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Experimental characterization of FRP composite-wood pile structural response by bending tests

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Abstract

A special prefabricated fiber reinforced polymer (FRP) composite shield or jacket was developed to repair wood piles in the field. Two types of load-transfer mechanisms between the wood pile and the FRP composite shield were developed and tested: (1) cement-based structural grout; and (2) steel shear connectors with an expanding polyurethane chemical grout. The objective of this paper is to characterize the structural response of full-size pre-damaged wood piles repaired with the FRP composite shield system. A three-point bending test procedure was used to simulate the response of a pile subjected to lateral loads. The load-deformation response, deflected shape profile, relative longitudinal displacements (slip), strain distribution, ultimate bending moment capacity and mode of failure were evaluated. Wood piles were pre-damaged by reducing approximately 60% of the cross-section over a portion of the pile. It was found that a pre-damaged wood pile repaired using the FRP composite shield with cement-based grout exceeded the bending capacity of a reference wood pile. The repair system using the FRP composite shield with steel shear connectors and polyurethane grout did not fully restore the bending capacity of a reference wood pile; however it can be used for marine borer protection when wood damage is not critical.

Keywords: Wood pile; Timber pile; Repair; Composite; FRP; Fiber-reinforced; Bending test; Marine borer; Damaged pile; Structural restoration

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Nomenclature

a	distance from support to FRP composite shield
d_w	wood pile design diameter at the mid-span section
E_w	modulus of elasticity of the wood pile
I_w	moment of inertia of the wood pile
L	total pile length
L_r	pre-damaged length
L_f	FRP composite shield length
L_s	simply supported span length
P	lateral load applied on the wood pile
p	normalized (dimensionless) applied load
δ	normalized (dimensionless) deflection
$\ddot{A}$	maximum deflection of a simply supported beam

Subscripts

w	wood

1. Introduction

1.1. Background

Wood piles have been traditionally used in many marine locations for piers and one to two story waterfront buildings, especially when loose granular materials are present. Locally available wood piles provide a low-cost foundation system. Untreated wood piles are subjected to deterioration from marine borers, crustaceans, fungi and other sources [1]. For this reason many wood piles have been treated in the past with preservatives, like creosote or chromated copper arsenate (CCA). With time, preservatives will be leached from the wood, and thus deterioration will begin in treated wood piles similar to that of untreated wood piles.

When wood piles deteriorate, the conventional repair is to dismantle the pier, extract the deteriorated piles, drive new piles and rebuild the pier over the new piles. In addition, treated extracted piles may need special disposal. For some facilities, especially when buildings sit on piers, extraction of all piles and driving of new piles can be difficult and costly. In these cases repair becomes a viable alternative. Repairs are possible since the portion of the pile below the mudline is normally fully intact. The major deterioration occurs in the portion of the pile in the inter-tidal zone and in the splash zone (above high-tide). The repair system can also reduce the rate of future deterioration by introducing a barrier that protects the wood pile from marine borer attacks.

1.2. Structural integrity

Structural wood piles are designed to withstand driving forces, axial gravity loads from the pier structure (sometimes tensile loads) and lateral loads imposed by wind pressure, wave action, ice formation or vessel docking impact. Lateral loads impose bending moments and shear forces on the pile.

When a wood pile has deteriorated, it typically loses cross-section and thus loses capacity to sustain design loads. In this paper only the capacity for lateral loading of a repaired pile will be covered. The lateral capacity has the most unknowns in repair. Driving stresses are not a repair concern. The capacity for compressive vertical loading is related to the cross-sectional area, and tensile vertical loading is less common.

The test method for piles subjected to lateral loads requires the driving of the wood pile into the ground followed by application of a lateral or a combination lateral and axial load as per ASTM D3966 [2]. However, in the repair case, a pile will not be re-driven and all the work is conducted above the ground surface, thus the structural integrity of the repaired pile is most important.

Thus it is possible to evaluate a repaired wood pile by conducting a bending test with controlled loading and support conditions. In [3] a repair system for wood poles was evaluated by conducting bending tests in accordance to ASTM D1036 [4]. Decay damage was simulated by mechanically modifying the wood pole section at the ground line.

1.3. Objective

The objective of this paper is to characterize the structural response in bending of full-size pre-damaged wood piles repaired with a specially developed fiber reinforced polymer (FRP) composite shield. The FRP composite shield was designed to fit around installed wood piles in the field. Two types of repair system were designed, installed and tested: (1) An FRP composite shield with cement-based grout between the shield and the wood pile; and (2) An FRP composite shield with shear connectors through the pile and shield and with polyurethane grout between the wood and the shield.

Installed wood piles behave as cantilever columns, where the point of fixity is assumed to be located at a given depth below the mud line. A simply supported beam with a concentrated load at mid span develops a bending moment and shear force diagram equivalent to a cantilever beam with one-half the span length and one-half the applied tip load. Therefore, a three-point bending test procedure was adopted to test the response of a pile subjected to lateral loads. The proposed test set-up was designed using ASTM D1036 [4], a standard test procedure for poles, as a guide. The load-deformation response, deflected shape profile, relative longitudinal displacements (slip), strain distribution, ultimate bending moment capacity and the mode of failure were evaluated.

2. Materials and methods for pile repair

2.1. Pile prototype specimens

Commercial piles were utilized for all testing. Nine meter long, class B, southern yellow pine wood piles treated with CCA preservative were selected [5]. Intact piles were tested to compare to repaired damaged piles. Damaged piles were obtained by cutting the pile to a reduced cross-section near the center of the pile. The average moisture content of the repaired wood piles prior to testing was approximately 10–12%.

Pre-damage to three wood piles was achieved by reducing the diameter of the cross-section over a segment of length $L_d = 900\,\mathrm{mm}$ from the center span toward the pile tip. In this way, it was possible to load the pile at mid-span next to the pre-damaged segment. The reduction in radius simulated the type of *Limnoria* damage found in a field inspection of the Portland, Maine harbor [1]. Approximately 62% reduction of the total cross-sectional area was applied in the laboratory to simulate *Limnoria spp*. necking damage. The extent of pre-damage was selected based on the requirement that any wood piles losing 50% of their cross-sectional area or more be replaced [6].

Two wood piles were used as reference and control specimens. The reference wood pile (IW) was tested undamaged or intact. The control wood pile (DW) was pre-damaged prior to the bending test. The specimen selection served to: (1) quantify the bending stiffness and strength increase resulting from the proposed repair systems by comparing with the reference pile, IW; and (2) establish if the capacity of a damaged wood pile, DW, can be restored with the proposed repair systems.

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^{TM}) [7]. These especially constructed shells can be applied over existing damaged piles in the field. Two FRP composite shells with a thickness of approximately 3.3 mm were used in encasing each of two pre-damaged wood piles.

A unidirectional woven E-glass fabric with a 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 non-continuous and 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 is 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 damage 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 lay-up of the FRP composite shell is [CSM/0/90/0/0/CSM]. A low viscosity epoxy-based vinyl ester resin, Derakane 411-C50, was selected as the matrix for the composite shells [8]. The epoxy-based vinyl ester resin was selected because of its high flexibility and impact resistance, its lower cost compared to other resin systems, such as epoxies, and its good performance in harsh marine environments.

The two fabricated shells were bonded together with an adhesive to form the FRP composite shield or jacket that encased the wood pile section. An underwater curing epoxy adhesive, trade name Hydrobond 500 [9], was selected based on the performance requirements for a wood pile repair system, [10]. Durability of this underwater epoxy adhesive to freeze-thaw cycles was tested [11]. The longitudinal gaps of each shell were staggered at an angle of 180° to avoid lines of weakness in the FRP composite shield. The space between the wood and the FRP composite shells was filled with one of the grouting systems.

The first repair system, B, used a cement-based underwater structural grout [12] with a specified compressive strength at 28 days of 51.7 MPa to provide contact between the FRP composite shield and the wood pile, as well as to complete the isolation of the damaged wood portion from marine borers. This repair system relies primarily on mechanical interlocking at the interface between the wood pile and the cement-based grout to transfer shear stresses.

The second repair system, C, used shear connectors (steel threaded rods) through the shield and the pile to transfer shear forces and used an expanding polyurethane non-structural grout [13] to complete the isolation of the damaged wood portion from marine borers.

The cement-based grout used in repair system B was placed from the bottom up to avoid segregation of the materials and air entrapment. The thickness of the grout was approximately 60 mm. In the grouting operation for the polyurethane chemical grout used for repair system C, the two part grout was mixed according to the supplier specifications and pumped from the bottom of the repaired section using a paint pot and pressurized air. As the mixture reacted with water, it expanded to fill the space between the wood pile and the inner FRP composite shell with a final thickness of approximately 13 mm. Four steel threaded rods with a diameter of 19 mm were used at each end of the FRP composite shield as shear connectors in repair system C. The steel threaded rods were spaced along the pile axis approximately 102 mm and rotated approximately 30° in the circumferential direction.

A summary of the four pile specimens tested is summarized in Table 1. The wood piles, graded according to ASTM D25 [5], had variable diameters and taper as shown in Table 2.

2.2. Three-point bending test method

To test the structural response of the repaired wood piles, three point bending tests were performed using ASTM D1036 [4] for wood poles as a guide. The simply supported test method was selected to simplify the experimental setup. The wood piles were supported at the butt and the tip, and the load was applied at the center.

The span length between the two end supports was $L_s = 8.84$ m, while the total length of the piles was $L = 9.14$ m. Each steel end support had a roller mounted on a hinge that was resting on a concrete block (See Figs. 1 and 2), which provided enough space under the pile to accommodate deflection. Since the wood piles are circular in cross-section, wooden saddles and straps were placed on top of the end

Table 1
Wood pile systems configuration

System	Wood pile	FRP Composite shield	Grout	Shear connectors	Pile length, L (m)	Span length, L_s (m)
Intact reference (IW)	Intact	N.A.	N.A.	No	9.14	8.84
Damaged control (DW)	Pre-damaged	N.A.	N.A.	No	9.14	8.84
Repair system B	Pre-damaged	Yes	Cement-based	No	9.14	8.84
Repair system C	Pre-damaged	Yes	Poly urethane	Yes	9.14	8.84

Table 2
Wood pile systems pre-damage and bending test results

System	Diameter at butt (mm)	Diameter at tip (mm)	Diameter at load point (mm)	Diameter damaged section (mm)	Cross-section reduction (%)	Peak load (kN)	Max. deflection at mid-span (mm)
Intact Reference (IW)	363	305	340	N/A	0	79.0	204
Damaged Control (DW)	356	305	308	186	63	8.1	179
Repair system B	362	240	284	182	62	115.5	197
Repair system C	365	267	315	197	61	52.0	158

supports to avoid lateral movements (See Fig. 3). Another saddle with a length of 305 mm was used at mid-span for load transfer from the actuator to the pile without slippage. The load was applied with an Instron servo-hydraulic actuator mounted underneath the structural floor using a steel frame placed on top of the wooden saddle, which resulted in a stable loading configuration.

Testing was conducted in a displacement control mode with a constant deflection rate. The peak or maximum load was anticipated based on a beam structural model [1]. Loading was applied in cycles with increasing amplitude to assess residual deformation. A dual ramp generator available from the Instron control software was used to apply a constant deflection rate. Load cycles that represented 10%, 20% and 40% of the expected failure load were applied to each specimen. Finally, the pile specimen was loaded to failure, which is defined by the peak load. After the failure

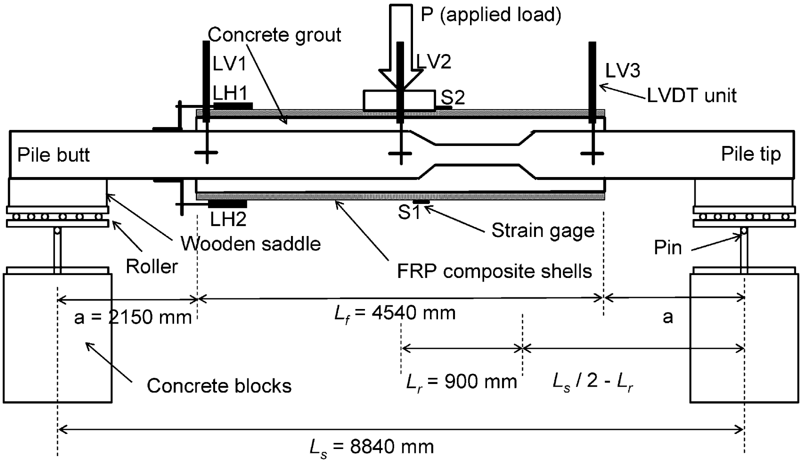

Fig. 1. Schematic of test set-up for repair system B.

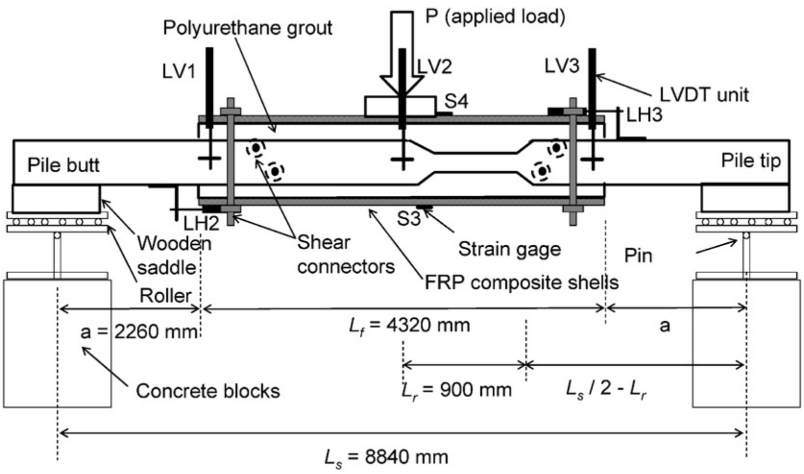

Fig. 2. Schematic of test set-up for repair system C.

load was reached, the repaired specimens, B and C, were reloaded to evaluate the behavior of the system after it was load damaged.

Vertical deflections were measured at three different locations along the length of the pile using linear variable differential transducer (LVDT) units to obtain the deflected shape. Deflections were measured at mid-span, and at the two ends of the FRP composite shield. Horizontal movement (slip) between the wood pile and the FRP composite shield was measured on the top and bottom at the ends of the encasing shield using LVDT units. Strain gages (CEA-06-250UW-350) were bonded [14] on the top and bottom of the FRP composite shield, in the longitudinal

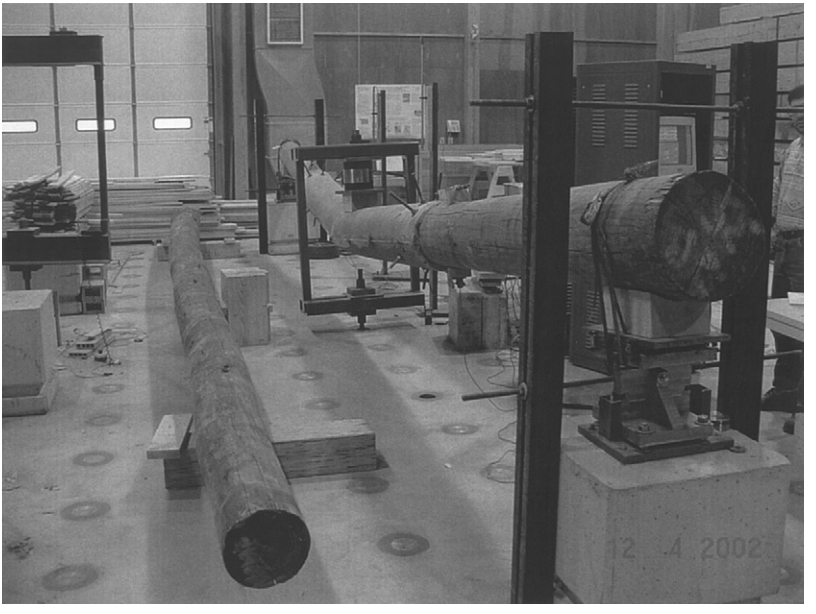

Fig. 3. Test set-up for repair system C.

direction, to monitor strains during the test (See Figs. 1 and 2). Lab View 6.0 [15] was used to collect deflections, load and strain data.

3. Results and discussion

3.1. Intact reference pile (IW)

The reference wood pile, IW, was tested intact to provide the baseline response. The load-deflection response of the reference pile was linear to failure, as shown in Fig. 4. The peak load reached by the reference pile was 79 kN. The wood pile under bending failed in tension at the mid span location where the load was applied. After failure, re-loading was not possible for the reference pile.

3.2. Pre-damaged control pile (DW)

The control pile, DW, was pre-damaged with its cross-sectional area reduced by 63%. This pile was tested to characterize the behavior of a damaged wood pile. The load-deflection response of the control pile is shown in Fig. 4. The peak load corresponding to the control pile was 8.1 kN. The 63% reduction in cross-sectional area diminished the wood pile bending capacity to one-sixth of the intact reference pile (IW) value. Under bending, the damaged control pile failed in tension at the damaged section. After failure, re-loading was not possible for the control pile.

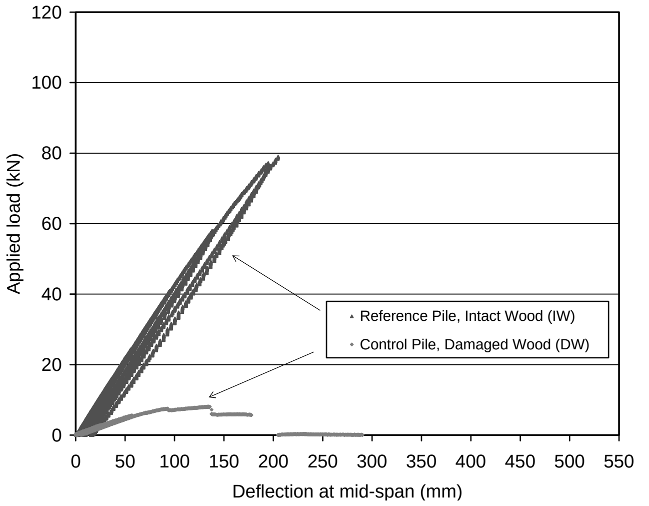

Fig. 4. Load-deflection response for intact reference pile (IW) and damaged control pile (DW).

3.3. Repair system B (FRP composite shield/cement grout)

A pre-damaged pile with its cross-sectional area reduced by 62% over a portion of the pile was repaired using system B (FRP Composite Shield/Cement Grout). The response of the repair system B was linear to failure (See Fig. 5). Under bending, the wood pile failed at a peak load of 115 kN (see Table 2) in tension at the end of the FRP composite shield, as shown in Fig. 6(a). After unloading, approximately 15% of the total deflection was not recovered, which was attributed to damage accumulation. The specimen was reloaded after failure (See second loading curve depicted in Fig. 5). The re-loading curve was also linear with approximately the same load-deflection slope as the peak loading curve. Failure occurred in the wood pile outside the segment encased with the FRP composite shield. It was hypothesized that the FRP composite shield restored enough bending capacity to the wood pile pre-damaged section to prevent failure at this location.

Two LVDT units (LH1 and LH2) that measured the horizontal differential movement (slip) between the wood pile and the FRP composite shield were located close to the end of the shield, as shown in Fig. 1. Load-slip curves are presented in Fig. 7. Positive slip, which was measured on the bottom side of the pile, indicates that the wood surface moved out of the shield, and thus the shield was subjected to tension stresses. The negative slip at the top indicates that the shield was subjected to compressive stresses. The maximum slip value recorded was approximately 5 mm for both LVDTs. The load-slip curve indicates that there is partial interaction between the wood pile and the FRP composite shield. Since top and bottom slip values are similar, this indicates that the FRP composite shield bent about the same neutral axis as the wood pile. Having the two components, shield and wood pile, bending about

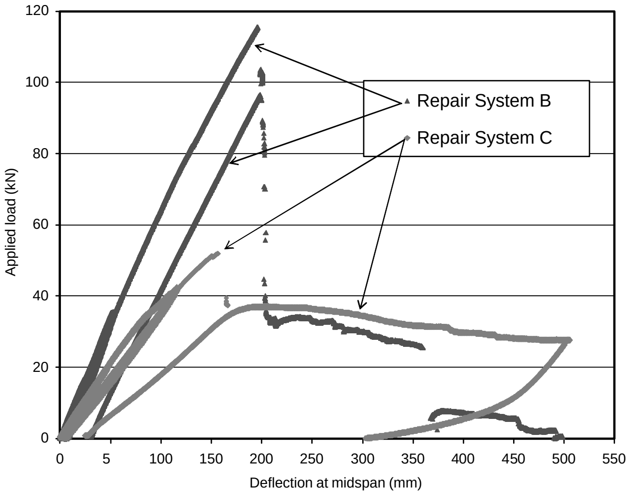

Fig. 5. Load-deflection response for repair systems B and C.

one single neutral axis validates the design basis that the repaired pile under lateral loads behaves as a beam system.

During re-loading, a shear crack initiated at the edge of the FRP composite shield and started propagating in the FRP composite shield towards mid-span. The crack was located at the position where the slit of the inner shell was placed. The load capacity of the repaired system was drastically reduced when the crack initiated. After the crack reached mid-span, the wood pile section at the pre-damaged location failed. This was attributed to the observation that the pre-damaged wood pile section had no load bearing contribution from the cracked FRP composite shield. This secondary failure of the wood pile diminished the ability of the system to further support any significant lateral loads.

3.4. Repair system C (FRP composite shield/shear connectors/polyurethane grout)

A pre-damaged pile with its cross-sectional area reduced by 61% over a portion of the pile was repaired using system C (FRP composite shield/shear connectors/ polyurethane grout). The load-deflection response of system C was linear up to failure, as shown in Fig. 5. The peak load for the pile specimen was 52 kN. At the peak load, the FRP composite shield failed in compression in the axial direction at mid-span (end of wood saddle), as depicted in Fig. 6(b). This damage was attributed to the observation that the compressible polyurethane grout did not provide load bearing support between the wood pile and the FRP composite shield. Approximately 16% of the total deflection was non-recoverable (inelastic).

The pile specimen was re-loaded after reaching the peak load. The pile was able to support approximately 70% load of the peak load during reloading with a lower load-deflection slope. As more damage was introduced to the FRP composite shield, the load capacity of the system was reduced (see Fig. 5). The flexibility of the system

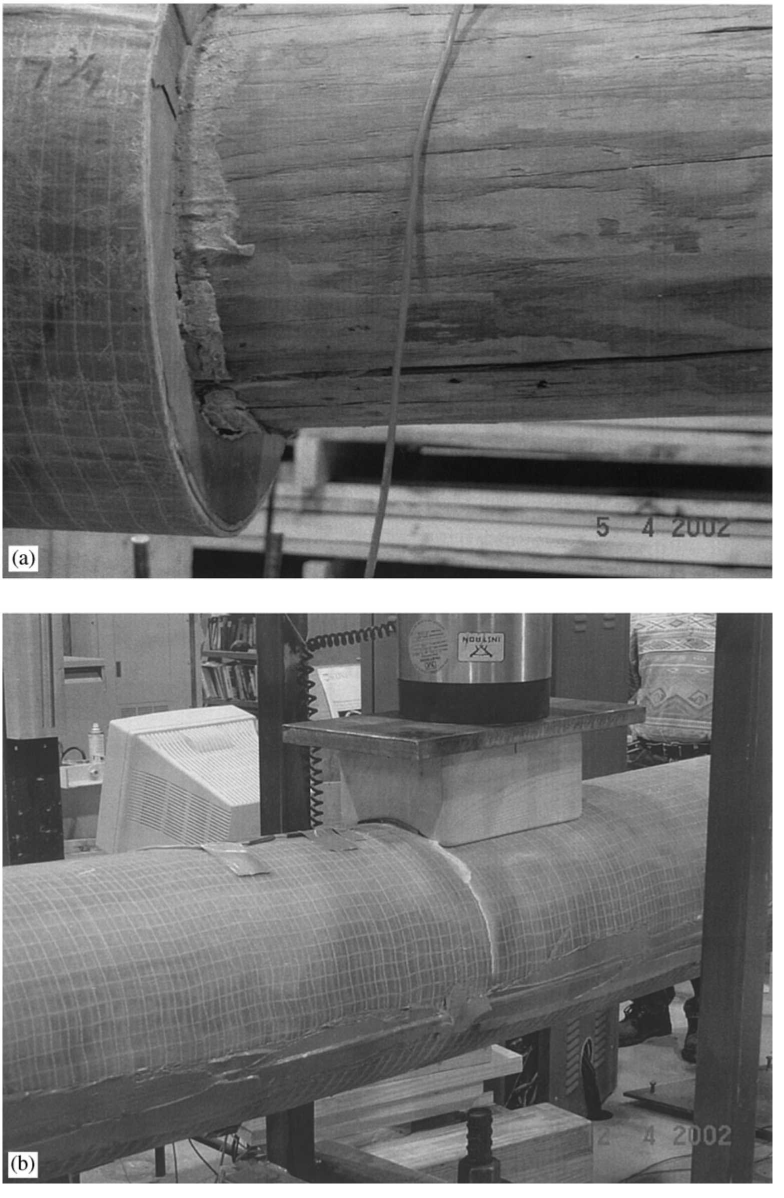

Fig. 6. Failure modes: (a) Tension failure in wood pile at shield end (repair system B); (b) Compression failure in FRP composite shield (repair system C).

using shear connectors was illustrated by the fact that the pile was loaded until reaching the maximum stroke of the servo-hydraulic actuator (500 mm) without catastrophic failure.

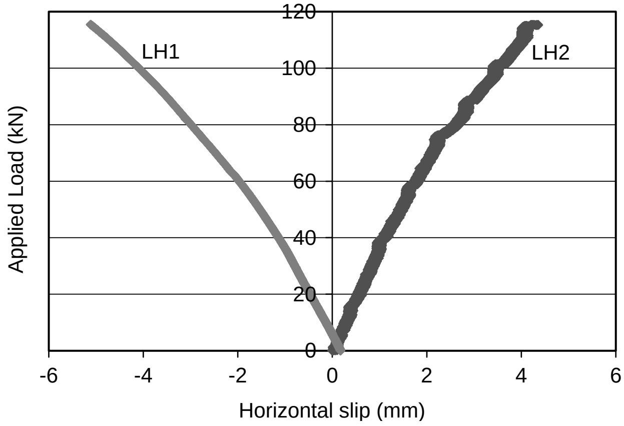

Fig. 7. Load–slip response for repair system B (load cycle to failure).

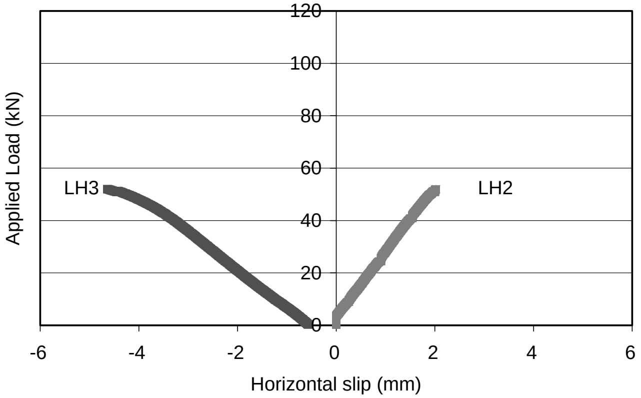

Fig. 8. Load–slip response for repair system C (load cycle to failure).

Maximum relative horizontal movement (slip) between the wood pile and the FRP composite shield measured with two LVDT units (LH2, and LH3) is presented in Fig. 8. The maximum horizontal slip recorded was approximately 5 mm for the bottom LVDT (LH2), and less than half of that value for the top LVDT (LH3). The difference in horizontal slip at the top and the bottom indicates that the FRP composite shield does not bend about the same neutral axis as the wood pile does. The observed failure mode, localized FRP composite compression failure, also supports the observation that the shield does not behave in beam bending with the wood pile.

3.5. *Deflected profile assessment*

The deflected profiles at peak load for all pile systems are depicted in Fig. 9. It was found that the repair system B with the cement-based grout resulted in a maximum

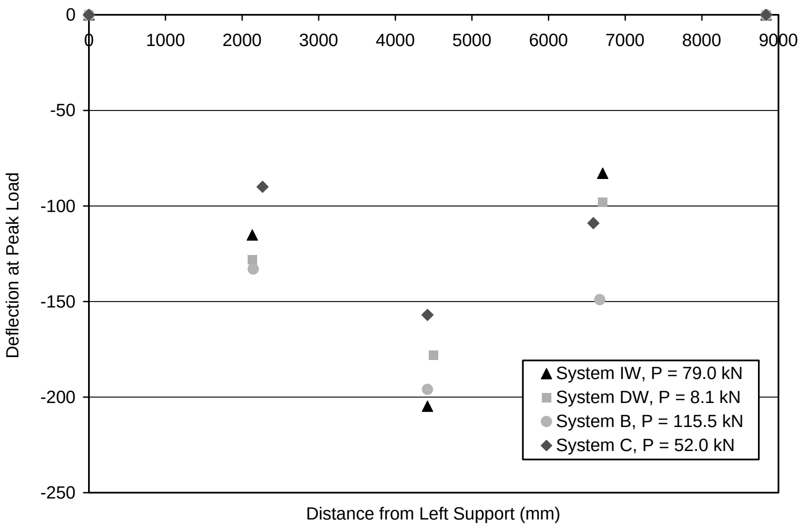

Fig. 9. Deflected shape at peak load for all pile systems.

mid-span deflection of 196 mm, which is similar to the corresponding value for the reference intact wood pile IW, 205 mm. The repair system B resulted in a decrease in curvature in the maximum bending moment region compared to the reference and control piles (i.e., smoother change in deflection slope along the pile axis). This is a consequence of the increase in bending stiffness over the repaired length of the pile.

3.6. Strain distribution in the FRP composite shield

Longitudinal strains at the top and bottom of the FRP composite shield were monitored during the load test for repair systems B and C. Load–strain distribution for both repair systems are presented in Fig. 10 (see Figs. 1 and 2 for strain gage locations). The axial strains at peak load for the repair system with the cement-based grout, B, were –3800 micro strains on the top and 6700 micro strains on the bottom of the FRP composite shield. Axial strains at peak load for the repair system with the steel shear connectors, C, were –2760 micro strains on the top and 2710 micro strains on the bottom of the FRP composite shield.

The difference in axial strains between the two repair systems was attributed to the different load transfer mechanisms and flexibility. The cement-based grout in repair system B transferred stresses between the FRP composite shield and the wood pile resulting in higher strains before failure compared to repair system C. In repair system C, the flexibility resulting from using the steel shear connectors between the shield and the wood pile was much greater than the repair system B with the cement-based grout system. The polyurethane grout did not contribute to reducing the overall flexibility in repair system C.

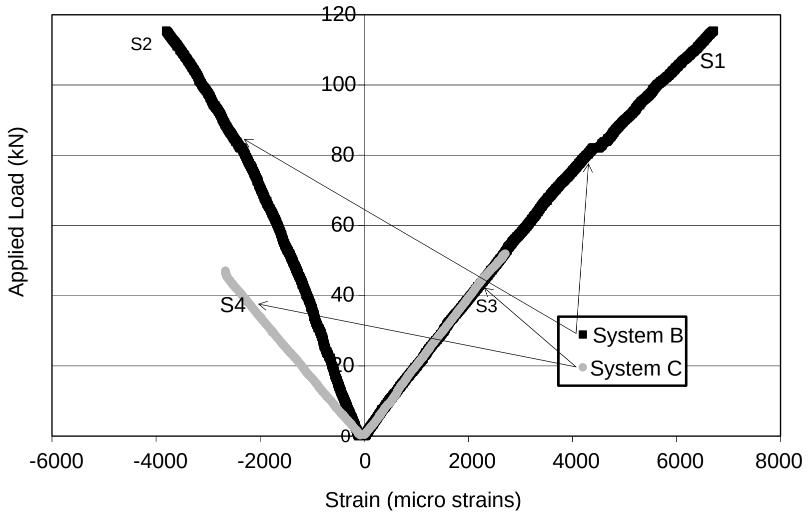

Fig. 10. Load–strain response for repair systems B and C.

4. Load and deflection normalized parameters

To provide a meaningful comparison among the different piles evaluated (with different diameters and taper) the experimental load-deflection response was normalized. The expression for the maximum deflection of a simply supported beam with constant cross-section is considered for normalizing load and deflection values, as follows:

$$\Delta = \frac{PL_s^3}{48E_wI_w}, \tag{1}$$

where (E_wI_w) is the product of the modulus of elasticity by the moment of inertia of the wood pile at the design section. The design section is defined as the section of the wood pile at mid-span. The value of E_w was obtained from the timber poles and piles supplement of the LRFD Manual for Engineered Wood Construction [16]. The moment of inertia of the circular cross-section was calculated as follows:

$$I_w = \frac{\pi d_w^4}{64}, \tag{2}$$

where d_w is the design diameter of the wood pile. Rearranging Eq. (1) results in

$$\frac{\Delta}{L_s} = \frac{1}{48}\frac{PL_s^2}{E_wI_w}. \tag{3}$$

From this equation, the applied load, P, was normalized by the bending stiffness and the span length, as follows:

$$p = \frac{PL_s^2}{E_wI_w}, \tag{4}$$

where p is the normalized (dimensionless) applied load. Similarly, the deflection at mid-span was normalized by dividing by the span length, as follows

$$\delta = \frac{\Delta}{L_s}, \tag{5}$$

where δ is the normalized (dimensionless) deflection.

It is worth noticing that the proposed normalization is only based on the bending stiffness of the wood pile and does not represent the partial composite action developed by the FRP composite shield. The normalization method is only valid for comparing piles that exhibit a linear response to failure. Based on the load-deflection response observed for the intact reference and pre-damaged control piles (Fig. 4), and the repair pile systems B and C (Fig. 5), the normalization method was implemented. The normalized load-deflection response for all four specimens is shown in Fig. 11. The normalized maximum load and deflection for all pile specimens is summarized in Table 3. The normalized load capacity of the damage specimen, DW, was approximately 15% of the intact reference wood pile, IW. Repair system B exhibited the highest load-deflection slope of all the tested pile systems due to the stiffness and quasi-integral response provided by the cement-based grout. For example, repair system B had a normalized peak load of 2.93 and a normalized maximum deflection at mid-span of 0.022, while repair system C with a normalized peak load of 0.87 had a normalized maximum deflection of 0.018. Bending of the shear connectors in repair system C with the non-structural polyurethane grout resulted in a relatively flexible response.

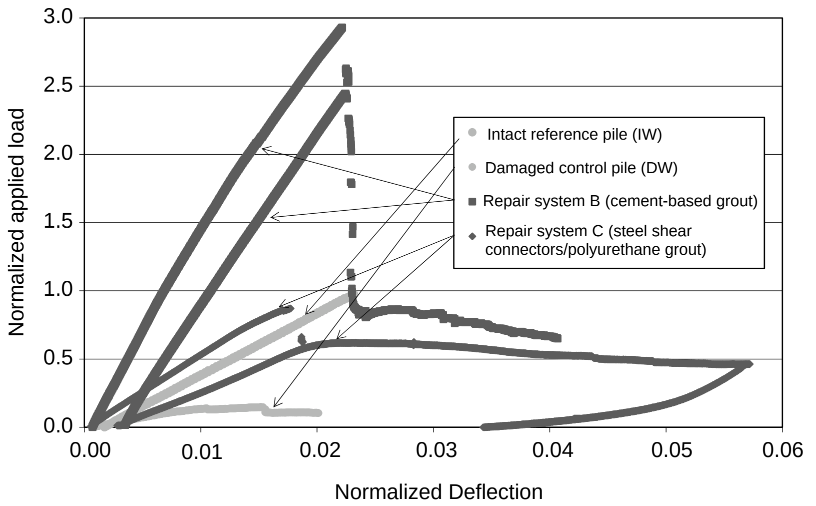

Fig. 11. Normalized load-deflection responses for all wood pile systems.

Table 3
Normalized load and deflection

System	Span length, L_s (m)	MOE, E_w (GPa)	Moment of inertia, I_w ($10^{-4}\,m^4$)	Normalized peak load	Normalized max. deflection
Intact wood (IW)	8.84	9.65	6.56	0.97	0.023
Damaged wood (DW)	8.84	9.65	4.42	0.15	0.021
Repair system B	8.84	9.65	3.19	2.93	0.022
Repair system C	8.84	9.65	4.83	0.87	0.018

5. Conclusions

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

1. A reduction in cross-sectional area of approximately 60% on a portion of the wood pile length decreased the wood pile bending capacity to one-sixth of the intact value. This demonstrated the importance of repairing damaged wood piles.
2. Use of FRP composite shells with slit openings can be applied over damaged piles and can serve as part of a system to fully restore the bending strength of a damaged wood pile.
3. A pre-damaged wood pile with approximately 60% reduction in cross-section on a portion of the length was repaired using the FRP composite shield with cement-based structural grout. It exceeded the bending capacity of an intact reference wood pile. When peak load normalization is considered to account for the variations in wood pile diameter and taper, this repair system resulted in three times the normalized peak load capacity of the intact reference wood pile.
4. A pre-damaged wood pile with approximately 60% reduction in cross-section on a portion of the length was repaired using the FRP composite shield with shear connectors and polyurethane grout. It only restored the bending capacity to two-thirds of an intact reference wood pile. When peak load normalization is considered to account for the variations in wood pile diameter and taper, this repair system resulted in 90% the normalized peak load capacity of the intact reference wood pile.
5. Transfer of stresses from the FRP composite shield to the wood pile is better accomplished using cement-based grout than with more flexible steel shear connectors. The bending strength of the FRP composite shield/cement grout repair system is more than double the bending strength of the FRP composite shield with steel shear connectors repair system.

6. The FRP composite shield combined with grouting provides a strong impervious containment of a damage pile section. Currently existing systems of repair do not have impervious containment or the containment shell does not have sufficient strength. Impervious containment of the damaged pile section discourages further marine borer damage to the pile.
7. The laboratory findings were based on a limited number of experiments and, therefore, the applicability of the pile repair method needs to be validated through monitoring waterfront installations subjected to actual marine borer damage and exterior environmental conditions.

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