Timber Abutment Piling Rehabilitation and Repair

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Summary

This paper provides an overview of the completed project for the Iowa Department of Transportation and Iowa Highway Research Board by Iowa State University's Bridge Engineering Center (BEC) regarding the repair and rehabilitation of timber abutment piling [1]. A large number of bridges on the county-level roads around Iowa are constructed using timber piles and these structures are increasingly being labeled as structurally deficient because of the condition of these components. Repair and rehabilitation methods specifically aimed at piling could potentially upgrade a progressively aging fleet of timber bridges thereby extending their service life. The objective of this study was to identify effective methods of repair that are currently being used around the state and to improve upon these methods or develop other methods that can be economically implemented.

Keywords: Timber Piling, Repair, Timber Strengthening

1. General

1.1 Introduction

Based on previous National Bridge Inventory data, the state of Iowa has nearly 25,000 bridges which rank it number 5 in the nation behind Texas, Ohio, Illinois, and Kansas. In Iowa, close to 80 percent of these bridges are on low volume roads (LVRs) and, thus, are the responsibility of the county engineers. Of the bridges on the county roads, 24 percent are structurally deficient and 5 percent are functionally obsolete. A large number of the older bridges on the LVRs are built on timber piling. In many cases, as timber abutments and piers age, the piling deteriorate at a rate faster than the bridge superstructure. As a result, a large percentage of the structurally deficient bridges on LVRs are classified as such because of the condition of the timber substructure elements. This situation is especially common for bridges constructed in the period 1950-1970 that have reinforced concrete stringers and decks or reinforced concrete decks with steel stringers and timber substructure elements. The soil/water/air interface area of the piling is particularly prone to severe cracking and rot. Because there have been instances where bridges with legal rated superstructures and no load posting have failed under traffic loading due to pile failure, this represents a critical infrastructure situation.

As funds for replacing bridges decline and construction costs increase, effective rehabilitation and strengthening techniques for extending the life of the timber substructures in bridges with structurally sound superstructures has become even more important. Several counties have implemented various techniques to strengthen/repair damaged piling, however, there is minimal data documenting the effectiveness of these techniques. There are numerous instances where cracked and failed piling have been repaired. However, there are no experimental data on the effectiveness of the repairs or on the percentage of load transferred from the superstructure to the sound pile below.

1.2 Research Objectives and Scope

The objectives of this investigation were to:

- Review existing products for timber preservation and repair and to document their effectiveness in extending the life expectancy of various bridge components.
- Determine techniques used by county engineers and other engineers to repair and restore load carrying capacity of piling damaged by deterioration and cracking.
- Review methods used to repair failed piling.
- Determine/develop effective methods for transferring bridge loads through the failed portion of the pile.
- Determine that safe load capacity is restored by the repair methods (existing or new) determined to be structurally efficient.

2. Deterioration Mechanisms and Condition Assessment

In Iowa, low volume bridge foundation problems are often associated with timber substructures [2]. Timber piles are subjected to deterioration, which, at initial stages, can be difficult to detect. Furthermore, information regarding the soil profile and pile length at a given bridge site is often unavailable. There are currently no reliable means to estimate the residual capacity of an in-service deteriorated pile; and thus, the overall safety of the bridge cannot be determined with confidence. Although the majority of inadequate substructures have timber piling, there are numerous cases in which the steel substructures are inadequate (problems with corrosion, misalignment, damage due to impact, etc.). If procedures can be developed to assess the integrity of existing timber substructures and rehabilitate/strengthen inadequate substructures components, it will be possible to extend the life of those bridges and have increased confidence in predicting their performance.

2.1 Biological Deterioration

In most timber bridge applications, decay fungi are the most destructive organisms [3]. Fungi are microscopic thread-like organisms whose growth depends on mild temperatures, moisture, and oxygen. There are numerous species of fungi that attack wood, and they have a range of preferred environmental conditions. Decay fungi are often separated into three major groups; brown rot fungi, white rot fungi, and soft rot fungi. Soft-rot fungi generally prefer wetter, and sometimes warmer, environmental conditions than brown or white rot fungi.

Termites rank second to fungi with respect to damage to wood structures in the US [3]. Their damage can be much more rapid than that caused by decay, but their geographic distribution is less uniform. Termite species in the US can be categorized by ground-inhabiting (subterranean) or wood inhabiting (non-subterranean) termites. Most damage in the US is caused by species of subterranean termites.

Other types of insects such as powderpost beetles and carpenter ants can cause notable damage in some situations, but their overall significance pales in comparison to the decay caused by fungi and termites. Other organisms, including bacteria and mold can also cause damage in some situations, and several types of marine organisms degrade wood placed in seawater.

The two greatest factors influencing regional biodeterioration hazards are temperature and moisture [4]. The growth of most decay fungi is negligible at temperatures below 2 °C and relatively slow at temperatures below 10 °C. The growth rate then increases rapidly, with most fungi having optimum growth rates between 25 °C and 35 °C. The natural range of native subterranean termites is generally limited to areas where the average annual temperature exceeds 10 °C. Decay fungi require a moisture content of at least 20 percent to sustain any growth, and higher moisture contents (over 29 percent) are required for initial reproduction [4]. Most brown and white rot decay fungi prefer wood in the moisture content range of 40 to 80 percent. In almost all cases, wood that is protected from ground contact, precipitation, or other sources of water will have insufficient moisture to sustain growth of decay fungi. In contrast, wood that is in contact with the ground often has sufficient moisture to support decay, even in relatively dry climates. On the other hand, wood can be too wet to support fungal growth. For example, void spaces in the wood are increasingly filled with water as the moisture content exceeds 80 percent. The lack of oxygen and build-up of carbon dioxide in the water limits fungal growth [3].

2.2 Physical Deterioration

There are several forms of physical deterioration that occur in timber bridge piling. In almost all cases the physical deterioration causes exterior damage that breaks down the protective preservative barrier and allows entry of biological decay mechanisms into the untreated wood. One of the most common types of physical deterioration is abrasion or debris damage. This generally occurs by the impact of floating debris and/or ice in a channel [2]. The velocity of water moving past the pile and the quantity, shape, size, and hardness of particles being transported have been linked to the rate of abrasion [5].

Overloading of piles can result from continuous heavy loads, infrequent severe loads, loss of the pile structural capacity, or more frequently, complete loss of adjacent supports [2]. Failure of one pile requires the adjacent piles to carry additional load. Overloading can be caused by vertical and/or horizontal loads. Continuous overloading results in several modes of compression failure including splitting of the top portion and misalignment or "mushrooming" at a hollow portion after breakage [6]. These stages include development of initial entry holes, active deterioration of the inner core with a significant increase in the size of the hollow space, compression failure of the shell, and finally separation of the hanging top portion of the pile from the pile cap [7]. In addition, overloading can occur from the mechanical fasteners used to connect bridge elements. Many times fasteners are over tightened causing bulging around the head, nut, or washer. The bulge generally leads to entry holes for deterioration of the inner portions of the timber to occur.

Fire is a threat to all timber bridge elements and has the potential to destroy an entire bridge in a matter of hours. However, thermal degradation of wood occurs in stages. The degradation process and the exact products of thermal degradation depend upon the rate of heating as well as the temperature [2]. A timber pile has a generally uniform strength throughout its cross section. Thus, the unburned section of the timber pile retains its strength, and its load carrying capacity is reduced in proportion to the loss of cross section. When exposed to high temperatures, wood will decompose providing an insulating layer of char that retards further degradation. Therefore, the amount of charring of a cross section controls the fire endurance of a timber pile [6].

Other noteworthy physical agents that damage timber piles are connection failure, which exposes untreated wood allowing entry for fungi or insects, ultraviolet (UV) degradation, chemical degradation, and foundation settlement [8].

2.3 Condition Assessment

A number of tools exist to assist the inspector with the diagnosis of deterioration and preventative maintenance [3]. The tools vary considerably in the amount of experience required for reliable interpretation, accuracy in pin-pointing a problem, ease of use, and cost. No single test should be relied upon for inspection of timber bridge components. Rather, a standard set of tools should be used by inspectors to ensure conformity in inspections and consistency between inspectors. These tests and tools include: visual assessment, probing and pick test, moisture measurement, sounding, stress wave devices, drill resistance devices, core boring, and preservative retention analysis.

3. Pile Maintenance State of Practices

Ritter [9] divided pile maintenance activities into three categories. The first category is preventative maintenance, in which the repair involves keeping the structure in a "good state". At this stage, deterioration has not started, but the conditions or potential are present. The second category is early remedial maintenance. At this stage, deterioration is present; however, the capacity or performance of the structure is not affected. More severe damage is imminent unless corrective action is taken. The last category is major maintenance, which involves immediate corrective measures to restore the structure to its original condition [2].

Preventative maintenance includes such things as moisture control, in-place treatments (surface treatments, pastes, and fumigants), and small crack repair by epoxy injection. Remedial maintenance includes posting/splicing, concrete jacketing, PVC wrapping, FRP wrapping, and epoxy injection. Major maintenance includes the addition of supplemental piles and/or removal of deteriorated existing piles.

4. Field Testing of Existing Timber Repair Methods

Upon completion of the field reconnaissance, the researchers along with the technical committee selected four bridges for live load testing. The goal of the testing was to determine how each repair performed when loaded and how that performance differed from that of a non-repaired pile in good condition. Of all bridges considered, three repair systems were tested; these include 1) encasing the weak pile in concrete, 2) posting, and 3) installing additional piles. Each of the tested bridges included at least one of these repairs; the results are discussed in the following sections.

4.1 Bridge Test 1

Bridge 1 is a 38.4 m long bridge with three equal spans. The continuous span superstructure consists of three steel girders and a concrete deck, while the substructure consists of timber piles, five at each abutment and pier. The only timber pile repairs were located at a single pier; two of the five piles were repaired using the concrete encasement method. One of the repaired piles was completely encased, while the other was only partly encased.

One can assume by visual inspection that the concrete encasement stiffens inadequate piles, yet the need exists to quantify the actual force transferred to the encasement. Each of the five piles within the pier were instrumented with multiple strain gages placed to enable quantification of the force carried by the concrete encasement and, when accessible, the timber piles. It is evident by the strain data that the concrete encasement did carry part of the total load imposed on the repaired piles. As one might expect, the strain values measured on the encasement were considerably less than those measured on the timber piles alone. This can be attributed to the substantial difference in total cross-sectional area between the timber pile and concrete, along with the greater modulus of elasticity of the concrete. It is assumed that the concrete encasement does not carry the entirety of the load imposed on the pile. This phenomenon would most likely happen only in circumstances where the entire cross-section of the timber has been lost; this method of repair would not have been appropriate if that were the case. The bridge geometry is mirrored on the centerline of the bridge. Likewise, the load paths of the test vehicle were mirrored on the bridge centerline. Subsequently, when comparing the strain values measured in the fully encapsulated pile to the timber pile on the opposite side of the pier, the percentage of total load introduced to the concrete encasement can be derived. After calculating the force induced into the piles given the strains and cross-sectional properties, it was determined that the concrete encasements carried between 50 and 70 percent of the total load imposed on the respective piles. That is not to say the repaired piles were only capable of carrying 30 to 50 percent of the total load. Rather, it more likely reflects the stiffness of the concrete encasement with respect to the timber and its inherent tendency to carry a greater portion of the load.

4.2 Bridge Test 2

Bridge 2 is a single span 5 m long Greenwood flume bridge. The superstructure consists of timber decking and 21 timber stringers bearing on a timber pile cap, while the substructure at each abutment consists of eight original timber piles and six added timber piles. Additionally, the base of all piles at the waterline was encapsulated in concrete.

The added piles were essentially the same size as the existing piles and were placed directly adjacent to them. The bearing conditions appeared to be consistent between all existing and new piles. After plotting the strain data, it was observed that the strains in the new and old piles were very nearly the same. Assuming that adjacent piles receive equal load, this gives evidence that the load is approximately split between the two piles, thus reducing the load capacity required by any one pile to half.

The condition of the original piles was unknown prior to the addition of new piles and concrete footing. Nonetheless, the remaining visible portion of the original piles is in good condition. With that said, the strain data also gives evidence to the good condition of the visible portion and the effects of the concrete encasement at the base of all piles. With near equal strain values, the pile stiffness and, therefore, condition must be nearly equal. Additionally, the formed concrete footing that encapsulates the bases of each pile provides a solid base for which the load can be transferred from the piling.

4.3 Bridge Test 3

Bridge 3 is a 16 m long bridge with simple spans of 4.5 m, 7 m, and 4.5 m for the first, second, and third spans, respectively. The superstructure consists of 20 timber stringers and timber decking bearing on a timber pile cap; the substructure at each abutment consists of four timber piles, a timber backwall, and timber wingwalls. Additionally, the bottom 0.6 m of piles above ground have been encapsulated by timber planking and concrete infill. Each of the two piers has six piles. Three piles in the eastern pier have been encapsulated in a corrugated metal pipe with concrete infill, whereas in the western pier, one pile has been encapsulated.

As the objective of the load test was to determine how the repaired piles respond to applied load, the researchers decided that strain sensors would be placed on each pier pile and the piles within the eastern abutment. Strain sensors on the pier and abutment piles were placed above and below the encapsulated portions where applicable.

At the piers, the measured strains revealed that part of the applied load was distributed to the formed cast portion around the existing pile. The strain values measured on the cast portion were generally smaller than those measured on the timber-only portion, which should be expected given the difference in total cross-sectional area and combination of materials used at the casted portion. Moreover, where compression and tension strains were measured in the timber-only portions of the pile (top), the strain values in the strengthened portion followed. The total load applied to the piles was calculated assuming the piles were primarily in axial compression. It was also assumed the strains measured at the strengthened portion were uniform throughout each respective cross section. A comparison was made of the total load calculated in each pile to the calculated load distributed to each component (concrete and timber) within the strengthened portion. The observable differences in total load between the top of the pile and strengthened portion can be attributed to such unknown attributes as the modulus of elasticity of each material, slight variances in cross-sectional area, or bending behavior. Nonetheless, it is evident that a significant portion of the load is distributed to the concrete within the strengthened portion of the pile.

At pier 2, the only repaired pile carried very little load in all load cases. It is possible the bearing condition between the pile cap and pile has separated enough to inhibit immediate load transfer. It may also be possible that the non-viewable portions of the pile below the ground line have deteriorated to a condition that prevents load transfer to the ground. Given the apparent load transfer within the casted portions of the piles in pier 1, it can be assumed the cast effectively strengthens and restores stiffness to the pile when the pile is in otherwise good condition beyond the casted portions.

The behavior seen in the abutment piles was consistent with the vehicle configuration and load path traveled. Strain data collected at the face of the timber planking mirrored the data collected near the top of the pile, though the strain magnitudes were different. This phenomenon gives evidence for load sharing between the piles and timber planking; it is likely the load is shared with the concrete infill as well. By visual observation, it was clear the timber planking and concrete infill system shortens the effective length of the pile in the transverse direction, protects the bottom half of the piles from damage due to debris flow, and provides support to the existing backwall.

4.4 Bridge Test 4

Bridge 4 (total length of 18 m) has three spans of equal length. The superstructure consists of 13 timber girders and a timber deck, while the substructure consists of timber pile caps and timber piles, five at each abutment and four at each pier. The only timber pile repair was located at the easternmost pier; one of the four piles was repaired by removing the timber pile from between the ground and the pile cap and replacing it with a steel H-pile.

Only the pier where the pile repair is located was instrumented with strain gages. Strain gages were placed on each pile and the pile cap. Strain results from three load paths were obtained; 0.6 m from left curb, centerline, and 0.6 m from right curb.

The strain results obtained from the test on Bridge 4 were typical of those anticipated by the researchers based on the fairly simple overall structure (simple spans and vertical timber piles with diagonal cross-bracing). However, the results obtained from the steel pile, were unusual especially given that the only connections to the pile were at the pile cap and at the cut end of the original timber pile, i.e., no diagonal bracing. The researchers anticipated significant compression loading in the steel pile and, at a minimum, compression loading on one side of the pile if bending occurred. Given the position of one load path in particular with respect to the position of the steel pile, it would appear very unlikely the pile would be in tension. However, this was the case. Moreover, the strain results in the original timber pile to which the steel pile was connected indicated compression loading. The researchers questioned the validity of the results because of this unusual and seemingly illogical phenomenon; thus, the researchers decided to retest the pile in question. After retesting the pile, the results from the original test were verified to be correct. Without a much greater amount of instrumentation and significant investigation, this puzzling occurrence may be left unsolved.

This incident may be attributable, at least in part, to the connections of the steel pile to the original pile and pile cap. The pile cap did not achieve full bearing on the post. Rather, the pile cap achieved bearing only on one edge of the post. Additionally, lag screws were used to connect each component. It is possible that when a load was introduced to this connection, the localized load path induced tension into the pile. Regardless of the unusual results, and possibly despite little structural assistance of the repaired pile, the bridge has been able to carry vehicular loads.

5. Development of New Strengthening System

The researchers, after having developed several potential strengthening systems, with the purpose of creating constructible and economical solutions to timber pile strengthening and/or improvement to existing solutions, summarized details for these schemes and subsequently, consulted the TAC to propose lab testing on a selected few. Three were of particular interest; two of which could be completed in the ISU structures lab, while the third would be a field demonstration.

The two options selected for laboratory testing were 1) steel channel attached to opposite sides of the deteriorated portion extending to sound timber above and below, and 2) revision of steel posting connection to enable field adjustment for full bearing.

5.1 Control Specimens

Prior to completing axial load tests on the two selected potential strengthening systems, three control specimens were created using timber piles obtained from former bridge structures. Each was cut to simulate 50 percent cross-sectional area loss. These control specimens were created to compare the results of a strengthened pile load test to that of a non-strengthened pile. Information regarding the material properties and, maybe even more noteworthy, the capacity of a reduced section and failure mechanism is determined from the axial load tests.

The minimum modulus of elasticity was found to be 5.2 Gpa, while the maximum was found to be 9.0 Gpa. The maximum stress calculated for the three tests varied from 21.3 Mpa to 24.7 Mpa.

As was previously mentioned, the piles used to create the specimens were from former bridges within the state of Iowa. Additionally, the sizes used are typical of those at existing bridges. Subsequently, the total capacity of the specimens in and of itself, even with the simulated 50 percent decay was noteworthy. The smallest failure load measured for any of the specimens was 498 kN – a load significantly greater than that individual pile are currently subjected to at existing bridges. One should not assume that piles even in a decayed state can withstand loads to this magnitude, as the field conditions most likely differ from that of a controlled test, i.e., length and degree of decay, lateral unbraced length, induced bending, etc. Rather, one could assume that a significant amount of reserve capacity exists in piles that have experienced moderate decay.

Also noteworthy was the way each of the piles eventually failed. During loading, the reduced section began to balloon in the radial direction until most exterior fibers would splinter and peel away from the specimen. If any checks were present prior to loading, the size of the checks was magnified and propagation often ensued.

5.2 Steel Posting Connection

The ability to remove deteriorated portions of an existing pile and replace it with a steel pile that fits exactly in a given location can be difficult given the conditions beneath bridges and tools required. That is not to say it is impossible because that task has been successfully completed many times. However, a solution that provides field adjustment capabilities could improve the process and hopefully would achieve full bearing on the replaced pile. In the previous section, the bridge which was the subject of bridge test 4 could have potentially benefitted from a repair method with such field adjustability. As previously noted, the pile cap did not entirely bear on the replacement steel pile and therefore could have potentially contributed to the unusual load transfer through the pile observed during testing.

The researchers created a mockup of a connection that exhibits field adjustability. This mockup consisted of a timber pile section, steel H-pile section welded to a base plate, four 2.5 cm diameter threaded rods, and four 1 cm thick steel angles. Each steel angle was bolted to the timber pile using 1.5 cm diameter lag bolts and leveling nuts were placed between the angles and base plate on the threaded rods. The leveling nuts enabled the adjustment of the base plate.

The connection was tested in axial compression using the laboratory's universal testing machine. The load versus deflection behavior provides evidence the connection has the capacity required in most timber piles. However, the deflection values were higher than desired. This issue could be easily remedied by using a thicker base plate or base plate stiffeners, as a majority of the deflection was a result of base plate bending. The recommended base plate thickness is greater than the 0.5 cm thickness used in the mockup. Near the end of the test, the slope of the load deflection curve significantly increased. This was the result of the base plate coming into contact with the top of the timber pile. This also provides evidence the capacity of the connection would be greater with a thicker base plate as the total load had not yet reached the capacity of the pile.

5.3 Steel Sisters

Commonly, when loss of section is discovered in timber piles and where visual inspection may indicate an inadequate pile, only a short length of the pile has decreased load carrying capacity. A majority of the pile may very well be intact and able to withstand the desired vehicular loading. Where this is the case and localized section loss has advanced to a degree where replacement or reinforcement is desired, a method that could be considered is to sister steel sections to the pile. This method is comprised of spanning and reinforcing the damaged or decayed portion of the pile with steel "sisters" which are anchored above and below within the remaining solid portions of the pile.

The researchers included this method is their laboratory investigation and testing. A pile was modified to simulate a 50 percent cross-sectional area loss over a one foot length. Two M6x4.4 (A =8.32 cm^2) steel sections were used to span the section loss and were anchored by four 2.5 cm diameter threaded steel through rods. Both steel sections were instrumented with strain gages on each flange at the midpoint of simulated decay.

The specimen was axially loaded for purposes of comparison with the control section without the steel sisters. It was found in this test that the steel resisted minimal load until the failure of the pile was imminent and the steel sisters became engaged – the tolerances around the anchor rods were enough that a certain amount of deformation in the pile was required before the rods would bear on the sisters. Even with the simulated 50 percent section loss, the pile performed very well before the sisters were engaged. In fact, the performance was well enough to withstand loads commonly seen by these piles due to vehicular traffic. Nonetheless, with minor changes in how the sisters are attached to the pile, it is likely that one would be able to engage the steel sections almost immediately upon loading.

The observed maximum stress of 25.6 MPa in the timber is on the same order as that observed in the control specimens, thus providing assurance that the sistered pile was a representative specimen. Additionally, upon failure of the pile, the maximum stress observed in the steel was only 80.6 MPa – well below the yield stress of steel. This would lead one to believe that the overall capacity of the pile would be even greater than the capacity achieved in the load test if the steel were fully engaged earlier in the loading process. Even more, the possibility exists that if the test was not stopped the steel would have become fully engaged and the total load would have reached levels corresponding to the yield stress of the steel.

Similar to the load versus deflection curves of the control specimens, the rate of deflection increased significantly only after reaching approximately 7.6 mm of total deflection. This gives more evidence that the specimen was representative of other timber piles and the fact that the steel was not becoming fully engaged until the timber began to fail.

6. Summary, Conclusions, and Recommendations

Tens of thousands of bridges within Iowa are maintained at the county level. Of those bridges, a significant percentage are constructed using timber piles, girders, and decks. The superstructures are often sufficient to carry the traffic for which they are required. Even so, the advancing decay of substructure elements, such as timber piles, pose a problem to the longevity of the overall structure. With such a large number of bridges requiring attention and the fact that available funds are decreasing while maintenance costs are increasing, it becomes important to improve or identify the best currently used maintenance methods for timber substructures.

The objectives of this research were to complete the following:

- Review existing products for timber preservation and repair and to document their effectiveness in extending the service life of various bridge components.
- Determine techniques used by county and other engineers to repair and restore the load carrying capacity of piling damaged by deterioration and cracking.
- Review methods used to repair failed piling.
- Determine/develop effective methods for transferring bridge loads through the failed portion of the pile.
- Determine that safe load capacity is restored by the repair methods (existing or new) determined to be structurally efficient.

Deterioration of timber substructure elements can be attributed to either biological or physical deterioration mechanisms. Included in the biological mechanisms are decay fungi, termites, powderpost beetles, and carpenter ants. These mechanisms often have a direct correlation with the temperature and moisture conditions present. Alternatively, physical deterioration mechanisms include abrasion, debris contact, and overloading.

Condition assessment should be conducted using a multitude of tools. These tools include 1) visual assessment, 2) probing and picking, 3) moisture measurement, 4) sounding, 5) stress wave devices, 6) drill resistance devices, 7) core boring, and 8) preservative retention analysis. Any single method may give an incomplete or inaccurate assessment of the given substructure element.

Maintenance activities depend entirely on the extent of deterioration present within the substructure element. Depending if the deterioration is minor, moderate, or severe, the maintenance activities will either be preventative, remedial, or major, respectively. Preventative maintenance includes moisture control, in-place treatments, and/or epoxy injection of small to medium sized cracks. Remedial maintenance includes posting/splicing by means of mechanical splicing, concrete jacketing, FRP or PVC wraps, and/or injection of epoxy. Major maintenance corrective measures are conducted when deterioration has progressed to the point where major structural components have experienced moderate to severe strength loss and repair or replacement is mandatory to maintain the load carrying capacity. Often the only method that can be employed with this level of decay is to install supplemental piles.

Four Iowa bridges utilizing different methods of repair or strengthening were subjected to live load testing. In each of these tests, the repairs proved to be effective in that the desired stiffness was restored.

At the first of these bridges, corrugated metal pipe was used to create a form around the decayed or damaged portions of the pile which was filled with concrete, thereby creating a cast and providing additional stiffness. The near term performance of this method appears to be adequate to maintain a functioning bridge. Being as the method of repair has not been observed over the long term, conclusions regarding its indefinite performance cannot be made.

At the second bridge, supplemental piles were placed adjacent to each existing pile. Though seemingly a more expensive option, when installed correctly, this method effectively restores the bridge substructure system to its original condition. Theoretically, the original piles would not require additional maintenance procedures and could progressively lose bearing capacity without any adverse effects on overall bridge performance.

At the third bridge, a cast system similar to that used in the first bridge was used to stiffen the pier piles, whereas at the abutment piles, timber planking was installed across the stream-side face of the piles and the created void between the planking and existing backwall was subsequently filled with concrete. This method, at a minimum, provides much greater protection to the piles from debris flows. Even more, the piles are reinforced in the transverse direction and, as such, may have a greater bearing capacity.

At the fourth bridge, a posting method of repair was used. One pile had been partially removed and replaced with a steel section extending from the sound portion of the existing pile near the ground surface to the pile cap. If installed correctly and proper bearing is achieved at the pile cap and existing pile, the method is quite adequate. One should note that only select piles in any one pile bent should be repaired using this method, as the lateral stiffness in the piles and, therefore, the bridge would be lost at the pile/post connection.

Following the completion of field testing of four Iowa bridges, details of new strengthening systems were developed with the purpose of creating or improving constructible and economical solutions to timber pile strengthening needs. Laboratory testing was completed for two of these solutions.

The first solution involved modifying the existing method of posting with a steel H-pile or the like. Field adjustment of the spliced portion can be necessary when not fabricated to exactly fit the removed portion of pile. A base plate and leveling bolts were implemented to allow for vertical adjustment at the connection between the existing timber pile and new steel post; the connection detail proved to be a promising solution.

The second strengthening system entailed adding steel “sisters” to a decayed or damaged pile. Each sister was bolted to the pile opposite of each other and extended beyond the simulated section loss. In the end, the “sisters” only aided in the strengthening when failure in the remaining portion of the pile was imminent, though it is assumed that modification to the connection details would engage the sisters earlier in the loading process.

The researchers provide the following recommendations regarding the assessment, preservation, repair, and rehabilitation of timber substructure elements.

- Utilize multiple methods to more accurately assess the condition of timber substructure elements including any or all of those previously mentioned in the summary.
- Make provisions for physically protecting timber structure elements from environmental conditions (e.g., precipitation), debris, and other damage-causing objects.
- Adhere to the AWPA Standards for the treatment and care of timber bridge elements.
- Be cognizant of applying preservative treatments to cut or fastened portions of timber substructure elements to avoid point of entry for biological decay mechanisms.
- When decay or damage is present, conduct maintenance activities at earliest possible stage to avoid increased cost associated with maintenance postponement.
- The addition of mild-steel reinforcement in the form of angles, channels, w-shapes, or similar has the ability to provide increased load capacity to mild or moderately decayed existing pile.
- Field adjustability can be achieved with few minor and relatively inexpensive parts when completing the posting method of repair.
- The current method of casting a single pile with corrugated steel pipe and concrete effectively restores the desired stiffness within the casted portion of the pile; this method has been used in numerous locations around the state of Iowa.

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