Fiber Reinforced Polymer Composite–Wood Pile Interface Characterization by Push-Out Tests

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Abstract: Structural restoration of spliced or damaged wood piles with fiber reinforced polymer (FRP) composite shells requires that shear forces be transferred between the wood core and the encasing composite shells. When a repaired wood pile is loaded, shear stresses develop between the wood pile and the FRP composite shell through the grouting material. Alternatively, shear force transfer can be developed through mechanical connectors. The objective of this study was to characterize the interfaces in wood piles repaired with FRP composite shells and grout materials. Two interfaces were studied: wood pile/grout material and a grout material/innermost FRP composite shell. A set of design parameters that control the response of both interfaces was identified: (1) extent of reduction of cross section of wood pile due to deterioration (necking); (2) type of grout material (cement-based or polyurethane); (3) use of mechanical connectors; and (4) addition of frictional coating on the innermost shell. Push-out tests by compression loading were performed to characterize the interfaces and discriminate the effect of the design parameters. The outcome of the push-out tests was evaluation of the shear stress and force versus slip response and characterization of the failure mechanism. A set of repair systems that represent different combinations of the design parameters was fabricated and the interfaces evaluated. It was found that the combination of cement-based grout and polymer concrete overlay on the innermost shell provided the most efficient shear force-slip response. A simplified piecewise linear model of shear stress versus slip at the wood/grout and grout/FRP composite interfaces with and without mechanical connectors is proposed to synthesize the experimental response.

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Introduction

Marine wood piles that support waterfront structures are designed to support vertical gravity loads from the pier structure, top-side facilities, and mobile equipment and vehicles. Horizontal loads due to wind pressure, wave action, ice formation and eventual vessel impact are exerted on wood piles and need to be considered in the design process. When extensive damage is imposed on the wood piles by marine organisms or mechanical action (Lopez-Anido et al. 2004b), e.g., drifting ice, floating debris or docking vessels, the capability of the wood piling system to support the vertical and horizontal design loads is compromised.

In structural restoration of wood piles with fiber reinforced polymer (FRP) composite shells, the shear transfer capability between the wood core and the encasing composite shells is required to splice the damaged portion (Lopez-Anido et al. 2004c). When a wood pile repaired with FRP composite shells is subjected to bending moment, shear forces or axial forces, shear stresses develop between the wood pile and the FRP composite shell through the grouting material (Lopez-Anido et al. 2003). Alternatively, shear force transfer between the wood pile and the FRP composite shells can be attained through the use of a number of mechanical connectors. A representative test method is required to assess the shear force and deformation response between wood piles and FRP composite shells.

Push-out tests (British Standards Institution 1979; CEN 1997) are utilized to characterize shear force transfer and slip response in structural connections. For example, a push-out test configuration for shear connectors in steel-concrete composite beams was developed to assess the strength and load/slip characteristics of connectors embedded in concrete (Menzies 1971). The test specimen configuration effectively characterized the connection interface between the concrete slab and the steel girder. Push-out tests were also performed to investigate the feasibility of using a new type of steel shear connector called a perforbond rib in composite beams (Veldanda and Hosain 1992). The influence of the shape of the deck profile on the shear resistance of connectors (studs) used in composite construction was investigated through push-out tests (Lawson 1996). Push-out tests were performed to evaluate the strength and the load/slip characteristics of a new shear stud connector (Arroyo and Francois 1996). A push-out test setup applied to column-beam connections of FRP composite pultruded profiles was developed to evaluate adhesive and bolted joints (Lopez-Anido et al. 1999). A push-out test set up to investigate strength, stiffness, slip capacity and fatigue endurance of shear connections with a full-depth precast slab was presented by Shim et al. (2000). Alternatively, the load transfer mechanism between FRP composite-glulam beams and concrete slabs using lag screws was studied using short-span bending tests (Brody et al. 2000). A

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Fig. 1. Predamaged wood pile specimen

test protocol for push-out tests of FRP composite bridge decks connected to supporting beams was also proposed (Karbhari 2001).

The resistance to delamination of FRP-wood bonded interfaces during accelerated exposure to wetting and drying was evaluated based on a cyclic delamination test (Herzog et al. 2003; Tascioglu et al. 2003a). This test method provides a relative measure of the FRP-wood bond durability subjected to combined exposure to soaking, drying, elevated temperatures and the resulting differential shrinkage/swelling of bonded materials. In addition, the property retention of E-glass FRP composite materials for wood reinforcement exposed to wood preservative treatments (Tascioglu et al. 2002) and fungal biodegradation (Tascioglu et al. 2003b), which are of concern for exterior applications, were studied. Furthermore, the structural response in bending of full-size predamaged wood piles repaired with FRP composite shields was characterized (Lopez-Anido et al. 2003).

The objective of the study described in this paper was to characterize the interfaces in wood piles repaired with FRP composite shells and grout materials. Characterization of two interfaces was required: a wood pile/grout material and a grout material/innermost FRP composite shell. A set of design parameters that

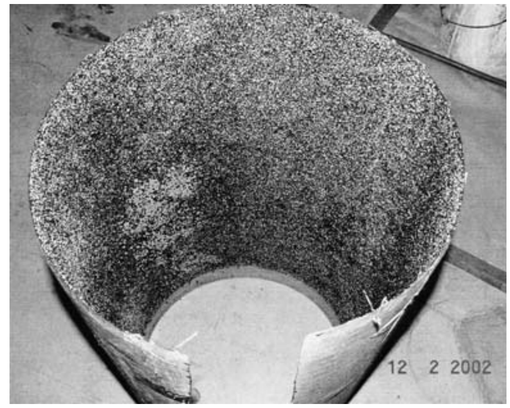

Fig. 2. Polymer concrete coating on interior surface of the fiber reinforced polymer composite shell

control the response of both interfaces was identified: (1) extent of reduction of cross section reduction of the wood pile due to deterioration; (2) type of grout material; (3) use of mechanical connectors; and (4) addition of frictional coating on the innermost shell. To discriminate the effect of the identified design parameters on the two interfaces, push-out tests by compression loading were performed. The expected outcome of the push-out tests was characterization of the load/slip non-linear response and progressive failure mechanism. For this reason, a set of repair systems that represent different combinations of the design parameters was fabricated and the interfaces evaluated through push-out tests.

Performance Criteria and Material Selection

Wood Pile Specimens

Commercial piles were utilized for all testing. Nine meter long, class B, southern yellow pine wood piles treated with chromated copper arsenate (CCA) preservative were selected (ASTM 1999). The piles were cut into segments for testing with a length that ranged between 610 and 864 mm. Due to tapering of the pile the resulting diameters varied between 229 and 356 mm. Intact piles were tested to compare to repaired damaged piles. Damaged piles were obtained by cutting the pile to a reduced cross section. The average moisture content of the repaired wood piles prior to testing was approximately 10–12%.

Predamage to wood piles was achieved by reducing the diameter of the cross section of a segment. The reduction in radius simulated the type of *Limnoria* damage found in a field inspection of the Portland, Maine, harbor (Lopez-Anido et al. 2004b). Approximately 62% reduction of the total cross-sectional area was applied in the laboratory to simulate *Limnoria spp*. necking damage (see Fig. 1). The extent of predamage adopted was based on

Table 1. Design Parameters Evaluated through Push-Out Tests

Repair system	Wood pile	Grout	Mechanical connector	Polymer concrete coating	Number of specimens
A	Intact	Cement	No	No	2
B	Predamaged	Cement	No	No	2
C	Intact	Polyurethane	Yes	No	2
D	Intact	Cement	Yes	No	2
E	Intact	Cement	No	Yes	1

Table 2. Specimen Configuration and Dimensions

Repair system specimen	Wood pile length (mm)	Wood pile diameter, $2r_w$ (mm)	FRP shield length, h (mm)	Number of FRP shells	Grout thickness, t_g (mm)	Number of threaded rods
A1	680	229	521	2	57	0
A2	768	254	610	2	63	0
B1	864	235	737	2	57	0
B2	851	254	737	2	51	0
C1	648	330	546	2	20	3
C2	762	318	648	2	13	3
D1	610	248	499	2	46	3
D2	800	317	648	2	46	3
E1	660	356	635	2	38	0

Note: FRP=fiber reinforced polymer.

the requirement that any wood piles losing 50% of their cross-sectional area or more be replaced (U.S. Army et al. 1978).

Fiber Reinforced Polymer Composite Shells

Cylindrical FRP composite shells or sleeves with a longitudinal opening or gap along their length were fabricated using the licensed Seemann Composites Resin Infusion Molding Process (SCRIMP) (TPI 2001). These specially constructed shells can be applied over existing damaged piles in the field. Two FRP composite shells with thickness of approximately 3.3 mm were used to encase predamaged wood piles.

A unidirectional woven E-glass fabric with weight of 880 g/m^2 was selected as the primary continuous reinforcement for the FRP composite shell. Chopped strand mat (CSM) weighing 305 g/m^2 was used as secondary noncontinuous, randomly oriented reinforcement. The FRP composite shell fiber architecture consisted of three layers of unidirectional continuous fabric reinforcement in the longitudinal or axial direction (0°), one layer of unidirectional continuous fabric reinforcement in the hoop or circumferential direction (90°), and two outer CSM layers. The fiber architecture design was based on maximizing fiber reinforcement in the axial direction with a minimum amount of fibers oriented in the hoop direction. Axial fiber reinforcement contributes to both bending and axial stiffness and strength of the shell, which is required to splice the damaged portion of the wood pile. Hoop fiber reinforcement provides adequate integrity to the flexible shell with the required shear strength and mechanical fastener support. One CSM layer was placed on each face of the shell laminate to provide improved bonding to the substrate and to develop a resin rich area for environmental protection. The resulting laminate layup of the FRP composite shell was [CSM/0/90/0/0/CSM]. A low viscosity epoxy-based vinyl ester resin was selected as the matrix for the composite shells (Dow 1999). The epoxy-based vinyl ester resin was selected because of its high flexibility and resistance to impact, its lower cost compared to other resin systems, such as epoxies, and its good performance in harsh marine environments.

Underwater Curing Epoxy Adhesive

Two fabricated shells were bonded together with an underwater curing epoxy adhesive (Superior Polymer 2000) to form the FRP composite shield or jacket that encases the wood pile specimen. The performance of this underwater curing epoxy after exposure to freezing and thawing cycles was investigated (Lopez-Anido et al. 2004a). The longitudinal gaps of each bonded shell were staggered at an angle of 180° to avoid lines of weakness in the FRP composite shield.

Cement-Based Structural Grout

The space between the wood and the FRP composite shells was filled with a grouting material. A cement-based underwater structural grout (Five Star 2001) with a specified compressive strength at 28 days of 51.7 MPa was selected to provide contact between the FRP composite shield and the wood pile, as well as to completely isolate the damaged wood portion from marine borers. Shear transfer between the wood pile and the cement-based grout relies primarily on mechanical interlocking at the interface. The thickness of the grout typically varied from 40 to 60 mm.

Expanding Polyurethane Nonstructural Grout

An expanding polyurethane nonstructural grout (Sika 1998) was selected to completely isolate the damaged wood portion from

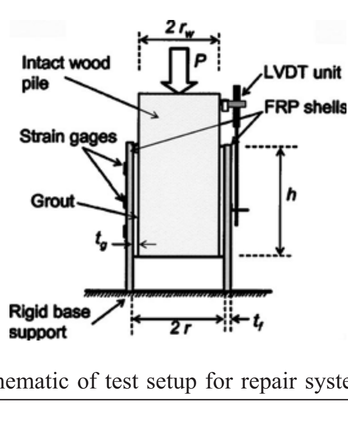

Fig. 3. Schematic of test setup for repair systems A and E

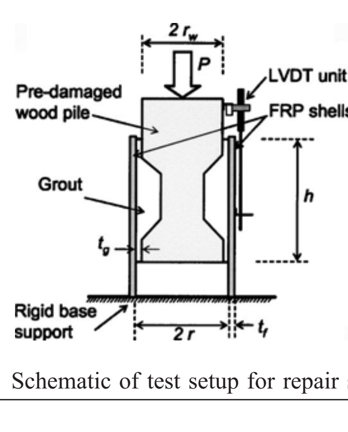

Fig. 4. Schematic of test setup for repair system B

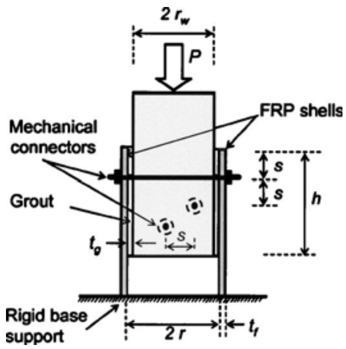

Fig. 5. Schematic of test setup for repair systems C and D

Table 3. Summary of Push-Out Tests by Compression Loading

Repair system specimen	Slip compressive load, P_0 (kN)	Ultimate compressive load, P_P (kN)	Mode of failure
A1	90.9	288.7[a]	Grout—FRP interface
A2	118.1	295.2	Grout–FRP interface (slip) Wood–grout interface (ultimate)
B1	167.8	315.8[a]	Grout–FRP interface
B2	146.9	433.4[a]	Grout–FRP interface
C1	126.0	370.8	FRP crushing by connectors
C2	144.0	364.8	FRP crushing by connectors
D1	182.9	453.4[a]	FRP crushing by connectors
D2	261.9	529.5	FRP crushing by connectors
E1	180.5	402.3[a]	Wood–grout interface

Note: FRP=fiber reinforced polymer.

[a]Reached test setup maximum displacement.

marine borers. The polyurethane chemical grout was a two-part grout mixed according to supplier specifications and pumped using a paint pot and pressurized air. As the mixture reacts with water, it expands and fills the space between the wood pile and the inner FRP composite shell. The thickness of the grout typically varied from 10 to 20 mm.

Mechanical Connectors

Mechanical connectors (steel threaded rods) through the FRP composite shells and the wood pile were selected to transfer shear forces. The threaded rods have a diameter of 19 mm and were spaced along the pile axis and placed in several radial directions.

Polymer Concrete Coating

A polymer concrete coating or overlay was selected to provide interlocking between the cement-based grout and the FRP composite shells (TRANSPO 2000) as shown in Fig. 2. The total thickness (epoxy resin and aggregates) of one layer of the coating was approximately 3 mm.

Repair Systems

Five different repair systems (A, B, C, D and E) that represent relevant combinations of the proposed design parameters were investigated. Two specimens were fabricated and evaluated for each repair system with the exception of repair system E where only one specimen was available (see Table 1). The dimensions and configuration of the specimens fabricated and evaluated are provided in Table 2.

Repair System A

This system consists of an intact (undamaged) wood pile specimen encased by FRP composite shells and the structural cement-based grout. A schematic of application to both repair systems A and E is shown in Fig. 3.

Repair System B

Repair system B consists of a predamaged (approximately 62% reduction in cross-sectional area) wood pile specimen encased by FRP composite shells and the structural cement-based grout (see Fig. 4).

Repair System C

Repair system C consists of an intact (undamaged) wood pile specimen encased by FRP composite shells, the nonstructural polyurethane grout and mechanical connectors. A schematic of application to both repair systems C and D is shown in Fig. 5.

Repair System D

Repair system D consists of an intact (undamaged) wood pile specimen encased by FRP composite shells, a cement-based grout and mechanical connectors (see Fig. 5).

Repair System E

Repair system E consists of an intact (undamaged) wood pile specimen encased by FRP composite shells, the cement-based

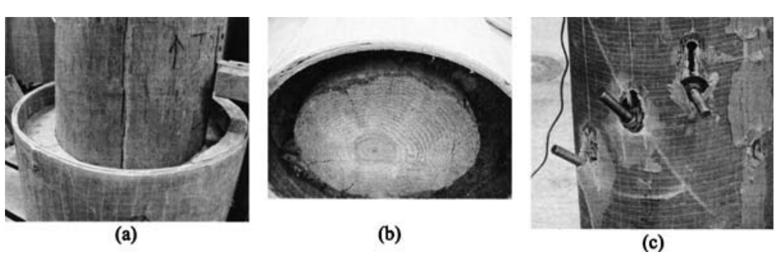

Fig. 6. Typical failure: (a) Interface between the fiber reinforced polymer (FRP) composite shield and cement-based grout; (b) interface between wood pile and cement-based grout; and (c) crushing of FRP composite shield by mechanical connectors

Table 4. Normalized Experimental Results for Repair Systems A, B, D, and E

Repair system specimen	Interface	Interface overlap contact area (m^2)	Slip interface apparent shear strength, τ_0 (kPa)	Ultimate interface apparent shear strength, τ_P (kPa)
A1	Grout/FRP	0.478	190	—
A2	Grout/FRP	0.562	210	—
A2	Wood/grout	0.375	—	780
B1	Grout/FRP	0.723	232	—
B2	Grout/FRP	0.680	216	—
D1	Grout/FRP	0.480	381	—
D2	Grout/FRP	0.631	415	—
E1	Wood/grout	0.425	425	—

Note: FRP=fiber reinforced polymer.

grout and a polymer concrete coating on the interior surface of the innermost shell (see Fig. 3). The polymer concrete coating applied on the interior surface of a shell is shown in Fig. 2.

Specimen Fabrication

Cylindrical FRP composite shells with a longitudinal opening or slit were fabricated in the laboratory using the licensed SCRIMP process (TPI 2001). A detailed description of the shell fabrication process is available elsewhere (Lopez-Anido et al. 2004c). A total of 18 FRP composite shells were fabricated for the push-out tests.

The space between the wood pile and the FRP composite shield was filled with one of the grouting materials selected. Grouting was conducted with the specimens placed upside down using a sealed wood form. After curing, the form was removed. For the cement-based structural grout at least 3 days were allowed for curing before testing to develop the required strength (Five Star 2001).

Push-Out Test Method

Setup and Procedure

The push-out tests were conducted using a 500 kN Instron servo-hydraulic testing system with a T-slotted table base located in an environmentally controlled room, with ambient temperature of 22±1°C and relative humidity of 45±5%. One of the repair systems, which exceeded 500 kN load capacity, was tested on a 1,400 kN Instron actuator mounted on a loading frame with a

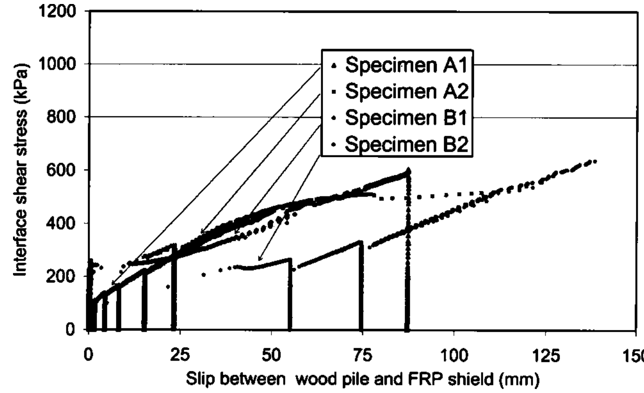

Fig. 7. Shear stress-slip response for repair systems A and B

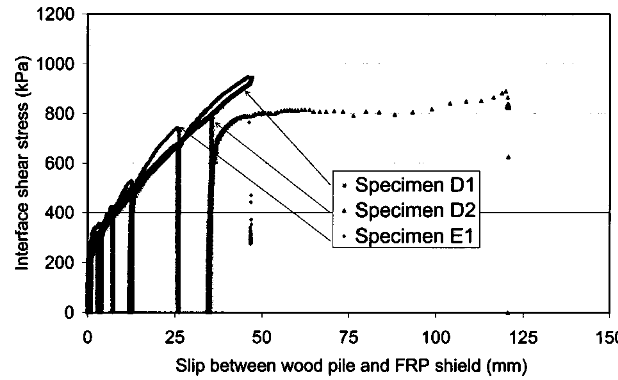

Fig. 8. Shear stress-slip response for repair systems D and E

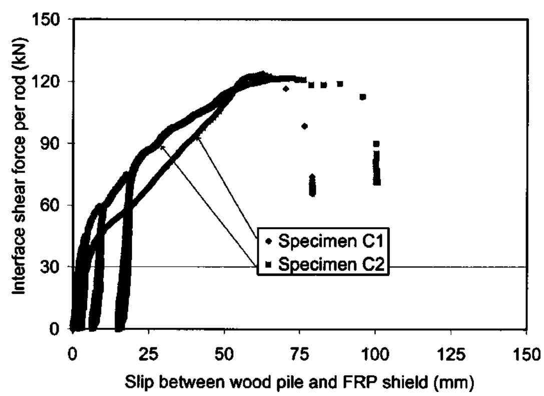

Fig. 9. Shear force-slip response for repair system C

Table 5. Hoop Strain on Outer Fiber Reinforced Polymer Composite Shell

Repair system specimen	Wood pile	Strain gauge number	Strain gauge location: Distance from shell bottom (mm)	Strain gauge location: Hoop angle (deg)	Slip load level: P_0 (kN)	Slip load level: Hoop strain, ϵ_θ ($\mu\epsilon$)	Ultimate load level: P_P (kN)	Ultimate load level: Hoop strain ϵ_θ ($\mu\epsilon$)
A1 (h=521 mm)	Intact	1	445	0	90.9	1179	288.7	1,929
		2	279	0		664		1,798
		3	114	0		372		1,374
		4	279	90		935		2,001
B2 (h=737 mm)	Predamaged	1	673	0	146.9	191	433.4	−103
		2	432	0		74		5
		3	190	0		234		2,750

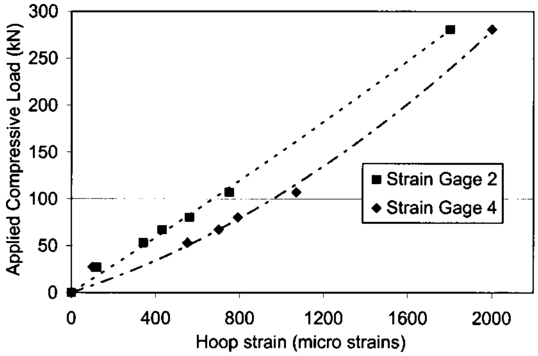

Fig. 10. Hoop strain versus compressive load applied at opposite circumferential locations for specimen A1

structural floor base. The compression load was applied to the wood pile, and it was transferred to the grouting material and the FRP composite shield by friction and interlocking at the interfaces and shear force at the connectors, depending on the repair setup (see Figs. 3, 4 and 5). The FRP composite shield was supported by the base of the testing system.

The tests were conducted in load control mode, i.e., a constant load rate was applied independent of the amount of relative displacement between the wood pile and the FRP composite shield. Load control mode was selected because the repair systems had no relative movement (slip) between the wood pile and the FRP composite shield until the shear strength of the interface between the cement-based grout was exceeded. A loading rate that allowed the test to be completed between 10 and 20 min was selected depending on the specific repair system. The first specimens tested, A1, C1 and D1, were loaded at a rate of 17 kN/min. The rest of the specimens were loaded at a rate of 27 kN/min. Loading was applied in cycles using a dual ramp generator (i.e., loading and unloading of the specimen as a single step) available from the controller of the servo-hydraulic testing system (Instron 1998). Typically, five or six loading cycles were applied for each specimen to evaluate the relative displacement or slip. If the relative displacement between the wood pile and the FRP composite shield recovered after unloading, the system was considered linear elastic.

Instrumentation

Linear variable differential transducer (LVDT) units were used to measure the relative movement (slip) between the wood pile and the FRP composite shield. One LVDT unit was mounted on the

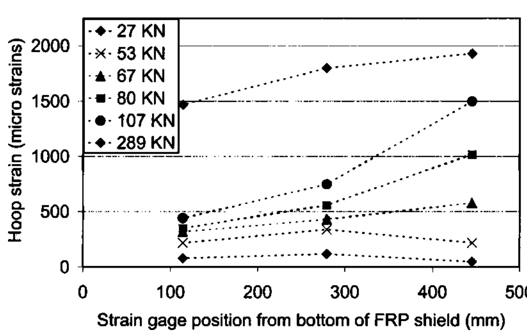

Fig. 11. Hoop strain distribution on outer fiber reinforced polymer (FRP) shell at different load levels for repair system A (specimen A1)

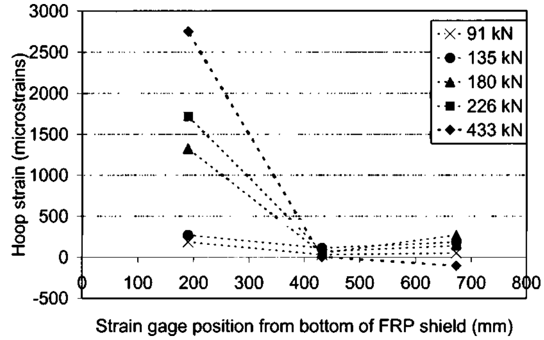

Fig. 12. Hoop strain distribution on outer fiber reinforced polymer (FRP) shell at different load levels for repair system B (specimen B2)

wood pile with a reference point, a bonded aluminum angle, on the FRP composite shield. A schematic of the test setup with the LVDT unit mounted for repair system B is shown in Fig. 4. All test data were collected using the *LabView 6.0* software and data acquisition system (National Instruments 2000).

On some of the specimens, with the cement-based grout, strain gauges (type CEA-06-250UW-350) were surface mounted on the FRP composite shield (Measurements Group 1997). Three strain gauges were bonded on one side at three different locations to determine hoop strain along the length of the FRP composite shield. Another strain gauge was bonded on the opposite side of the shield at the same height as the middle gauge to determine whether bending stresses were present due to any eccentricity of the load.

Results and Discussion

Interface Mode of Failure

In the case of repair systems with cement-based structural grout (A, B, D and E), the wood pile/grout and grout/FRP composite shell interfaces were characterized. The effect of necking damage on the behavior of the system was also evaluated. In the case of the polyurethane grout (repair system C) the shear force transfer through mechanical connectors was characterized. The shear transfer response with the combination of structural cement-based grout and mechanical connectors was also evaluated (repair system D). A summary of experimental results obtained for the nine specimens evaluated is presented in Table 3.

The mode of failure for repair systems A and B was fracture of the structural grout/FRP composite interface, as shown in Fig. 6(a). The addition of a polymer concrete coating in repair system E provided friction and interlocking between the grout and the innermost FRP composite shell and forced failure to occur at the wood/grout interface at a much higher level of load, as shown in Fig. 6(b). The hour-glass shape (necking) of the predamaged wood pile in repair system B prevented the wood/grout interface from breaking since for such failure to occur it would be necessary to shear through the cement-based grout. Repair systems C and D employed mechanical connectors (threaded rods) for transfer of shear forces to the FRP composite shield. Although these repair systems employed different grout materials, the mode of failure was similar: crushing of the FRP composite shield at the threaded rod location, shown in Fig. 6(c). An increase in the peak load of approximately 44% for repair system D compared to repair system C was attributed to the structural support provided by the cement-based grout.

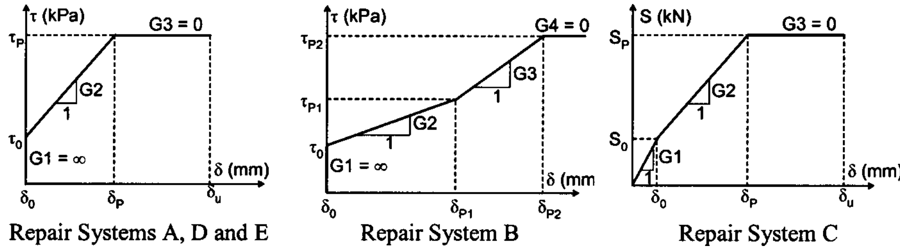

Fig. 13. Simplified model of shear stress (shear force) slip

Slip and Ultimate Shear Strength

To compare the performance of the different repair systems the results were normalized by computing the apparent interface shear strength (see Table 4). The apparent slip-shear strength of the grout/FRP composite interface, τ_0, was calculated by dividing the vertical compressive load, P_0, at the onset of relative displacement (slip) by the interface overlap contact area as follows:

$$\tau_0 = \frac{P_0}{2 \cdot \pi \cdot r \cdot h} \tag{1}$$

where r = inner radius of the FRP composite shield; and h = height of the overlap interface (Fig. 3). The apparent ultimate-shear strength of the grout/FRP composite interface, τ_p, was calculated as

$$\tau_P = \frac{P_P}{2 \cdot \pi \cdot r \cdot h} \tag{2}$$

Similarly the apparent slip- and ultimate-shear strength of the wood/grout interface, τ_0 and τ_p, respectively, were calculated as

$$\tau_0 = \frac{P_0}{2 \cdot \pi \cdot r_w \cdot h} \tag{3}$$

$$\tau_P = \frac{P_P}{2 \cdot \pi \cdot r_w \cdot h} \tag{4}$$

where r_w = radius of the wood pile (see Fig. 3). The normalized load displacement responses of repair systems A, B, D and E are depicted in Figs. 7 and 8.

For repair system C, the slip and ultimate interface shear force per mechanical connector (threaded rod), S_0 and S_P, respectively, were computed as

$$S_0 = \frac{P_0}{n} \tag{5}$$

$$S_P = \frac{P_P}{n} \tag{6}$$

where n = number of mechanical connector rods. Shear force per rod versus displacement response for repair system C ($n=3$) is shown in Fig. 9. Each 19-mm diam threaded rod was able to transfer approximately $S_P = 122$ kN of force prior to crushing the FRP composite shield. The length required for FRP composite shells can be calculated by multiplying the number of rods, *n*, by the rod spacing, *s*, as shown in Fig. 5. The end distance adopted was equal to the rod spacing ($s = 102$ mm) (see Fig. 5).

Hoop Strain Distribution

The hoop strain profile along the height of the FRP composite shield for repair systems A and B was evaluated by bonding strain gauges at different locations (see Fig. 3 and Table 5). Since the wood pile specimens were tapered and had the larger diameter on the top, vertical movement at the wood/grout interface produced radial pressure on the grouting material due to wedge action, which resulted in hoop strain in the FRP composite shield. The relative importance of the Poisson effect on the FRP composite shield hoop strain depends on the level of axial compressive stress on the wood pile in the overlap region. Compressive stresses applied on the top surface of the pile vary through the pile length and attain a value of 0 at the bottom surface to satisfy equilibrium. By correlating measurements from hoop strain gauges placed midheight of the shell, at opposite circumferential locations, a difference in strain attributed to unavoidable load eccentricity was observed for specimen A1 (see Fig. 10). The strain profiles for repair systems A (specimen A1) and B (specimen B2) are depicted in Figs. 11 and 12 for various loading levels, respectively.

In the case of specimen A1 (intact wood pile), an almost uniform strain distribution was observed for the initial loading levels (see Fig. 11). When slip developed at the interface between the grout and the innermost FRP composite shell, hoop strain increased markedly with the height (i.e., the upper portion of the shell was subjected to greater hoop strain).

In the case of specimen B2 (predamaged wood pile), an almost uniform strain distribution was also observed for the initial loading levels (see Fig. 12). However, when slip developed at the interface between the grout and the innermost FRP composite shell, hoop strain increased markedly in the lower strain gauge. It is hypothesized that the observed hoop strain peak at the lower portion of the shell was caused by interlocking between the wood pile with necking and the grout, which differentiates the

Table 6. Simplified Model Parameters for Repair Systems

System	Interface	δ_0 (mm)	τ_0 (kPa)	S_0 (kN)	$G1$ (kPa/mm)	δ_P (mm)	τ_P (kPa)	S_P (kN)	$G2$ (kPa/mm)	δ_u (mm)	$G3$ (kPa/mm)
A	Grout/FRP	0	190	—	∞	61	500	—	5.4	112	0
B	Grout/FRP	0	210	—	∞	57	440	—	1.9	NA	7.0
C	Grout/FRP	6	—	45	23	58	—	122	4.7	90	0
D	Grout/FRP	0	370	—	∞	37	810	—	14.7	120	0
E	Wood/grout	0	390	—	∞	47	1,000	—	16	NA	NA

Note: FRP = fiber reinforced polymer; and NA = not applicable.

specimen B2 response with respect to that of specimen A1 response. The maximum hoop strain recorded, 2,750 microstrain for specimen B2, did not produce failure of the FRP composite material.

Simplified Model

A simplified piecewise linear model is proposed to represent the apparent interface shear stress versus slip response, shown in Figs. 13(a and b). Similarly, the interface shear force per rod versus slip response is represented by the piecewise linear model in Fig. 13(c). The interface parameters that define the shear stress-slip and shear force-slip stepwise linear curves for the simplified models of each repair system are summarized in Table 6.

The piecewise linear model for shear stress slip and shear force slip can be conveniently used as a preliminary guide using graphs in combination with Table 6 as follows: (1) for repair systems A, D and E (intact wood pile) apply the first graph in Fig. 13; (2) for repair system B (predamaged wood pile) apply the second graph in Fig. 13; and (3) for repair system C (intact wood pile with mechanical connector rods) apply the third graph in Fig. 13.

Preliminary application of the model is illustrated for repair system E by computing the height of the overlap interface, h, which corresponds to the FRP composite shell length. The following design data are considered: $r_w = 140$ mm and $t_g = 50$ mm. The required vertical load that needs to be transferred through the repair is $P = 160$ kN, with a safety factor $(\mathrm{SF}) = 2$ to prevent slip.

From Table 6, the repair system E shear strength that corresponds to slip at the wood/grout interface is $\tau_0 = 390$ kPa. Substituting $P_0 = \mathrm{SF} \times P$ in Eq. (3) and solving for h results in

$$h = \frac{\mathrm{SF} \cdot P}{2 \cdot \pi \cdot r_w \cdot \tau_0} \tag{7}$$

The required shell length is $h = 933$ mm. Based upon the preliminary test data, this design will result in a safety factor for interface ultimate shear strength of

$$\frac{\mathrm{SF} \cdot \tau_P}{\tau_0} = \frac{(2) \times 1{,}000 \ \mathrm{kPa}}{390 \ \mathrm{kPa}} = 5.2$$

The reader should be cautioned that a statistically significant number of specimens that represent typical field conditions (e.g., actual marine borer damage, *in situ* installation and marine environment) should be tested to generate parameters that can be used for design.

Conclusions and Recommendations

Based on the results presented in this paper the following conclusions are drawn:

1. The proposed push-out test method can characterize the shear versus slip response of the wood/grout and grout/FRP composite interfaces;
2. A simplified piecewise linear model is useful to synthesize the shear stress and force versus slip response from push-out tests;
3. Damage in the wood pile in the form of necking, which simulates *Limnoria* attack, provided interlocking with the grout thereby increasing the interface slip shear strength; and
4. Application of a polymer concrete coating layer on the interior surface of the innermost shell prevented slip at the grout/FRP composite interface and modified the model of failure.

The following commentary and proposed practical recommendations are suggested.

1. The findings presented were based on a limited number of experiments under ideal laboratory conditions and, therefore, the applicability of the pile repair method needs to be validated through monitoring waterfront installations subject to actual marine borer damage, variations in moisture content and marine environmental conditions.
2. Use of the polymer concrete coating on the interior surface of the inner shell is recommended to improve friction at the grout–FRP composite shield interface.
3. Use of shear studs or other shear connectors, such as lag screws, embedded in the wood pile that extend through the thickness of the cement-based grout, but not through the FRP composite shield, is recommended. These connectors can increase the wood/grout interface slip strength and also serve as spacers.
4. In field repair of wood piles, it is recommended that the wood surface be cleaned with pressurized water or a scraper to eliminate the presence of marine organisms and loose materials that may affect shear transfer at the wood pile/grout interface.

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Notation

The following symbols are used in this paper:

h = height of overlap interface (FRP composite shell length);
n = number of mechanical connector rods;
P = compressive load applied;
P_P = ultimate vertical compressive load;
P_0 = slip vertical compressive load;
r = inner radius of FRP composite shield;
r_w = radius of wood pile;
S_P = ultimate interface shear force per rod;
S_0 = slip interface shear force per rod;
s = spacing of mechanical connector rods;
t_f = thickness of FRP composite shield;
t_g = thickness of grout;
τ_P = ultimate interface apparent shear strength; and
τ_0 = slip interface apparent shear strength.

Subscripts

f = FRP composite shield;
g = grout; and
w = wood pile.

References

Arroyo, M. R., and Francois, J. J. (1996). "New shear stud connector proposal." 1996, Composite construction in steel and concrete III, *Proc., Engineering Foundation Conf.*, ASCE, Reston, Va., 298–311.

American Society for Testing and Materials (ASTM). (1999). "D25-91 standard specification for round timber piles." West Conshohocken, Pa.
British Standards Institution. (1979). "Steel, concrete and composite bridges: Design of composite bridges." *BS 5400, Part 5*.
Brody, J., Richard, A., Sebesta, K., Wallace, K., Hong, Y., Lopez-Anido, R., Davids, W., and Landis, E. (2000). "FRP–wood–concrete composite bridge girders." *Structures Congress 2000, Advanced Technology in Structural Engineering*, ASCE, Reston, Va.
Dow. (1999). "Derakane epoxy vinyl ester resins/chemical resistance and engineering guide." Dow Chemical, Midland, Mich.
European Committee for Standardization (CEN). (1997). "Eurocode 4: Design of composite steel and concrete structures. Part 2. Composite bridges." Brussels, Belgium.
Five Star. (2001). "Structural concrete underwater PG (pump grade underwater repair)." Five Star Products, Inc., Fairfield, Conn.
Herzog, B., Goodell, B., Lopez-Anido, R., Muszynski, L., Gardner, D., Halteman, W., and Qian, Y. (2003). "The effect of creosote and copper naphthanate preservative systems on the adhesive bondlines of FRP/glulam composite beams." *Forest Prod. J.*, in press.
Instron. (1998). "Instron fast track 8802 materials test control system." *M21-10006-EN*, Instron, Canton, Mass.
Karbhari, V. (2001). "HITEC evaluation plan for FRP composite bridge decks." Civil Engineering Research Foundation, Washington, D.C.
Lawson, M. R. (1996). "Shear connection in composite beams—Influence of steel deck shape." 1996, Composite construction in steel and concrete III, *Proc. Engineering Foundation Conf.*, ASCE, Reston, Va., 312–324.
Lopez-Anido, R., Michael, A. P., and Sandford, T. C. (2003). "Experimental characterization of FRP composite-wood pile structural response by bending tests." *Mar. Struct.,* 16(4), 257–274.
Lopez-Anido, R., Michael, A. P., and Sandford, T. C. (2004a). "Freeze–thaw resistance of FRP composite adhesive bonds with underwater curing epoxy." *J. Mater. Civ. Eng.,* 16(3), 283–286.
Lopez-Anido, R., Falker, E., Mittelstadt, B., and Troutman, D. (1999). "Shear tests of FRP pultruded beam-to-column connection with clip angles." *Materials and Construction: Exploring the Connection*, ASCE, Reston, Va., 92–99.
Lopez-Anido, R., Michael, A. P., Goodell, B., and Sandford, T. C. (2004b). "Assessment of wood pile deterioration due to marine organisms." *J. Waterw., Port, Coastal, Ocean Eng.,* 130(2), 70–76.
Lopez-Anido, R., Michael, A. P., Sandford, T. C., and Goodell, B. (2004c). "Repair of wood piles with prefabricated FRP composite shells." *J. Perform. Constr. Facil.,* in press.
Measurements Group. (1997). "Strain gauge applications with M-Bond AE-10 adhesive system." Measurements Group, Inc., Raleigh, N.C.
Menzies, J. B. (1971). "CP 117 and shear connectors in steel–concrete composite beams made with normal density or lightweight concrete." *Struct. Eng.,* 49, 137–154.
National Instruments. (2000). *LabView*, National Instruments Corp., Austin, Tex.
Shim, C. S., Kim, J. H., Chang, S. P., and Chung, C. H. (2000). "The behaviour of shear connections in a composite beam with a full-depth precast slab." *Struct. Build.,* SB140(1), 101–110.
Sika, (1998). "SikaFix HH expanding, polyurethane, chemical grout." Sika Corp., Lyndhurst, N.J.
Superior Polymer. (2000). "Technical data sheet: Hydrobond 500 underwater epoxy adhesive." Superior Polymer Products, Calumet, Mich.
Tascioglu, C., Goodell, B., and Lopez-Anido, R. (2002). "Effects of wood preservative treatments on mechanical properties of E-glass/phenolic pultruded reinforcement for wood." *Forest. Prod. J.,* 52(11/12), 53–61.
Tascioglu, C., Goodell, B., and Lopez-Anido, R. (2003a). "Bond durability characterization of preservative treated wood and E-glass/phenolic composite interfaces." *Compos. Sci. Technol.,* 63(7), 979–991.
Tascioglu, C., Goodell, B., Lopez-Anido, R., Peterson, M., Halteman, W., and Jellison, J. (2003b). "Monitoring fungal degradation of E-glass/phenolic fiber reinforced polymer (FRP) composites used in wood reinforcement." *Int. Biodeterioration Biodegradation,* 51(3), 157–165.
TPI. (2001). "An overview of the SCRIMP™ technology." TPI Technology, Inc., Warren, R.I.
TRANSPO. (2000). "Multiple coat epoxy overlay T-48." Technical data sheet, New Rochelle, N.Y.
U.S. Army, U.S. Navy, and U.S. Air Force. (1978). "Chap. 2: Timber structures." Maintenance of Waterfront Facilities, Hyattsville, Md., 2.1–2.14.
Veldanda, M. R., and Hosain, M. U. (1992). "Behaviour of perfobond rib shear connectors: Push-out tests." *Can. J. Civ. Eng.,* 19, 1–10.