.9	8.0394	0.01097	4.4139
Within Groups	342125.1	18	19006.9			
Total	494929.0	19				

FRP-FRP
VEW 260 B with Unmodified GP 4242/4554
and VEW 260 C with GP 5022/4822
80 psi Pressure

Sample	GP4242	GP5022	Sample
U-F1-1	1325	1102	C3-1-1
U-F1-2	1336	886	C3-1-2
U-F1-3	1395	1138	C3-1-3
U-F1-4	1112	1339	C3-1-4
U-F1-5	1320	1378	C3-1-5
U-F2-1	1512	864	C3-2-1
U-F2-2	1418	1444	C3-2-2
U-F2-3	1511	1572	C3-2-3
U-F2-4	1482	1647	C3-2-4
U-F2-5	1451	1348	C3-2-5
		1124	C4-1-1
		1554	C4-1-2
		1080	C4-1-4
		1636	C4-1-5
		1067	C4-2-1
		982	C4-2-2
		1280	C4-2-3
		1354	C4-2-4
		1585	C4-2-5

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
GP4242	10	13862.9	1386.3	14613.6
GP5022	19	24382.0	1283.3	63509.3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	69545.5	1	69545.5	1.4731	0.23537	4.2100
Within Groups	1274688.8	27	47210.7			
Total	1344234.4	28				

Wood-Wood
Unmodified GP 4242/4554 and GP 5022/4822
80 psi Pressure

Sample	GP4242	GP5022	Sample
U-WC-1	1123	1074	C1-C-1
U-WC-2	1278	1603	C1-C-2
U-WC-3	1051	1222	C1-C-3
U-WC-4	1012	1483	C1-C-4
U-WC-5	1223	1608	C1-C-5
U-FC-1	1182	914	C2-C-1
U-FC-2	1258	1451	C2-C-2
U-FC-3	1269	1443	C2-C-4
U-FC-4	1316	1479	C2-C-5
U-FC-5	1367		

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
GP4242	10	12079.9	1208.0	13209.5
GP5022	9	12276.1	1364.0	58129.3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	115307.6	1	115307.6	3.3570	0.08450	4.4513
Within Groups	583919.8	17	34348.2			
Total	699227.4	18				

FRP-Wood
VEW 260 B with Unmodified GP 4242/4554
and VEW 260 C with GP 5022/4822
80 psi Pressure

Sample	GP4242	GP5022	Sample
U-W1-1	1496	927	C1-1-1
U-W1-2	1109	1268	C1-1-2
U-W1-3	1115	1346	C1-1-3
U-W1-4	1478	1296	C1-1-4
U-W1-5	1208	1460	C1-1-5
U-W2-1	1220	880	C1-2-1
U-W2-2	1348	1338	C1-2-2
U-W2-3	956	1574	C1-2-3
U-W2-4	1285	1602	C1-2-4
U-W2-5	1370	1687	C1-2-5
		1634	C2-1-1
		1905	C2-1-2
		1755	C2-1-3
		1802	C2-1-4
		1792	C2-1-5
		1699	C2-2-1
		1211	C2-2-2
		1909	C2-2-3
		1802	C2-2-4

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
GP4242	10	12584.9	1258.5	29386.4
GP5022	19	28887.0	1520.4	94913.1

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	449335.4	1	449335.4	6.1493	0.01968	4.2100
Within Groups	1972912.5	27	73070.8			
Total	2422247.9	28				

Appendix C:

Interlaminar Shear Data

Table C1: Interlaminar Shear Data - U 72 - 10 Fabric, Standard Sizing, 4242 Resin, 0 Minute Open Time, 80 Psi Pressure

Specimen	Width (in)	Thickness (in)	Load at Yield (lb)	Shear Strength (psi)
72-0-1	0.249	0.261	87.1	1005
72-0-2	0.248	0.266	91.3	1038
72-0-3	0.249	0.271	92.6	1029
72-0-4	0.249	0.266	86.4	979
72-0-5	0.250	0.267	85.4	959
72-0-6	0.249	0.267	92.0	1038
			Mean	1008
			StndDeviation	33.3
			COV	3.3

Table C2: Interlaminar Shear Data - U 72 - 10 Fabric, Standard Sizing, 4242 Resin, 40 Minute Open Time, 80 Psi Pressure

Specimen	Width (in)	Thickness (in)	Load at Yield (lb)	Shear Strength (psi)
72-40-1	0.250	0.267	94.0	1056
72-40-2	0.250	0.266	92.1	1039
72-40-3	0.250	0.253	83.6	992
72-40-4	0.250	0.260	92.9	1072
72-40-5	0.250	0.261	93.7	1077
72-40-6	0.250	0.263	96.0	1094
			Mean	1055
			StndDeviation	36.3
			COV	3.4

Table C3: Interlaminar Shear Data - U 72 Z - 10 Fabric, Standard Sizing, 4242 Resin, 0 Minute Open Time, 80 Psi Pressure

Specimen	Width (in)	Thickness (in)	Load at Yield (lb)	Shear Strength (psi)
72 Z-0-1	0.250	0.261	85.6	984
72 Z-0-2	0.251	0.244	68.5	838
72 Z-0-3	0.250	0.248	74.1	896
72 Z-0-4	0.250	0.276	96.3	1046
72 Z-0-5	0.250	0.261	88.8	1020
72 Z-0-6	0.250	0.263	98.8	1024
			Mean	968
			StndDeviation	82.7
			COV	8.5

Table C4: Interlaminar Shear Data - U 72 Z - 10 Fabric, Standard Sizing, 4242 Resin, 40 Minute Open Time, 80 Psi Pressure

Specimen	Width (in)	Thickness (in)	Load at Yield (lb)	Shear Strength (psi)
72 Z-40-1	0.250	0.261	74.7	859
72 Z-40-2	0.250	0.262	73.1	837
72 Z-40-3	0.251	0.275	93.4	1015
72 Z-40-4	0.250	0.267	89.8	1009
72 Z-40-5	0.250	0.267	93.0	1045
72 Z-40-6	0.250	0.266	89.0	1004
			Mean	961
			StndDeviation	89.3
			COV	9.3

Table C5: Interlaminar Shear Data - U 18 - 01 Fabric, Standard Sizing, 4242 Resin, 0 Minute Open Time, 80 Psi Pressure

Specimen	Width (in)	Thickness (in)	Load at Yield (lb)	Shear Strength (psi)
18-0-1	0.251	0.245	177.1	2160
18-0-2	0.250	0.226	137.8	1829
18-0-3	0.251	0.233	124.6	1598
18-0-4	0.251	0.227	137.0	1804
18-0-5	0.250	0.233	146.5	1886
			Mean	1855
			StndDeviation	202
			COV	10.9

Table C6: Interlaminar Shear Data - U 18 - 01 Fabric, Standard Sizing, 4242 Resin, 40 Minute Open Time, 80 Psi Pressure

Specimen	Width (in)	Thickness (in)	Load at Yield (lb)	Shear Strength (psi)
18-40-1	0.250	0.240	200.4	2505
18-40-2	0.250	0.227	185.8	2455
18-40-3	0.251	0.225	117.3	1558
18-40-4	0.249	0.235	143.5	1840
18-40-5	0.251	0.233	114.4	1467
18-40-6	0.252	0.237	102.7	1290
			Mean	1852
			StndDeviation	518
			COV	28.0

Appendix D:

Tensile Test Data

Table D1: Tensile Data - U 18 - 01 Fabric, Standard Sizing, 4242 Resin, 80 Psi Pressure

Specimen	Width (in)	Thicknes (in)	Peak Load (lb)	Tensile Str (psi)	MOE (ksi)
18-S-4242-80-1	0.501	0.227	6012	52860	6635
18-S-4242-80-2	0.499	0.219	7739	70820	5898
18-S-4242-80-3	0.496	0.215	5401	50650	5561
18-S-4242-80-4	0.503	0.217	6237	57140	4713
18-S-4242-80-5	0.499	0.219	6330	57920	4368
18-S-4242-80-6	0.497	0.237	6697	56860	8648
18-S-4242-80-7	0.498	0.243	7896	65250	6798
18-S-4242-80-8	0.500	0.241	7510	62320	8554
18-S-4242-80-9	0.500	0.253	7039	55640	5397
18-S-4242-80-10	0.499	0.235	7417	63250	4378
			Average:	59150	6095

*Samples 1-4 were fabricated with 40 minute open time, while samples 5 through 10 were fabricated with zero open time

Table D2: Tensile Data - U 72 - 10 Fabric, Standard Sizing, 4242 Resin, 80 Psi Pressure

Specimen	Width (in)	Thicknes (in)	Peak Load (lb)	Tensile Str (psi)	MOE (ksi)
72-S-4242-80-1	0.495	0.057	1045	37040	6668
72-S-4242-80-2	0.495	0.058	1261	43920	8834
72-S-4242-80-3	0.495	0.057	1271	45050	5562
72-S -4242-80-4	0.495	0.062	1137	37050	2750
72-S -4242-80-5	0.495	0.056	649.1	23420	6847
72-S -4242-80-6	0.495	0.055	870.6	31980	3671
72-S -4242-80-7	0.496	0.055	1206	44210	6242
72-S -4242-80-8	0.495	0.055	1682	61780	6128
72-S -4242-80-9	0.496	0.056	1633	58790	5737
72-S -4242-80-10	0.498	0.60	326.2	10920	5698
72-S -4242-80-11	0.498	0.60	965.6	32320	4490
72-S -4242-80-12	0.496	0.52	1010	39160	4945
72-S -4242-80-13	0.496	0.56	1068	38450	3845
			Average:	38774	5494

*Samples 1-6 had 40 minute open time, while samples 7-13 had zero open time.

Table D3: Tensile Data - U 72 - 10 Fabric with Z-fibers, Standard Sizing, 4242 Resin, 80 Psi Pressure

Specimen	Width (in)	Thicknes (in)	Peak Load (lb)	Tensile Str (psi)	MOE (ksi)
72z-S-4242-80-1	0.495	0.062	1037	33790	5830
72z-S-4242-80-2	0.495	0.061	1086	35970	4447
72z-S-4242-80-3	0.500	0.064	1289	40280	5114
72z-S -4242-80-4	0.495	0.060	1144	38520	3617
72z-S -4242-80-5	0.496	0.70	1101	31710	4766
72z-S -4242-80-6	0.495	0.056	845.6	30510	6522
72z-S -4242-80-7	0.498	0.080	943.1	23670	3906
72z-S -4242-80-8	0.499	0.073	848.0	23280	4007
72z-S -4242-80-9	0.498	0.065	920.5	28440	4020
72z-S-4242-80-10	0.498	0.065	720.0	22240	5499
72z-S-4242-80-11	0.497	0.060	951.9	31920	5484
72z-S-4242-80-12	0.496	0.058	889.9	30930	5288
72z-S-4242-80-13	0.497	0.058	596.0	20680	6137
72z-S-4242-80-14	0.504	0.058	1087	37190	8594
72z-S-4242-80-15	0.496	0.055	633.8	23230	6630
72z-S-4242-80-16	0.502	0.063	728.0	23020	3921
			Average:	29715	5168

*Samples 1-8 had 40 minute open time, while samples 9-16 had zero open time.

Table D4: Tensile Data - VEW 260 Fabric, Phenolic Sizing, 4242 Resin, 80 Psi Pressure

Specimen	Width (in)	Thicknes (in)	Peak Load (lb)	Tensile Str (psi)	MOE (ksi)
26-P-4242-80-1	0.496	0.142	3756	53328	5200
26-P-4242-80-2	0.503	0.145	4046	55474	6218
26-P-4242-80-3	0.497	0.139	4004	57959	5291
26-P-4242-80-4	0.501	0.133	4434	66544	6005
26-P-4242-80-5	0.497	0.129	4385	68474	5898
26-P-4242-80-6	0.500	0.124	3372	54387	5870
			Average:	59361	5747

Table D5: Tensile Data - VEW 260 Fabric, Standard Sizing, 4242 Resin, 80 Psi Pressure

Specimen	Width (in)	Thicknes (in)	Peak Load (lb)	Tensile Str (psi)	MOE (ksi)
26-S-4242-80-1	0.502	0.137	4374	63600	5221
26-S-4242-80-2	0.497	0.134	4502	67600	5805
26-S-4242-80-3	0.497	0.132	4407	67176	6083
26-S-4242-80-4	0.500	0.128	4336	67750	5718
26-S-4242-80-5	0.500	0.123	4258	69236	5756
			Average:	67072	5717

Table D6: Tensile Data - VEW 260 Fabric, Standard Sizing, 4242 Resin, 40 Psi Pressure

Specimen	Width (in)	Thicknes (in)	Peak Load (lb)	Tensile Str (psi)	MOE (ksi)
26-S-4242-40-1	0.489	0.130	3933	61869	5244
26-S-4242-40-2	0.506	0.132	4630	69320	5320
26-S-4242-40-3	0.491	0.132	4243	65466	5415
26-S-4242-40-4	0.498	0.136	4491	66309	5542
26-S-4242-40-5	0.500	0.139	4713	67813	5877
			Average:	66155	5479

Table D7: Tensile Data - VEW 260 Fabric, Phenolic Sizing, 5022 Resin, 80 Psi Pressure

Specimen	Width (in)	Thicknes (in)	Peak Load (lb)	Tensile Str (psi)	MOE (ksi)
26-P-5022-80-1	0.496	0.099	2560	52082	6861
26- P-5022-80-2	0.506	0.095	3652	75898	6937
26- P-5022-80-3	0.505	0.103	4364	83866	6756
26- P-5022-80-4	0.500	0.104	3977	76481	6562
26- P-5022-80-5	0.507	0.107	3495	64425	6602
26- P-5022-80-6	0.505	0.110	2631	47363	5755
			Average:	66686	6579

Appendix E:

Photographs of Test Beams

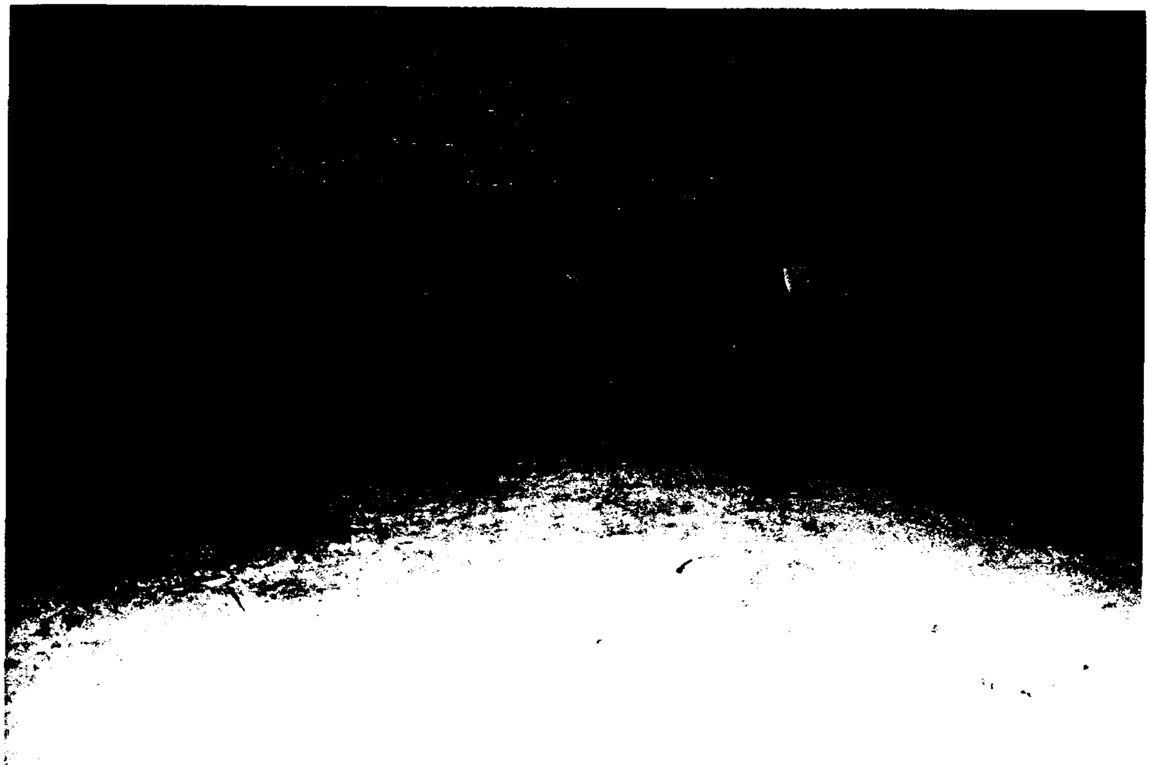

Figure E.5: Picture of Failed 4% Reinforced Beam, R4-7.

Description:

Two beams, R4-5 and R4-7, failed in shear rather than in bending. The shear failure can be clearly seen at the left side of this beam.

Figure E.4: Picture of Failed 4% Reinforced Beam, R4-3.

Description:

This beam failed outside the constant moment region, which is between the two load heads. It also failed at the inner tension lamination where bending stresses are lower, rather than at the outermost tension lamination. Failure began at a knot which can be seen at about the 1/4 point of the beam from the left, in the second wood lamination from the top. It can be seen that at the left end of the beam, the reinforcement remained bonded to the wood, and it was the wood that failed at the FRP-wood interface rather than an adhesive failure.

Figure E.3: Picture of 3% Failed Reinforced Beam, R3-7.

Description:

This is a good example of the failure mode seen for the 3% reinforced beams. The outer tension lamination failed at a knot at about 1/3 the length of the beam from the left. The bond between the reinforcement and the wood was stronger than the strength of the wood, and the tension lamination failed out to the end of the beam. It should be noted that the wood failure in the tension lamination, following failure at the knot, was shake. Shake is a common weakness in eastern hemlock.

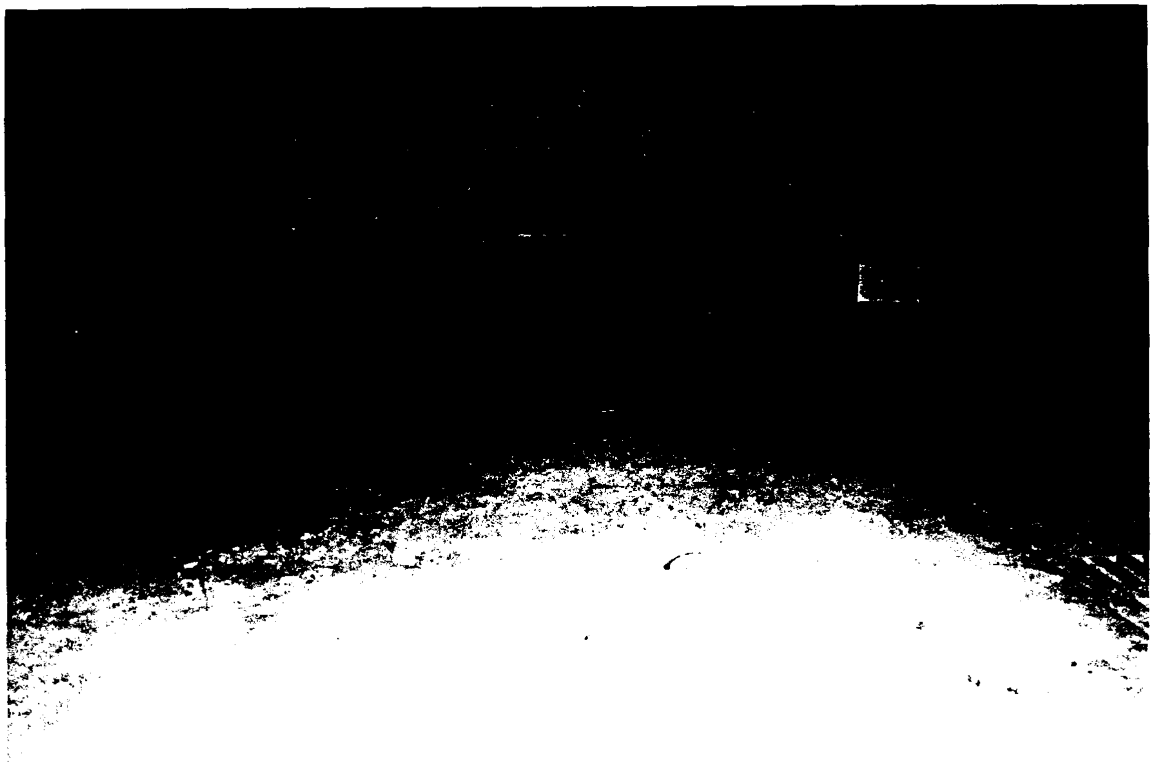

Figure E.2: Picture of Failed 2% Reinforced Beam, R2-1.

Description:

The tension failure in the outermost tension lamination is apparent in the picture. The failed lamination lifted up, separating the reinforcement. The beam could not carry any more load when this occurred.

Figure E.1: Picture of Failed Control Beam, C-7.

Description:

This is a classic example of an unreinforced beam failure. The tension failure in the outermost tension lamination (on the top of the beam) is easy to see. Following failure in the tension lamination, the beam can no longer support the load and the beam fails catastrophically.

Appendix F:

Cost Analysis

Given unit values of σallow, M, and S, if σallow is 139% greater for a reinforced beam than for an unreinforced beam, and knowing that σallow=M/s,

$$S = \frac{1}{2.39} = 0.418 \qquad S := 0.418$$

then the required section modulus for a reinforced beam is reduced by 58.2% This reduces the needed width, and therefore wood volume, by 58.2%, by only adding 2% reinforcement. Or rather, an unreinforced beam is 172% larger than a reinforced beam.

No. 2 & Better eastern hemlock lumber costs about $0.35 per board foot. One board foot is 1.5" x 5.5" x 12".

To make a 1.5" thick composite, 57.7 plies are needed with a 0.026" thick ply. A "board foot" of composite therefore requires 2.938 square yards of VEW 260 fabric, which is 76 ounces, or 4.775 lbs. At $1.30 per pound = $6.07. With the resin cost being $3.82 (assuming 50/50 resin/glass ratio by weight, and resin being $0.80 per pound), the cost of a board foot of composite is $10.03.

Assuming a reinforced beam cross-section, with a unit 1 ft. length, has 10 board feet of lumber; then, the cost of lumber is 10 x $0.35 = $3.50. The cost of reinforcement is 0.02 x 10 x $10.03 = $2.01. The cost of the reinforced beam then is $5.51 per foot length.

An unreinforced beam with the same allowable bending strength as the reinforced, will have 10 x 1.72 = 17.2 board feet, and cost 17.2 x $0.35 = $6.02.

The cost of a 2% reinforced beam is 8.5% less than the cost of an unreinforced of the same allowable bending strength.

BIOGRAPHY

Andrew R. Jordan was born in Preque Isle, Maine on July 18, 1974. He was raised in Ashland, Maine and graduated from Ashland Central High School in 1992. He attended the University of Maine and graduated in 1996 with a degree in Civil Engineering with a concentration in structures. He then began working as a research assistant for Professor Habib Dagher, and enrolled in graduate school. Andy is a candidate for the Master of Science degree in Civil Engineering from the University of Maine in August, 1998.