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Bond Strength of FRP-Wood Interface

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INTRODUCTION

THE STRUCTURAL UTILIZATION of laminated wood products, such as glued-laminated timber (Glulam), is usually limited by the relatively low bending stiffness and strength of the material in relation to other products like concrete and steel. One potential solution to increase the stiffness and strength of glued-laminated timber products, particularly Glulam, is to reinforce them at top and bottom surfaces with fiber-reinforced composite materials.The wood material used in this study is Yellow-poplar (*Liriodendron tulipifera*), which is an abundant hardwood species in West Virginia (30 million cubic feet of standing timber), and the composite material chosen is E-glass fiber-reinforced vinylester/polyester composite (FRP) produced by pultrusion. In the pultrusion-process, glass fiber-reinforced plastics of specific lengths and cross-sectional dimensions can be produced in large quantities at relatively low cost. The pultruded FRP composites can be laminated to wood laminates in a glulam plant. Thus, the motivation for selecting pultruded FRP is the possibility of commercially producing Glulam-FRP beams in current laminating plants using an adhesive compatible with existing production operations. For this reason, three potential wood/FRP adhesives were selected for this study: (1) Resorcinol Formaldehyde (RF) (INDSPEC, Pencolite G1131), which is a wood adhesive; (2) emulsion Isocyanate (ISO) (Ashland, Isoset WD3-C120/CX 47), which is essentially a crosslinked vinyl emulsion adhesive, and (3) Epoxy (Magnolia Plastics Magnabond 56), a strong FRP adhesive.

A comprehensive review of previous work on the reinforcement of wood beams

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was presented by Bulleit (1984) and Spaun (1979). The concepts explored by previous researchers, however, have not resulted in commercial applications. While many considerations determine the commercial success or failure of engineered materials, the feasibility of the manufacturing process is a major factor that influences the product cost. The study presented in this paper is part of an overall effort concerned with the eventual commerical production of wood-FRP laminates. We selected FRP as the reinforcing material, because it is the least expensive, continuous fiber, mass-produced, structural composite. We envisioned that FRP will be bonded to wood laminates with an adhesive compatible with the operating procedures used currently in wood laminating plants. As a result of the proposed manufacturing technique, the selection, qualification, and analysis of the performance of the adhesive are critical.

When the reinforcement is joined to the wood by mechanical fasteners, stress concentrations result. Adhesive bonding is a better way of attaching a reinforcement to wood, because of greater contact area resulting in a beter shear transfer from one substrate to another. The bond formed should be strong enough to transfer shear from one substrate to another and should be durable under exposure to exterior service conditions. The performace of adhesively bonded assemblies can be a function of the composition and properties of the adhesive, the conditions between adhesive and adherent, and the properties of the adherent itself. Ultimate failure of the assembly can occur in the adhesive, or the adherent, or the boundary region. In addition to sustaining the applied loads, bonded structural components are expected to perform adequately when exposed to the outside environment. Changes in environmental conditions, such as temperature and relative humidity, can significantly affect the durability of bonded assemblies. The changes in temperature can significantly affect the rheological properties of the adhesives, while changes in relative humidity can result in dimensional changes of the substrates, due to shrinkage or swelling. Therefore, the performance of the bond must be fully characterized before engineering applications can be implemented.

In this study, the performance of the selected adhesives is evaluated on small samples, under dry and wet conditions, following a modified ASTM D-905 test procedure. Since actual applications of wood-FRP composites will involve large components under a variety of loads and environmental conditions, analytical tools are needed to predict in-service behavior of the material. The objectives of this paper are: (1) to present a finite element stress analysis of the FRP-wood bond interface of Yellow-poplar/FRP shear-block samples under dry and wet conditions, and (2) to describe the determination of material properties and model parameters needed in the FE analysis. The model is correlated with experimental results of a qualification program (Gardner, Davalos, and Munipalle 1993; Munipalle 1992). A review of the experimental program is presented to define the problem to be modeled numerically, and the results of the experimental program are used to validate the numerical model.

EXPERIMENTAL DETERMINATION OF BOND STRENGTH

The Finite Element Model developed is validated by modeling the experimental shear-block test samples and comparing numerical predictions with experimental results. Therefore, a description of the test conditions, which are then modeled numerically, is presented next.

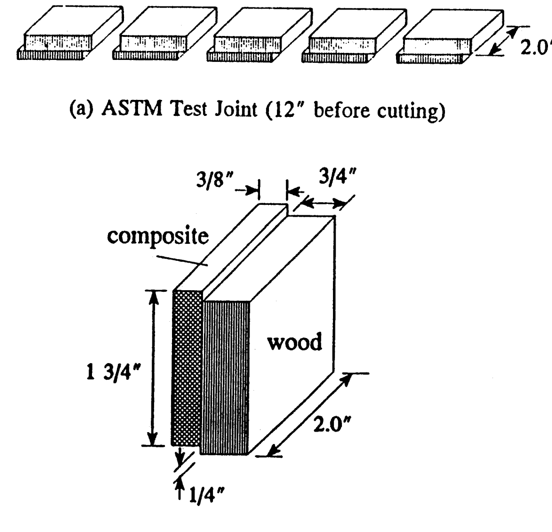

Figure 1. *ASTM D-905 specimen preparation: (a) before cutting, (b) final shear block.*

To evaluate the ultimate shear strength, bond-interface integrity, and percent wood failure, the experimental program (Gardner, Davalos, and Munipalle 1993) was organized in three parts: dry shear strength test, wet shear strength test, and a 5-cycle accelerated aging test. All of these tests were performed on shear-block test specimens (Figure 1), as described in ASTM D-905. The testing program followed most of the guidelines given in ASTM D-905 and some of the guidelines described in ASTM D-1101.

The behavior of the bond interface was studied by bonding wood-to-wood and wood-to-composite samples and testing them under dry and wet conditions. The dry shear strength tests were used to evaluate the ultimate strength of wood-wood and wood-conposite samples and to estimate the percent wood failure of the bond-interface area. In the wet shear strength test, the specimens were saturated in water by subjecting them to a vacuum-pressure-soak process, and then, the wet specimens were tested in shear. In the 5-cycle accelerated aging test, the specimens were subjected to five cycles of complete water saturation and oven drying. This test was used to establish the integrity of the interface. To evaluate the significance of the experimental results, the following two requirements given by the American Institute of Timber Construction (AITC 1987) for wood-to-wood bonded interfaces for Glulam were used: (1) a minimum dry shear strength of

1075 psi, and (2) a minimum percent wood failure of 80% under ambient conditions.

Test Samples

The pultruded composite material used in this study consisted of E-glass fibers embedded in either vinylester or polyester resin. The wood species used was yellow-poplar (*Liriodendron tulipifera*), select structural grade, conditioned at 12% moisture content. Both heartwood and sapwood samples were included to study the effects of permeability differences.

Prior to bonding, the composite was first hand sanded and then wiped with Ethanol to make the surface free from dirt and other impurities. The wood used was also sanded and air-cleaned to free the surface from impurities. The bonding of the substrates and testing of the shear block specimens were carried out in a conditioned room monitored at an equilibrium moisture content of 12%. Just before bonding, the composite and wood samples were sanded and cleaned as described earlier, and they were bonded using an adhesive spread rate of 50 lbs per 1000 ft^2 of single glueline. The open assembly time was less than five minutes, and the closed assembly time was approximately twenty minutes. An optimum pressure to obtain a good squeeze out of the adhesive was applied. Since the three adhesives used were room temperature curing, the preparation of test joints was performed in a conditioned room, and the pressure was applied for a period of 24 hours. Each test joint was removed from the conditioned room to cut five shear-block specimens (Figure 1). This operation required no more than five to six hours. The shear-block specimens were then returned to the conditioned room for three to four days before testing.

The specified ASTM D-905 shear test samples were slightly modified, because of the limitation in thickness of the available pultruded E-glass reinforced plastic. The thickness of wood was 3/4 inches as specified in ASTM D-905, but the composite was only 3/8 inches thick. The modified ASTM D-905 shear-block specimen is shown in Figure 1. These shear-block test specimens were used to test the following material combinations: sapwood-sapwood, heartwood-heartwood, sapwood-vinylester, heartwood-vinylester, sapwood-polyester, and heartwood-polyester.

The number of samples used for each material-adhesive combination is given in Table 1. To obtain statistically significant results, twenty samples were used for the dry and wet shear strength tests. Twelve samples were used for the 5-cycle accelerated aging test, which provided a qualitative assessment of glue-line integrity for the RF adhesive, identified as the most promising of all three adhesives. A total of six-hundred samples were tested.

The dry and wet shear strength tests were performed by following the guidelines given in ASTM D-905 for shear-block test samples. To saturate the samples with water, they were subjected to a vacuum-pressure-soak process, similar to the one specified in ASTM D-1101, and then tested according to ASTM D-905 guidelines to determine their remaining shear strengths. This testing procedure allowed a direct comparison with the FE analysis predictions of the response of the shear-block specimens. The numerical analysis presented in this paper was used to correlate quantitatively the dry and wet bond shear strengths, instead of the qualitative assessment provided by experimental tests.

The vacuum-pressure cycle to soak the specimens was modified from the one specified by the ASTM D-1101 standard. In this study, a vacuum of 20 to 25 inches Hg was applied for 40 minutes, and then, a pressure of 90 to 100 psi was applied for another 40 minutes. This procedure was found satisfactory for impregnating the wood layers with water. The increase in moisture content of the wood samples was 100 percent at the end of the cycle. The vacuum-pressure-soaked specimens were then tested wet for shear strength according to the ASTM D-905 method.

The shear-block samples were also used for the five-cycle accelerated aging test. This test was performed to establish the integrity of the adhesive bond under severe shrinkage and swelling of the wood layer bonded to the composite layer. The vacuum-pressure cycle used for this test was the same as the cycle used for the wet shear strength test (modified ASTM D-1101). This vacuum-pressure cycle was repeated five times. At the end of each cycle, the test specimens were dried in an oven at 105°C for 24 hours, which resulted in a total test period of six days.

Table 1. Summary of the ASTM tests performed.

	Test Type/Adhesive						
	Dry (ASTM D-905)			Wet (ASTM D-1101)			5-Cycle Aging
Combination	RF	PVA	Epoxy	RF	PVA	Epoxy	RF
Sapwood-Sapwood	20	20	20	20	20	20	—
Heartwood-Heartwood	20	20	20	20	20	20	—
Sapwood-Vinylester	20	20	20	20	20	20	12
Heartwood-Vinylester	20	20	20	20	20	20	12
Sapwood-Polyester	20	—	—	20	—	—	12
Heartwood-Polyester	20	—	—	20	—	—	12
Total No. of Tests	120	80	80	120	80	80	48
Grand Total	608 Shear Test Specimens						

Test Results

The predictions of the Finite Element Model are validated by comparing the stress-analysis results with the experimental responses summarized in this section. The three adhesives selected in this study were evaluated by testing the material combinations reported in Table 2. The dry and wet shear strengths and percent material failure of the tested samples are reported. The shear strength reported for each combination, as the mean value of twenty samples, is calculated by dividing the ultimate load by the area of the glued interface. Statistical analyses (SAS 1992) were conducted (Gardener, Davalos, and Munipalle 1993) to determine the differences among the three adhesives and among different

Table 2. Average bond shear strength and percent material failure with RF

Substrates	Shear Strength (Wet) Psi	Shear Strength (Dry) Psi	%Material Failure (Wet)	%Material Failure (Dry)
Heartwood-Heartwood (RF)	793	1676	98	97
Sapwood-Sapwood (RF)	718	1347	98	99
Heartwood-Vinylester (RF)	548	1219	28	71
Sapwood-Vinylester (RF)	721	1349	36	68
Heartwood-Polyester (RF)	833	1166	81*	99*
Sapwood-Polyester (RF)	955	1067	75*	97*

*FRP Failure

substrate combinations. These tests clearly indicate that both shear strength and percent material failure with resorcinol formaldehyde are significantly higher than with epoxy and isocyanate, for both dry and wet tests.

The American Institute of Timber Construction (AITC 1987) requires a minimum dry bond shear strength of 1075 psi and a minimum percent wood failure of 80% for dry tests. Based on these requirements, only the RF adhesive provided adequate strength for most material combinations. For the minimum required percent material failure (AITC 1987), the wood-to-wood bond with RF was satisfactory, but the wood-to-vinylester bonding was approximately 10% below the minimum. The shear strength of the glued interface can also be compared to the solid-wood shear strength for Yellow-poplar, obtained from similar solid wood shear block tests, reported in the Wood Handbook (1987) as 1190 psi for dry strength (at 12% moisture content) and 790 psi for wet strength. The testing program concludes with a 5-cycle accelerated aging test, used to evaluate the integrity of the bond interface with the RF adhesive only.

DETERMINATION OF MATERIAL PROPERTIES

Swelling coefficients and elastic material properties are needed for the analysis of the behavior of the bond interface under moisture and mechanical loads. The required properties were determined experimentaly and/or analytically, as described in this section.

Swelling Coefficients

Wood absorbs and loses moisture very rapidly in comparison to moisture diffusion in FRP composites. Wood shrinks and swells significnatly with changing moisture content, while the swelling expansion of FRP composites is relatively small compared to wood. Wood shrinks and swells very little along the grain, i.e., in the longitudinal direction (Figure 2). The swelling and shrinking in the tangential direction is greater than that in the radial direction.

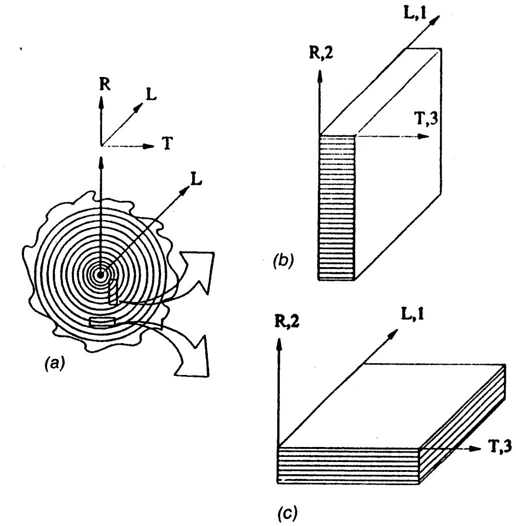

Figure 2. *Coordinate system used in the modeling of ASTM D-905 test.*

The equilibrium moisture content of wood with the environment is usually less than 19% by weight. If the FRP composite is bonded to wood at a certain moisture content (e.g., 12%), subsequent variations in moisture will cause shrinkage or swelling of wood. This shrinkage and swelling of wood induces strains and stresses in the wood and FRP substrates. It also results in warping of wood if the grain is oriented at an angle (cross grain) to the geometric longitudinal axis, *L*, of the sample (Figure 2). Since wood absorbs moisture faster and swells more than the FRP composites, stresses are induced at the interface. That is, wood swelling is constrained by a stiffer FRP composite. An experimental indication of the effect of moisture on the interface is obtained by the accelerated aging test described above, for which, the total time of vacuum-pressure-soak cycle is less than one and a half hours. This is a very short time for FRP composite to absorb moisture. Whereas, the moisture content of wood was found to increase up to 100 percent by weight. Due to the differential rate of moisture intake and swelling of wood and FRP composite, the adhesive interface is subjected to severe stresses. The stress analysis of the wood/FRP swelling mismatch is performed with the Finite Element Method. The capabilities of the Finite element model are demonstrated in the next section by analyzing the response of the shear-block test samples subjected to moisture.

The swelling coefficients were measured for radial and tangential directions only, as the longitudinal swelling and shrinking is small and can be neglected when compared to swelling in the other two directions. Samples were cut from selected lumber pieces without any cross grain. That is, the longitudinal, radial, and tangential directions were aligned with the geometric axes of the specimens (Figure 2). Specimens were cut with the growth rings parallel either to the smaller [Figure 2(a)] or larger [Figure 2(b)] cross-sectional dimensions to measure, respectively, radial or tangential swelling. Ten sapwood Yellow Poplar samples were used for each radial and tangential direction.

The specimens were placed in an environmental chamber, where they were conditioned to desired moisture contents by adjusting the relative humidity and dry/wet bulb temperature in the chamber. The radial and tangential dimensions were measured with a digital caliper (accuracy 10^{-4} inch) at moisture contents of approximately 0, 5, 10, 15, 20 and 25 percent by weight. The average of 10 samples was taken as the dimension at a particular moisture content. Using 12% as the reference equilibrium moisture content, strains were computed from the measured dimension changes due to shrinkage or swelling. Then, a linear regression equation was fit to the data (Figure 3), with strain as the dependent variable and the moisture content as the independent variable. The moisture-strain relationships obtained are:

$$\epsilon_T = 0.0025374\ (MC) - 0.0285142$$

$$\epsilon_R = 0.001766\ (MC) - 0.017936$$

where, MC is the moisture content.

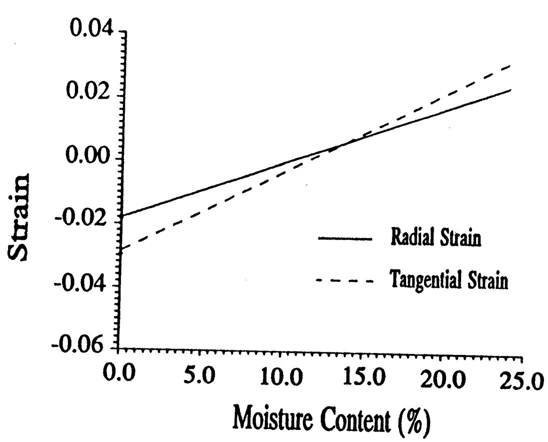

Figure 3. Determination of moisture expansion coefficient.

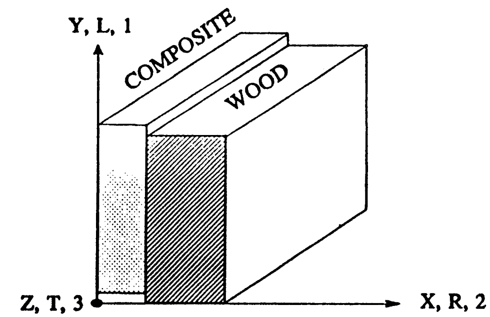

Figure 4. Coordinate system used for the determination of elastic constants of wood.

Elastic Constants

Based on the axes orientation of Figure 4, the following elastic constants are needed to model each layer of the wood/FRP laminate: three Young's moduli (E_i), three shear moduli (G_{ij}), and three Poisson's ratios (ν_{ij}). The elastic constants for wood given in Table 3 are obtained from Bodig and Jane (1989), and the elastic constants of FRP are obtained by a combination of micromechanics and classical lamination theory.

Fiber-reinforced composite materials are built with one matrix and several fiber systems like rovings, cloth, continuous strand mat (CSM), etc. The elastic constants of fiber (E_f, G_f, ν_f) and matrix E_m, G_m, ν_m) are combined to obtain the elastic properties of each fiber-matrix combination. The modulus in the fiber direction E_1, transverse to the fiber direction E_2, and the in-plane Poisson's ratio ν_{12} are computed by the rule of mixtures (Jones 1975)). The in-plane shear modulus is computed by the self-consistent formula (Christensen 1990).

Table 3. Elastic constants of Yellow-poplar

Elastic Constant	Magnitude (10^6 Psi)
Young's Modulus E_L	1.73
Young's Modulus E_R	0.1248
Young's Modulus E_T	0.056
Shear Modulus G_{LR}	0.0973
Shear Modulus G_{LT}	0.07
Shear Modulus G_{RT}	0.02245
Poisson's Ratio ν_{LR}	0.37
Poisson's Ratio ν_{LT}	0.5
Poisson's Ratio ν_{RT}	0.67

Fiber volume fraction, V_f, is defined as the ratio of the volume of the fiber to the total volume of the composite. The fiber volume fraction can also be computed as the ratio of area of the fibers in a cross-section to the total area of the cross-section, $V_f = A_f/A_c$, where A_f is determined from the number of fibers in the cross-section, the yield of the fibers (number of yards of roving weighing one pound), and the density of the fibers. For unidirectional fibers, $V_f = n/(y\,\varrho\,\tau_c)$, where "$n$" is the number of roving in the layer, "y" is the yield (m/kg) ϱ is the density of fibers (kg/m^3), and t_c is the thickness of the layer. For random fibers (continuous strand mat, etc.), $V_f = W/(\varrho\,\tau_c)$, where "$W$" is the weight per unit area of the CSM. The yield, number of roving, and weight per unit area of the CSM, as well as the stacking sequence (placement of the fibers) are given by the manufacturer (Creative Pultrusions 1989).

The material properties are grouped in a 3×3 reduced stiffness matrix $[Q]$ with coefficients given by Jones (1975). Various orientations of the fibers with respect to the longitudinal axis (L) of the sample are accounted for by a rotation of the stiffness coefficients (Jones 1975). The rotated stiffness coefficients are combined by classical lamination theory into the 3×3 in-plane stiffness matrix $[A]$, with coefficients given by Jones (1975).

Changing to the L-R-T index notation commonly used for wood, the equivalent properties of the laminate are obtained from the in-plane compliance matrix $[S] = [A]^{-1}$ as

$$E_L = \frac{t}{S_{11}} \; ; \; E_t = \frac{t}{S_{22}} \; ; \; G_{LT} = \frac{t}{S_{33}} \; ; \; \nu_{LT} = -E_L\, S_{12} \tag{1}$$

The remaining properties are inferred from the transverse isotropy assumption, i.e.,

$$E_R = E_T \; ; \; G_{LR} = G_{LT} \; ; \; \nu_{LR} = \nu_{LT} \tag{2}$$

The transverse Poisson's ratio ν_{23} and shear modulus G_{23} are computed using the fiber volume fraction averaged over the laminate cross section. The transverse shear modulus is computed by the formula derived from the generalized self-consistent method (Christensen and Lo 1979, Christensen 1990) and by the formula for composites with periodic microstructure (Luciano and Barbero 1993), both formulas giving close results. The transverse Poisson's ratio is computed (Chamis 1969) as

$$\nu_{TR} = V_f \nu_f + V_m\left(2\,\nu_m - \nu_{LT}\frac{E_T}{E_L}\right) \tag{3}$$

E-Glass fiber has an elastic modulus $E_f = 10.5 \times 10^6$ and Poisson's ratio $\nu_f = 0.3$. Vinylester resins have an elastic modulus $E_m = 0.49 \times 10^6$ and Poisson's ratio $\nu_m = 0.35$ (Creative Pultrusions 1989). The computed properties

Table 4. Elastic constants of composite.

Elastic Constant	Predicted (10^6 Psi)	Experimental (10^6 Psi)
Young's Modulus E_1	2.362	2.779
Young's Modulus E_2	1.211	1.653
Young's Modulus E_3	1.211	—
Shear Modulus G_{12}	0.466	0.549
Shear Modulus G_{13}	0.466	—
Shear Modulus G_{23}	0.23	—
Poisson's Ratio ν_{13}	0.2	—
Poisson's Ratio ν_{12}	0.39	0.276
Poisson's Ratio ν_{23}	0.43	—

are given in Table 4, which includes experimental data obtained from coupon samples. The tensile test for the determination of elastic moduli E_1 and E_2 were performed following test methods proposed by Barbero and Sonti (1989). The Poisson's ratios were determined by measuring longitudinal and transverse strains during the tensile tests. The shear modulus was determined by the Iosipescu and torsion tests (Sonti 1992).

ANALYSIS OF INTERFACIAL STRESSES

In this section, stress analysis is performed by the Finite Element Method. Our objective is to develop a Finite Element Model capable of predicting the stresses due to moisture and mechanical load and to validate this model by using the existing experimental data. Also, our objective is to understand the interface wet fail-

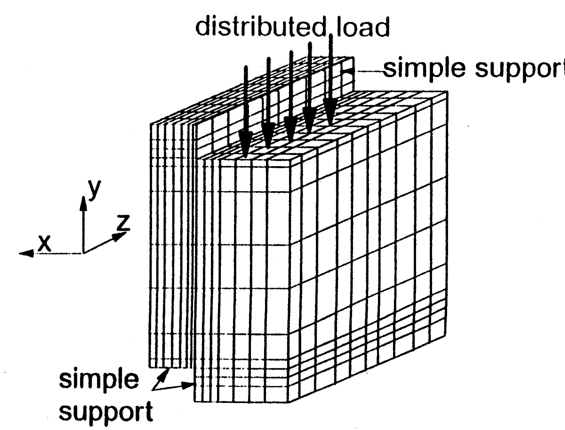

Figure 5. *Finite element model of ASTM D-905.*

ure response in relation to the dry failure response and to the shear strength of the wood layer.

To study the effects of moisture changes on the FRP-wood interface, a 3-D finite element modeling of the ASTM D-905 (Figure 5) shear block specimen was analyzed using ANSYS (Swanson Analysis 1991). Solid 3-D Brick elements, with 3 degrees of freedom (3 translations) per node, were used for the model. Nine elastic constants are needed to completely define the elastic behavior of an orthotropic material. These are, three shear moduli, three Young's moduli, and three Poisson's ratio. Elastic constants for the wood are given in Table 3. The composite elastic properties (Table 4) were theoretically determined, as these properties depend on the constituent properties of fiber and matrix, and fiber volume fraction, as shown in the previous section. Some of the elastic constants for the composite used in this study were also determined experimentally (Table 4).

The composite layer (Figure 4) was modeled with 8-node, 3-D solid brick elements. A 10 $\times$ 10 element mesh is used to divide the 1.75″ $\times$ 2.0″ surface of the composite, while seven elements are used through the thickness (Figure 5). The wood layer (thick layer in Figure 5) was also modeled with 8-node, 3-D solid brick elements. A 10 $\times$ 10 element mesh is used to divide the 1.75″ $\times$ 2.0″ surface of the wood, while seven divisions are used through the thickness (Figure 5). The through-the-thickness mesh is refined closer to the interface to better represent the gradient of deformation there. The mesh, loads, and boundary conditions are shown in Figure 5. The load and boundary condition represent closely the conditions on the ASTM D-905 test, while allowing for warping of the specimen as a result of the moisture expansion (Figure 5).

With the exception of the supports, the shear stress, τ_{LR}, is quite uniform at the bond interface and vanishes on the free surfaces of the sample. As will be shown next, the load is sustained mainly through shear stresses, τ_{LR}, that concentrate near the bond line. A view of the composite looking from the wood side, with the wood removed by the graphics program, is shown in Figures 6 and 7. A view of the wood looking from the composite side, with the composite removed by the graphics program, is shown in Figures 8 and 9. Figures 6 through 9 represent contour plots of shear τ_{LR} a distance 0.05 in. inside the composite (Figures 6 and 7) and wood (Figures 8 and 9). The results are presented 0.05 in. inside the material so that the stresses of elements with the same material type can be averaged at the nodes to produce the plots. In the displacement-based FEM, averaging cannot be used at the bond line because of the natural discontinuity of stresses computed from constitutive equations of dissimilar materials.

Figures 6 and 8 correspond to a sapwood-vinylester sample with a mechanical load of 4047 lb, equal to the average experimental failure load in a dry test with RF adhesive, which is reported as an average shear strength of 1349 psi in Table 2. Under dry conditions, a mechanical load of 4047 lb induces a maximum value of τ_{LR} = 639 psi (Figure 6) on the FRP, which indicates that no failure of the FRP is likely. The minimum value of $-$1586 psi on the cantilever end of the FRP occurs over a small region and it is well below the ultimate shear strength of 9880 psi reported by Sonti (1992). The minimum value of 2506 psi on wood (Figure

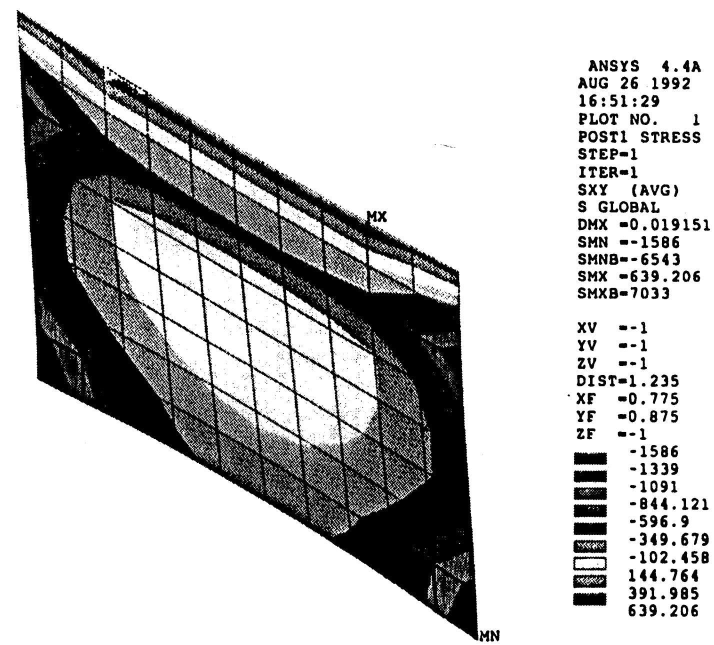

Figure 6. *View of composite with wood removed under a mechanical load equal to the experimental dry failure load.*

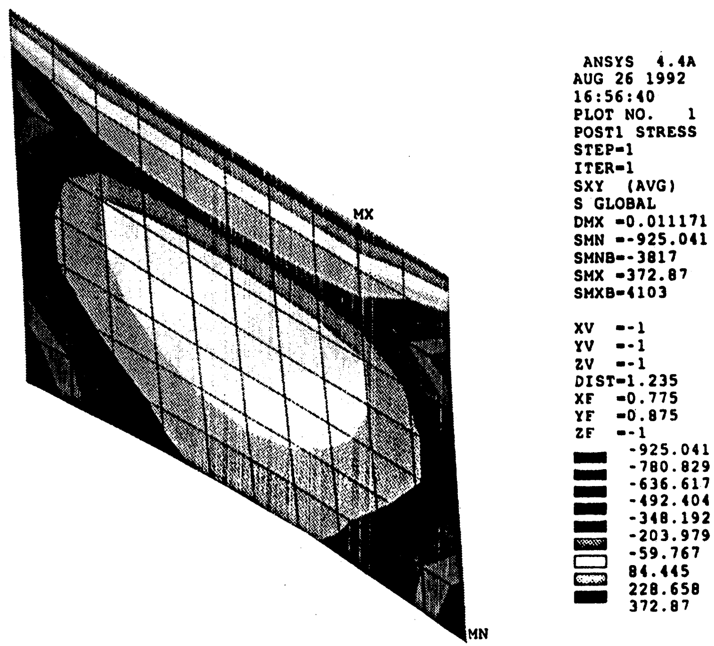

Figure 7. *View of composite with wood removed under mositure and mechanical loading similar to those that caused failure in experimental wet testing.*

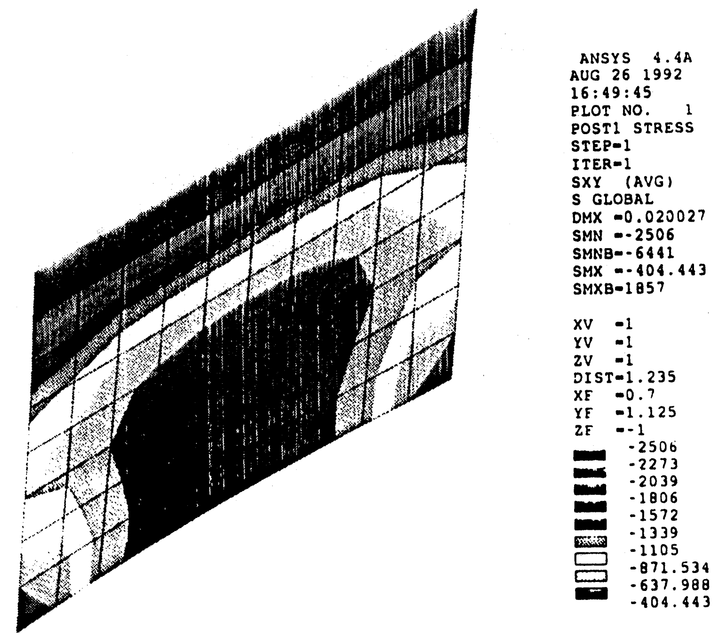

Figure 8. *View of wood with composite removed under a mechanical load equal to the experimental dry failure load.*

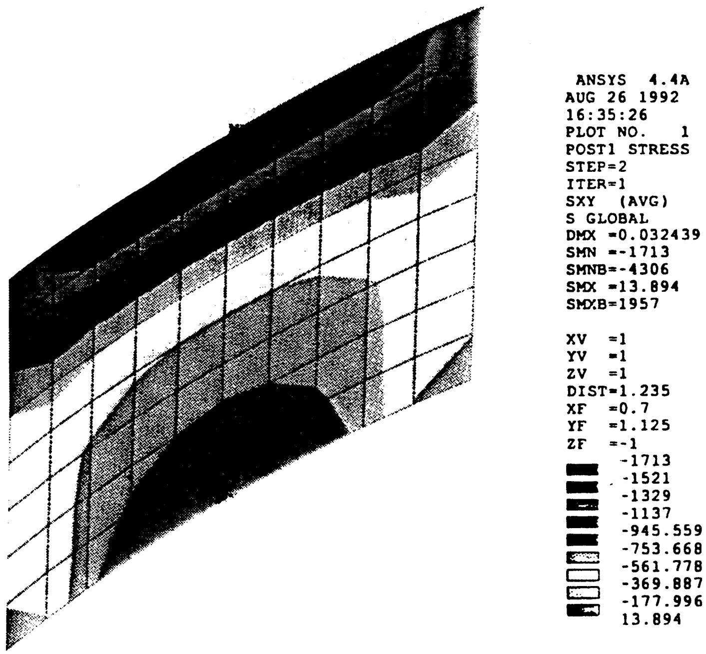

Figure 9. *View of wood with composite removed under moisture and mechanical loading similar to those that caused failure in experimental wet testing.*

8) occurs in the unbonded portion of the sample due to highly localized deformations there. The bonded portion of Figure 8 shows values of −2039 to −1572, where failure must initiate because the shear stress exceeds the wood shear strength of 1800 psi reported by Janowiak (1990) for solid wood Yellow-poplar shear-block samples.

Figures 7 and 9 correspond to the sample subjected to both moisture and mechanical loading similar to those that caused failure in the wet testing. The model is loaded with a combination of 30% wood moisture content (saturation MC for Yellow-poplar) and a mechanical load of 1442 lb (experimental average for 20 samples) reported as 721 psi in Table 2. Under moisture load only, the FRP shows no sign of failure under shear stresses between −550 and 1368 psi. It can be seen in Figure 9 that the stresses concentrate in a narrow band in the wood where failure is likely to initiate. The wood shows stresses of 1251 psi (Figure 9) just penetrating into the bond area, and failure initiates at that point and propagates through the wood, as established in the experimental samples. The application of moisture load alone induces small stresses not able to produce failure, but they cause out-of-plane warping of the sample.

Applying the average experimental failure loads, the FEM predicts maximum stress values close to the failure shear strength of 1800 psi for Yellow-poplar reported by Janowiak (1990). Within most of the bond interface region, the FEM stresses obtained by applying the mechanical load that produced failure in the dry test specimens are similar to the FEM stresses obtained by applying simultaneously the moisture and mechanical load that produced failure in the wet samples. These results indicate that the mechanical and moisture load effects can be treated approximately as linearly cumulative. The stresses computed are closer to the shear strength values in the wood substrate than in the FRP. This result is consistent with the large percentage of wood failure observed in the experimental tests. The analysis performed is not a failure prediction analysis since no failure criterion or failure propagation theory was invoked. However, the FEM stress analysis indicates qualitatively that shear stresses due to swelling mismatch can be predicted with some confidence. Also, the FEM analysis results reinforce the experimental results of the shear-block tests, since the stresses predicted are close to reported values for shear strength of Yellow-popular (Janowiak 1990, Wood Handbook 1987).

A measure of the correlation between experimental and numerical results is provided by the ratio of wet strength to dry strength (Table 5). The experimental

Table 5. Wet/dry strength ratio, experimental and FEM.

	Average bond strength		
	Dry	**Wet**	**Wet/Dry ratio**
Experimental	1350	721	0.53
FEM Average Stress	1338	754	0.58
FEM Maximum Stress	2039	1190	0.56

value is computed as the quotient of the average wet failure load over the average dry failure load (wet strength = 53% dry strength). Two numerical values of the dry/wet ratio are computed from the FEM results. First, the quotient of the average stresses predicted by the Finite Element Model for wet and dry conditions. Second, the quotient of the maximum stresses predicted by the Finite Element Model. The FEM stresses for the wet test are obtained by applying the average experimental mechanical load (1442 lb over the wood layer), but without the moisture load. It can be observed that the wet/dry ratios provided by both measures of FEM results (average and maximum) are quite close to the experimental values. Also, the values of dry and wet average bond strength provided by the FEM are quite close to the experimental values shown in Table 5.

CONCLUSIONS

It is shown that the stresses developed due to swelling mismatch of wood and FRP substrates can be predicted by the Finite Element Model. The ratio of wet to dry shear strength of wood-vinylester composite combination can be predicted with confidence by the FE model. The experimental wet shear strength is 53% of the dry shear strength, while the FE model predicts 58% and 56% for maximum and average stresses, respectively. There is not much deterioration of the adhesive bond due to moisture loading on the shear-block samples. This conclusion is based on the following observation: In the modeling of the wood-FRP swelling mismatch by the FE method, the deterioration of adhesive bond due to moisture is not accounted for. However, the Finite Element Model predicts a ratio of wet to dry strength (0.58 and 0.56 for maximum and average, respectively) in close agreement with the experimental ratio (0.53), and therefore, we can conclude that the deterioration of bond strength due to moisture must be very small, perhaps accounting for the discrepancy of experimental to FEM results. Also, very high stresses in the wood substrate were predicted by the analysis, as observed in the experiments by the significant percent wood failure. The FE model consistently predicted stresses in wood close to customary values for wood failure.

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NOMENCLATURE

MC : moisture content
n : number of roving
t_c : layer thickness
y : yield
$[A]$: laminate stiffness matrix
A_c : cross sectional area of composite
A_f : cross sectional area of fibers
E_L : FRP longitudinal stiffness modulus
E_T : FRP transverse stiffness modulus
E_R : FRP radial stiffness modulus
E_f : Modulus of elasticity of the fiber
E_m : Modulus of elasticity of the matrix
E_1 : Modulus of elasticity in the direction of the fibers (longitudinal)
E_2 : Modulus of elasticty in the direction perpendicular to the fibers (transverse)
G_{LT} : FRP longitudinal-transverse shear stiffness modulus
G_{LR} : FRP longitudinal-radial shear stiffness modulus
G_{TR} : FRP transverse-radial shear stiffness modulus
G_{12} : Shear modulus in the plane of the laminate
$[Q]$: lamina stiffness matrix
$[\bar{Q}]$: rotated lamina stiffness matrix
V_f : Fiber volume fraction
V_m : Matrix volume fraction
W : weight per unit area
ϵ_R : tangential strain
ϵ_R : radial strain
ν_f : Poisson's ratio of the fiber
ν_m : Poisson's ratio of the matrix
ν_{12} : Longitudinal-transverse Poisson ratio
ν_{21} : Transverse-longitudinal Poisson ratio
ϱ : density
ν_{LT} : FRP longitudinal-transverse Poisson ratio
ν_{LR} : FRP longitudinal-radial Poisson ratio
ν_{TR} : FRP transverse-radial Poisson ratio
θ : fiber lamination angle

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