Experimental Evaluation of Repair Options for Timber Piles

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An experimental investigation compared repair methods that could be used to repair timber piles in timber pile bridges. Five full-scale timber pile specimens with different levels of damages were prepared. The damage in each specimen was repaired with fiberglass-reinforced plastic wrap to encapsulate the damaged region, which was filled either with resin or grout or with resin and gravel. Ultimate load tests were carried out on the specimens to evaluate the effectiveness of the repair methods. Test results showed that grout was more effective than resin in repairing large cavity-type damage. Resin appeared to be more effective in repairing cracks and small cavities in timber piles. The failure load of the repaired pile specimens was at least five times greater than the design load capacity of the timber piles and indicated that the repair methods effectively restored the capacity of the damaged timber piles.

A large number of bridges built on low-volume roads use timber piles in their substructures, and many of those piles currently exhibit different types and extents of damage. Large cavity-type damage in timber piles often is difficult to repair. One option is to completely replace the pile. However, this option is more costly than rehabilitation. Posting and jacketing are two repair methods that have been investigated in the past.

REPAIR METHODS

Posting Repair Method

A posting pile repair procedure was developed in 1989 in which the deteriorated section was cut out of the pile and replaced with a new, treated pile section (*1*). The two sections were bonded with epoxy grouting. In some instances, the repair procedure required shoring. The repair procedure was evaluated through axial compression load tests on three repair specimens and one control specimen. The tests indicated that the original ultimate strength and axial stiffness of the pile were retained after the repair (*1*). The testing did not evaluate the effect of combined axial and lateral loads on the effectiveness of the repair procedure.

Two posting-type repair methods, Method A and Method B, were investigated in 2007 (*2*). Method A used lap splices at the end of each stub section. The sections were connected by long metal screws 0.5 by 12 in. in diameter. This repair method restored 70% of the axial capacity. The bending capacity, however, was significantly reduced. Method B used fiberglass-reinforced plastic (FRP) sheets and special epoxy to connect the sections. This repair method restored 100% of the axial capacity and 50% of the bending capacity of the piles. Limited tests also were conducted on the steel posting method and steel sister methods (*3*). These tests did not report the capacity restored by the repair methods.

Jacketing Repair Method

NCHRP Synthesis 200 describes concrete jacketing to repair timber, steel, or concrete piles (*4*). This method involves the creation of a form that is wrapped and sealed around the damaged area of the pile. Concrete is then pumped into the top of the pile jacket. A study investigated three concrete jacket repair methods used at the harbor in Portland, Maine (*5*). Problems observed with this repair method included damage to the jacket and the wood section above the repaired section and deterioration of the concrete fill. For these problems to be overcome, an alternative repair method was proposed that made use of FRP composite shells (*5*). FRP shells have been tried with an epoxy resin aggregate mix to repair the timber piles (*2*).

Thin and flexible FRP superlaminates have been effective for pile repair (*6*). The thin laminates can be wrapped easily around the damaged region in the piles, epoxy can be used to attach the wrap to the piles, and the annular space can be filled with resin or expansive grout. Limited studies have been carried out to investigate this repair method and to develop guidelines for the repair of different types of damage in timber piles.

OBJECTIVE

The objective of the research presented in this paper was to evaluate the effectiveness of repair methods with the use of FRP superlaminate and to develop a set of guidelines to retrofit damaged timber piles. This paper focuses on the experimental evaluation of repair methods that use FRP wrap and filler material to repair cavity-type damage in timber piles.

BACKGROUND

Experimental studies conducted on timber piles have considered axial compression and bending separately. It is important, however, to consider the effect of axial and bending together to evaluate the effectiveness of a repair method for timber piles.

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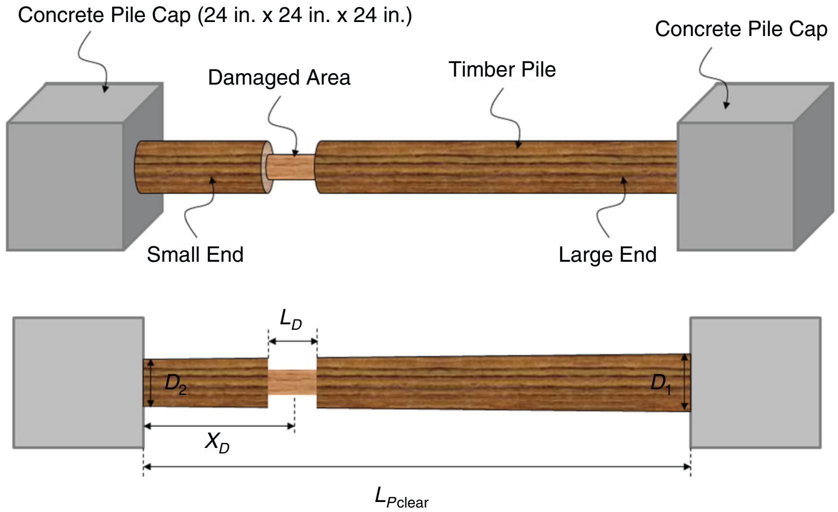


FIGURE 1 Description of test specimens (L_{Pclear} = clear length; L_D = length of damage; D_1 and D_2 = large and small end diameter, respectively).

The effect of combined axial compression and flexure was studied through experimental testing of wood specimens (*7*). The study found that the capacity of the specimens depended on the eccentricity of the applied load and the slenderness of the test specimen. The interaction of timber columns subjected to the simultaneous action of bending moment and axial compression showed nonlinear behavior, which depended on the slenderness of the column and the strength of the timber (*8*). A numerical study, calibrated with experimental data, suggested that the strength of timber piles decreased significantly under eccentric as opposed to concentric loads (*9*). These studies underlined the importance of testing the piles under the combined effect of axial compression and bending.

The main sources of eccentricity or bending loads in timber piles used in bridges include but are not limited to brake loads of traffic transferred from the deck to the timber piles, thermal expansion and contraction of the superstructure, and eccentricities in the axial load that arise from a nonuniform cross section as the result of damage. Thus it is essential to test the timber piles under combined axial compression and bending for a realistic evaluation of pile capacity after repair.

EXPERIMENTAL INVESTIGATION

Test Specimens

Thirty full-scale southern yellow pine timber piles were obtained for the test specimens. The piles were grouped by diameter. A group of five timber piles with relatively small differences in diameter was selected to prepare five full-scale test specimens. Each test specimen had a small end and a large end. The diameters of the small ends were approximately 8 in. with maximum variation in diameters of approximately 1 in. The diameters of the large ends were approximately 10 in. with a maximum variation in diameter of approximately 1 in. A concrete cap (24 × 24 × 24 in.) was cast at each end as shown in Figure 1. The length of the pile embedded in the concrete pile cap was 22 in. Each specimen had a damaged area offset at a distance X_D from the face of the concrete pile cap on the small end, which varied among specimens.

Details about the timber pile test specimens are provided in Table 1. The five test specimens had different levels and locations of damage and were repaired by different methods as shown in Table 1. Three damage levels were used in the test specimens. Specimens 2 and 3 had 1 and 1.5 in. of deep damage, respectively, and Specimens 4 through 6 had 2 in. of deep damage. The length of damage was kept constant for all test specimens. Different levels of damage are shown in Figure 2. Mechanically induced damage resulted in a smooth and clean surface, which differed from the rougher and irregular surface after naturally occurring damage and decay in a timber pile. Roughness in general helps different materials to bond with each other. Mechanically induced damage with its resultant smooth surface might reasonably provide a worse or more conservative bonding condition than natural damage would.

For the evaluation of the strength of the damaged and repaired section, the location of the section was situated close to the section

TABLE 1 Details of Timber Pile Test Specimens

Specimen	D_1 (in.)	D_2 (in.)	L_{Pclear} (in.)	L_D (in.)	Depth of Damage (in.)	X_D (in.)	Injection Material for Repair
1	10.19	7.88	205.00	16	1.0	28	Resin
2	9.63	8.30	201.50	16	1.5	28	Resin
3	10.42	8.83	207.50	16	2.0	28	Grout
4	9.91	8.28	202.25	16	2.0	8	Grout
5	9.55	7.88	204.00	16	2.0	28	Resin and aggregate

(a) (b) (c)

FIGURE 2 Damage in timber pile test specimens: (*a*) 1-in. deep, (*b*) 1.5-in. deep, and (*c*) 2-in. deep.

of expected failure. Theoretically, the pile section at the face of the concrete pile cap on the small end was the section most likely to fail. However, it was difficult to predict the precise location of the failure, given the heterogeneous timber material, nonuniform specimens, and accompanying loading eccentricities. In Specimens 1, 2, 3, and 5, location of the center of the damaged and repaired area was 28 in. from the face of the concrete pile cap at the small end. In Specimen 4, the center of the damaged and repaired area was located 8 in. from the face of the concrete pile cap at the small end. It was reasonable to assume that the section capacity of timber piles was small at the location of damage and that piles were likely to fail there unless the retrofitting provided enough strength to shift the failure to the other location.

Specimens 1 and 2, whose damage depths were 1 and 1.5 in., respectively, were filled with resin to repair the damaged area. However, resin is an expensive material, and large quantities of it would be required to fill a large damaged area. Thus three other specimens were repaired with different materials to assess the effectiveness of relatively cheap material to repair the piles. The damaged areas of Specimens 3 and 4, which were 2-in. deep, were filled with Sakrete, a nonshrinking construction grout. The damaged area of Specimen 5, which was 2-in. deep, was filled with aggregate and then injected with resin in the remaining space.

Repair Materials

This section briefly describes materials used for repair and their structural properties. Glass fiber–reinforced polymer (GFRP) superlaminates were wrapped around the damaged areas. GFRP laminates are made from sheets of glass fabric (whose fiber runs in two directions) and resin. GFRP superlaminates have high tensile strength [approximately 70 kips per square inch (ksi)]. The high tensile strength of the laminate provides confinement to the structures, and it helps them to resist bending moments applied to the structures. Typically, the laminates are .025-in. thick, which allows for easy bending and wrapping of laminates around the structures to be repaired. Carbon fiber reinforced polymer wraps also can be used for repair because of the similarity of their properties to those of GFRP.

The QuakeBond J201TC tack coat is a two-component, high-strength structural epoxy. The compressive strength (ASTM D695) of epoxy is 8 ksi, which is high compared with the nominal compressive strength of southern pines, which is 1.2 ksi. The epoxy was used to attach and seal the wrap around the damaged area. The other main advantage of this epoxy is its adhesive compatibility with wood and FRP wraps.

QuakeBond 320LV low-viscosity resin was used to fill the damaged cavity. The compressive strength (ASTM D695) of resin is 11.2 ksi. The main advantage of the resin as a filler material is its low viscosity, which allows the resin to flow through small cracks and completely saturate the damaged wood. The resin, however, is costly compared with other repair materials, such as construction grout.

Use of Sakrete, a nonshrinking construction grout, also was tested as another possible cheap alternative to resin. Seven days of compressive strength of flowable grout is approximately 6 ksi greater than the nominal compressive strength of southern pine wood. Although, grout is a cheap alternative to resin, it cannot flow through small cracks because of its high viscosity. Any nonshrinking construction grout with a dynamic flow of 9 in. measured in accordance with ASTM C1437 can be used for this application.

To decrease the quantity of resin required to fill damaged space, an aggregate might be used as a filler material. Air-dried coarse aggregates, which consisted of crushed stone (No. 4) with particles predominantly larger than 0.2 in, and generally between 0.4 and 1 in., were used to fill a damaged cavity before resin was injected. Once most of the damaged space was filled with resin, the quantity of resin required to fill the remaining space decreased significantly.

Repair Procedure

The repair procedure consisted of the following steps:

1. Thin and flexible GFRP superlaminates were cut to wrap around the pile a little more than twice (6). The laminate covered at least 1 ft of the undamaged pile on either side of the damaged region to be repaired.

2. The surface of the laminate was roughened with a 3M sand sponge to ensure a good bond between the wood and the laminate. A QuakeBond J201TC tack coat was used to attach and seal the laminate around the damaged area of the timber pile.

3. QuakeBond 320LV low-viscosity resin was injected through the notches cut in the pile before the laminate was attached.

4. A hole was cut in the GFRP laminate to inject the grout in the damaged region in the specimens repaired with grout.

Test Setup

Although timber piles are designed to carry only axial loads, instances occur in which timber piles in a bridge are subjected to axial and bending loads. The following are the main sources of bending loads in the timber piles used in bridges:

- Brake loads of traffic transferred from the deck to the timber piles,
- Eccentricities in the axial load that arise from nonuniform cross sections as a result of damage, and
- Thermal expansion and contraction of the superstructure.

The eccentricity was created through an increase in the lateral until the free end of the timber pile was moved 2 in. in a lateral direction.

The test setup consisted of two concrete blocks, hydraulic rams, and posttensioning rods set to apply axial and bending loads to the full-scale timber pile specimens. One of the concrete blocks was securely fixed to the ground and is referred to here as the fixed block. The other concrete block was movable as shown in Figure 3.

The fixed block was intended to provide a fixed support at the small end of the pile. The movable block was intended to transfer axial and lateral loads to the large end of the pile, while the rotation was kept free at the large end. With the large end of the pile free to rotate and the small end fixed, the failure was expected to occur in the pile section near the small fixed end of the pile. However, as discussed earlier, given the heterogeneous timber material, nonuniform specimens, and accompanying loading eccentricities, it was difficult to predict the precise location of the failure.

The fixed block was connected to the strong floor with vertical posttensioning rods (Figure 3). Hydrostone was used in between the strong floor and the bottom of the fixed block to eliminate unevenness and provide absolute fixity.

Timber piles were attached to the fixed and movable blocks with the help of concrete caps at the two ends of the piles. The concrete caps were placed in pockets of the concrete blocks and the extra space between the caps and pockets was filled with construction grout. The tests were conducted after the grout was set, and the caps were affixed to the blocks. No differential rotation between the blocks and pile cap was observed during the tests.

Two lateral and bending hydraulic rams (ENERPAC RRH-6010 with 90-ton capacity and 10-in. stroke) were placed under the movable block to apply a lateral and bending load on the piles. These hydraulic rams lifted the movable concrete block to a certain displacement to apply a lateral load to the timber pile. Polytetrafluoroethylene stripes were placed under these hydraulic rams to reduce the friction between the strong floor and the movable block.

An axial load was applied with two axial hydraulic rams (ENERPAC RCH-606 with 60-ton capacity and 6-in. stroke) that acted on two dywidag rods. Any imbalance in the load applied by the axial rams could result in the twisting of the pile specimen about the vertical axis. This result could introduce biaxial bending in the test specimens. For avoidance of this biaxial bending, the load imbalance was monitored, and the applied loads were adjusted as necessary to minimize bending during the test.

Instrumentation

Test specimens were instrumented to measure applied loads, deflection of the free end, and bending and axial stress near the fixed end of the full-scale timber pile specimens.

Four strain gauges were used at a distance of 12 in. from the face of the fixed block around the perimeter of the pile to measure both the bending and the axial stresses as shown in Figure 4. Two displacement transducers were attached to the movable block on both sides of the pile to measure axial deformation. One displacement transducer was attached to the pile at a distance of 12 in. from the face of the movable block to measure vertical deflection of the test

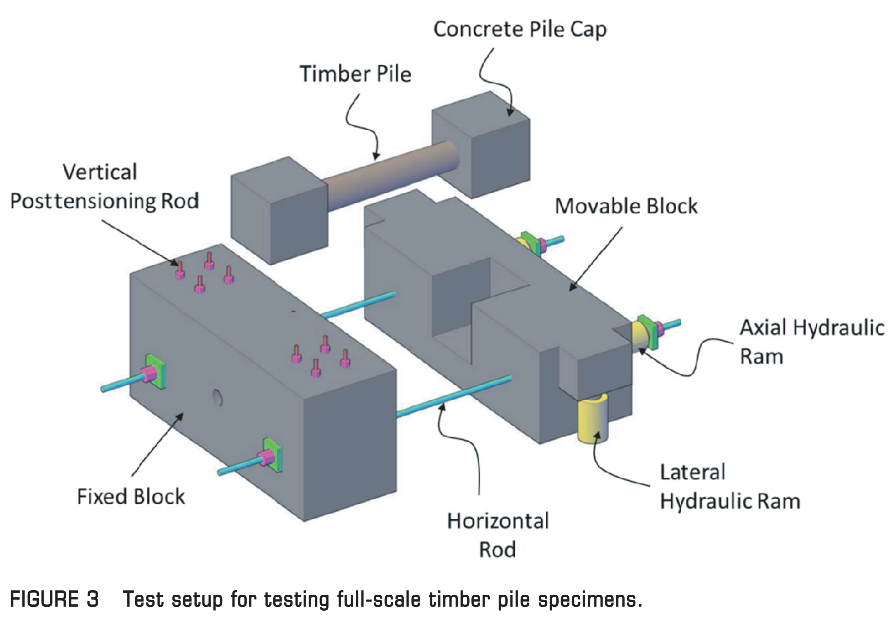


FIGURE 3 Test setup for testing full-scale timber pile specimens.

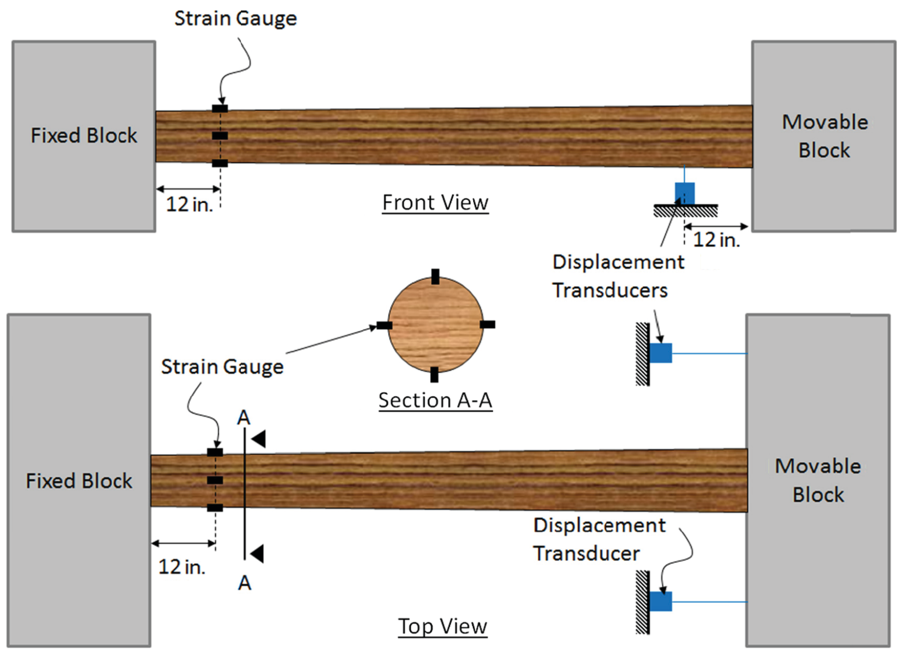


FIGURE 4 Instrumentation plan.

specimen. Four pressure transducers were used to measure the load applied by each hydraulic ram.

Testing Procedure

After the specimen was completely installed, some initial axial load was applied to the specimen to remove any slack in the test setup. After application of the axial load, the lateral load was applied in the form of lateral displacement of 2 in. near the free end. The lateral displacement induced lateral moment in the pile specimen and made the axial load eccentric. Because the movable block was free to rotate, the lateral deflection resulted in maximum lateral moment near the fixed block. After application of lateral displacement, the axial load gradually was increased until the sound of cracking wood was heard. The axial load was put on hold to see if the specimen failed as a result of progressive cracking and the failure of the wood. The load was again increased if the cracking sound stopped and the specimen had not failed; it continued to increase until the next cracking sound was heard or the specimen failed.

Test Results

Specimen 1, with damage 1-in. deep filled by resin, showed the highest ultimate load capacity of the five specimens tested as part of this study. The specimen failed at an approximately 177-kip axial load with rapid cracking. Major damage was observed at two locations after the failure of the specimen: near the fixed end, where the pile had a big longitudinal crack that split the pile into two halves, and at the repair location, where there was ripping and delamination of the GFRP jacket (Figure 5). The damage in both cases occurred at failure and was not progressive.

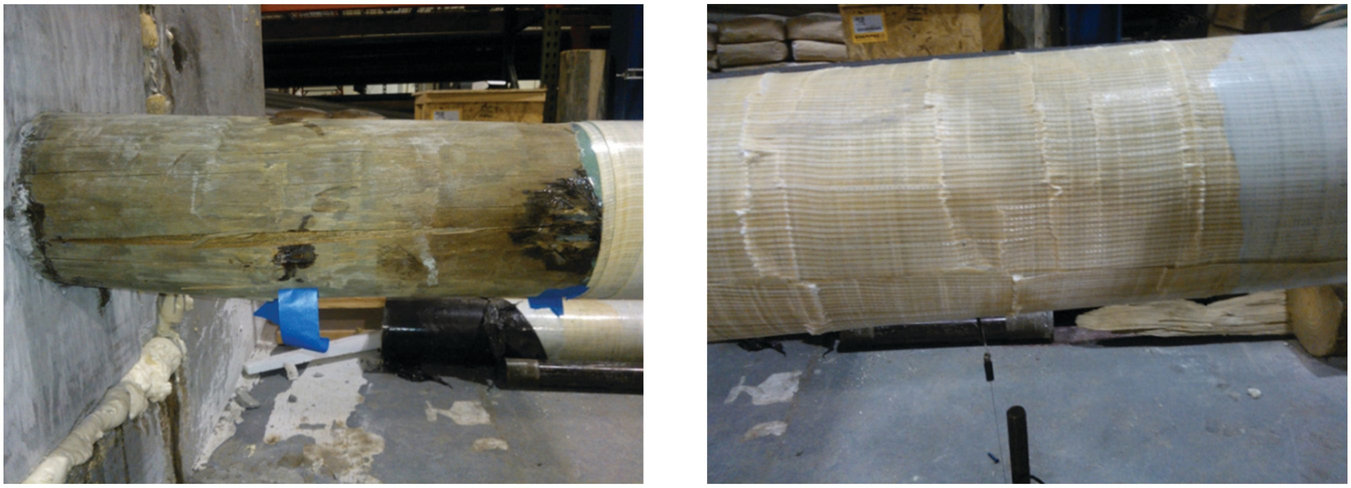
Specimen 2, with damage 1.5-in. deep filled with resin, showed the lowest ultimate load capacity (95 kips) of the five specimens tested in this study. This specimen failed mainly as the result of large gradual deflection at the repair location (Figure 6). The FRP jacket was damaged at the two ends of the 14-in.-long damaged region. The test continued even after the large downward deflection of the repaired region, which resulted in the cracking of the fixed end of the pile.

Specimen 3, with damage 2-in. deep filled with grout, took nearly a 120-kip maximum axial load before failure. The specimen showed no sign of damage in the repair region. The damage was observed at one end of the FRP wrap, which was 12 in. away from the boundary of the damaged region (Figure 7). Inspection of the failed specimen indicated bending-type failure, which resulted in crumpling top fibers and splintering bottom fibers. No damage to the FRP wrap was observed during this test.

Specimen 4 also had damage 2-in. deep filled with grout similar to that used for Specimen 3. However, the location of the damaged region was different. In Specimen 4, the damaged region was placed at the most critical location (fixed end) in an attempt to fail the specimen in the damaged region. The failure of this specimen, however, appeared away from the damaged region during the test (Figure 8). The specimen took an approximately 170-kip maximum axial load before failure. This specimen bent upward, unlike the other test specimens, which bent downward. This difference resulted from the failure onset, through the failure of weak grains at the bottom of the section, which reversed the bending direction of the test specimen.

Specimen 5, with damage 2-in. deep filled with resin gravel, failed at an approximately 115-kip axial load. The failure took place away from the repaired section (Figure 9). Insignificant damage was observed in the FRP jacket on the repaired section.

In summary, two timber pile specimens that were filled with resin (Specimens 1 and 2) showed some damage of the repaired area during the load test. The damage of the repaired section was insignificant in the specimen in which resin and gravel were used as filler materials (Specimen 5). No sign of damage was observed in the



(a) (b)

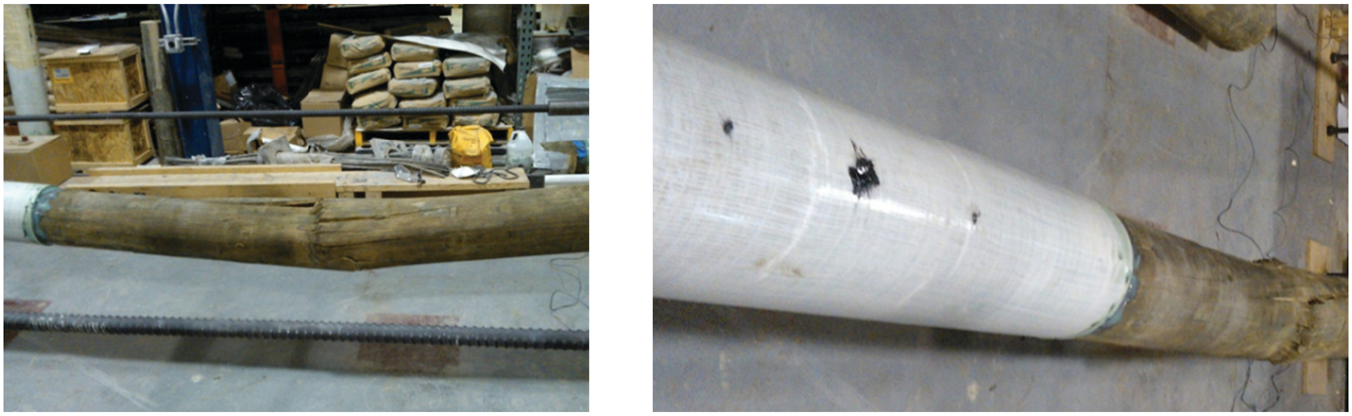
FIGURE 5 Failure of Specimen 1 (damage 1-in. deep filled with resin): (*a*) near fixed end and (*b*) at repair location.

(a) (b)

FIGURE 6 Failure of Specimen 2 (damage 1.5-in. deep filled with resin).

FIGURE 7 Failure of Specimen 3 (damage 2-in. deep filled with grout).

FIGURE 8 Failure of Specimen 4 (damage 2-in. deep filled with grout).



(a) (b)

FIGURE 9 Failure of Specimen 5 (damage 2-in. deep filled with resin and gravel): (*a*) damage away from repaired section and (*b*) insignificant damage to FRP jacket.

repaired region for the grouted specimens (Specimens 3 and 4). Further, in Specimens 3, 4 and 5, a clear failure took place outside the repaired region. In Specimens 1 and 2, partial or complete failure took place in the repaired region. It could be concluded from these observations that resin might not be effective to fill large cavities of damage in timber piles. One reason might be the large amount of heat from hydration from the bulk of resin that affected the quality of cured resin. Another reason might be the low modulus of elasticity of the resin material compared with the modulus of elasticity of wood. In both cases, the stiffness of the cured resin would be less than the stiffness of wood, which would result in a weak repaired section and force the failure to happen in the repaired section. The resin worked well when used with gravel, which indicated that resin was a good filler for small cavities and for damage caused by cracks. Further testing is required to confirm these conclusions. However, on the basis of limited testing, the use of grout is recommended to fill large cavity-type damage (i.e., localized damage with a volume greater than 1 gal), and resin is recommended to fill crack-type damage. Given resin's relatively low viscosity, it can fill cracks and small cavities more effectively than grout.

Load–deflection curves and the failure mode of the five specimens tested as part of this study are shown in Figure 10. There were small drops in the load–deflection curve of some of the specimens. For example, two load drops can be observed in the load–deflection

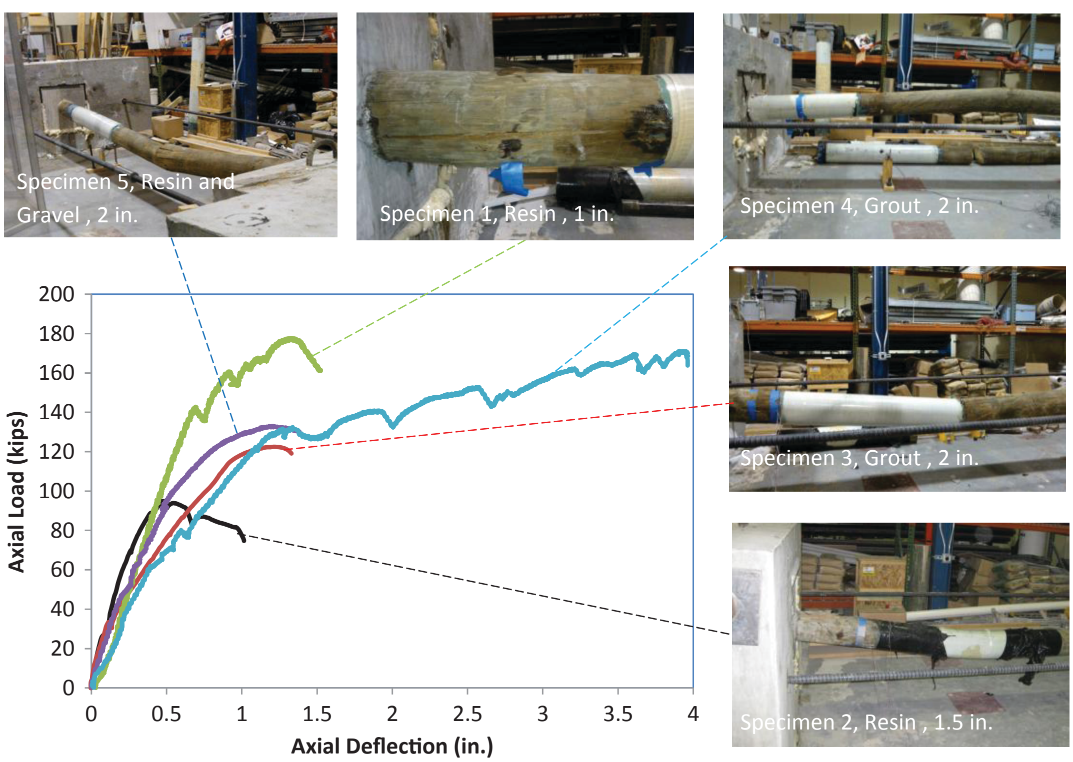


FIGURE 10 Load–deflection curve and failure mode of specimens.

TABLE 2 Maximum Axial Load and Design Capacity of Timber Pile Specimens

Specimen	Average Diameter (in.)	Depth of Damage (in.)	Repair Material	Maximum Axial Load (kips)	Design Capacity (kips)	Ratio of Maximum Axial Load to Design Capacity[a]
1	9.0	1	Resin	177.7	18	9.9
2	9.0	1.5	Resin	95.0	18	5.3
3	9.6	2	Grout	122.5	18	6.8
4	9.1	2	Grout	171.2	18	9.5
5	8.7	2	Resin and gravel	133.1	18	7.4

[a]Average = 7.8.

curve of Specimen 1 at approximately 140- and 160-kip loads. These load drops corresponded to the cracking of the wood during the test. Whenever a wood-cracking sound was heard, the load was put on hold to allow the failure to take place through progressive wood cracking. However, if the cracking sound stopped and failure had not taken place, the load was increased again until the next cracking sound was heard or until the complete failure of the test specimen occurred.

Timber piles are made of heterogeneous material. However, the effects of this heterogeneity on the structural behavior of timber piles are not pronounced at small load levels. Thus timber pile specimens showed similar initial axial stiffness as indicated by the load–deflection curves in Figure 10. The variability was more pronounced in failure loads and maximum deflection before failure. The maximum axial load for the specimens ranged from 95 to 178 kips. Similar maximum axial deflection before failure ranged from 0.5 to 4 in.

Table 2 shows the ratio of maximum axial load to design capacity of the timber piles. Maximum axial load was obtained from the tests carried out on the timber pile specimens described. According to the *Timber Pile Design and Construction Manual,* allowable pile capacity in compression is 60 kip for a pile with an 8-in. tip diameter if it can be assumed that the pile is fully supported laterally (*10*). The design capacity was obtained from the early 1990s design plans of timber pile bridges. The ratio of maximum axial load to design capacity in the last column of Table 2 was obtained by dividing the maximum axial load by the design capacity. This ratio had a minimum value of 5.3 for Specimen 2, which indicated that Specimen 2 could carry 5.3 times of the design capacity load before failure. The average value of the ratio of the maximum axial load to the design capacity was 7.8. This value indicated that the repaired timber piles could carry the design load with a large factor of safety.

CONCLUSIONS

Ultimate load tests were carried out on full-scale timber pile specimens with different levels of damage repaired by GFRP and filler materials. Comparison of the ultimate load with the design capacity of timber piles indicated that repair methods effectively restored the capacity of the damaged timber piles.

The timber pile specimens that were repaired only with resin showed some damage of the repaired area during the ultimate load test. Damage in the repaired section indicated that partial or complete failure took place in the repaired region. Limited or no damage within the repaired section was observed in specimens that were repaired with grout or with resin and aggregate. A clear failure took place outside the repaired region in these specimens.

These observations indicated that resin might not be effective to repair large cavity-type damage in timber piles. The resin worked well when used with aggregate, which indicated that its use was effective to fill small cavities and crack-type damage.

Grout is recommended to fill large cavity-type damage (i.e., localized damage with a volume greater than 1 gal). Resin is recommended to fill crack-type damage. Given resin's relatively low viscosity, it can fill cracks and small cavities more effectively than grout.

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