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Port Improvement via Exigent Repair (PIER) Joint Capability Technology Demonstration

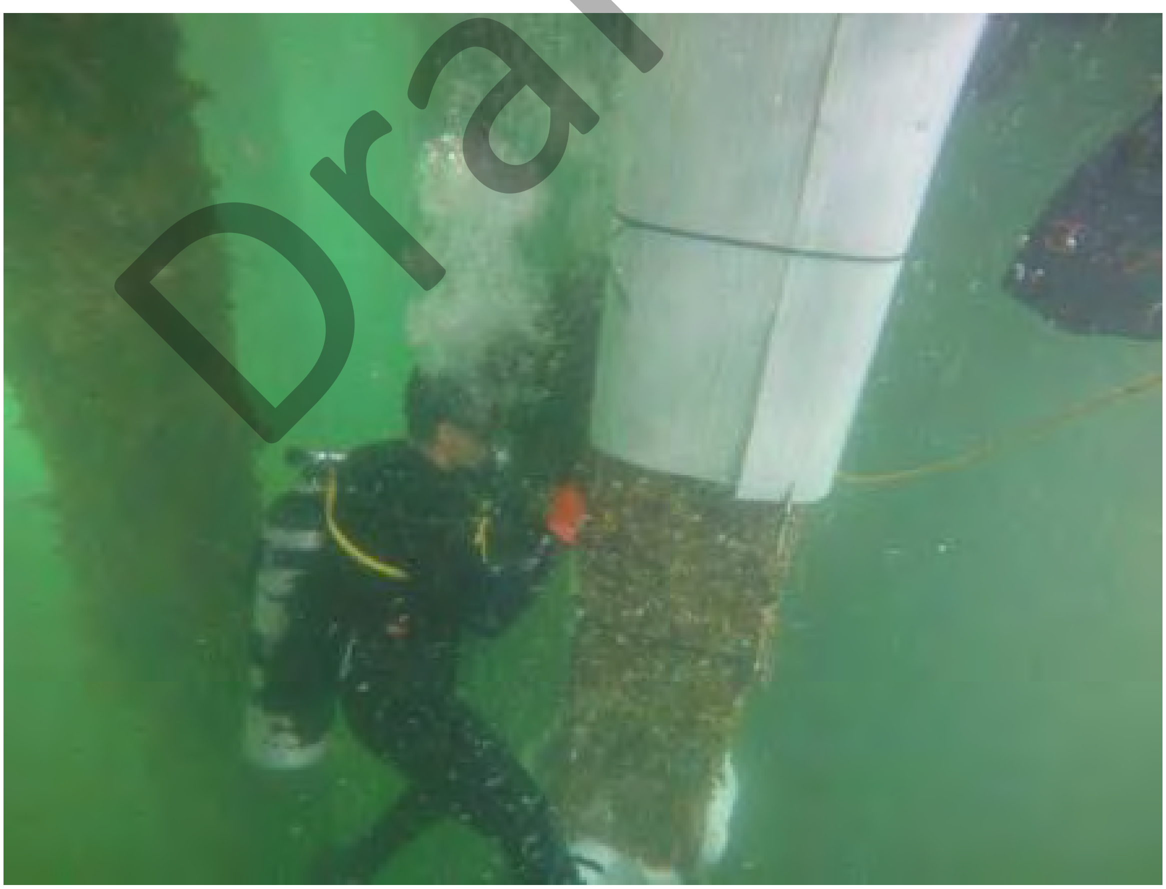
Pile Wrapping for Expedient Port Repair

PIER Spiral 1

Michael I. Hammons, Justin S. Strickler, John W. Murphy,
Christopher P. Rabalais, C. Kennan Crane, and Clint Barela

August 2018

Draft



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Pile Wrapping for Expedient Port Repair

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Interim report

Prepared for Deputy Assistant Secretary of Defense for Emerging Capability and Prototyping
Washington, DC

Under Port Improvement via Exigent Repair (PIER) Joint Capability Technology Demonstration (JCTD)

Abstract

Ensuring that critical load-bearing components of piers and wharves are competent to carry the required loads is an integral part of restoring damaged port infrastructure. The Port Improvement via Exigent Repair (PIER) Joint Capability Technology Demonstration (JCTD) identified and adapted a pile jacketing technology to expediently repair concrete or timber piles supporting piers, wharves, and other harbor structures. The materials and methods were identified from commercial off-the-shelf (COTS) technologies and adapted to enable warfighters to rapidly restore the pile axial capacity. The PileMedic® system by Quakewrap® was demonstrated to meet the axial capacity restoration requirements in an expeditionary environment as a capability complementary with current military engineering practices. Tactics, techniques, and procedures were developed and demonstrated to allow military divers to install the pile jackets in a manner compatible with current military engineering capabilities. Packaging kits were developed to aid in more efficient transport by military airlift or sealift. The related equipment and material for repair of damaged or degraded piles using pile jacketing technology, along with proposed tactics, techniques, and procedures, are an improvement over current pile repair processes. The pile jacket repair kits demonstrated significant capabilities for an efficient means to repair multiple damaged or degraded piles. Army and Navy repair teams were able to effectively apply the technology within the significantly shortened timeframe reflective of the project requirements. The capabilities demonstrated will result in the re-opening of a damaged or degraded pier/wharf much sooner than current military construction capabilities.

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Preface

This study was conducted for the Joint Capability Technology Demonstration Office as part of the Deputy Assistant Secretary of Defense (DASD), Emerging Capability & Prototyping (EC&P) Program, under the Port Improvement via Exigent Repair (PIER) Joint Capability Technology Demonstration (JCTD) Spiral 1 project. Mr. Thomas D. Cundiff was the Oversight Executive for DASD, EC&P. Dr. Michael I. Hammons of the U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL), was the Technical Manager.

The work was performed by the Geotechnical Engineering and Geosciences Branch (GEGB) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, ERDC-GSL. At the time of publication, Mr. Christopher G. Price was Chief, CEERD-GS-G; Mr. James L. Davis was Chief, GS; and Mr. Nicholas Boone, was Technical Director, Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Mr. Bartley P. Durst.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
ounces (mass)	0.02834952	kilograms
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

1 Introduction

1.1 Background

U.S. Indo-Pacific Command (USINDOPACOM) and U.S. Transportation Command (USTRANSCOM) share a common interest in countering anti-access and area-denial threats. A robust, organic capability to rapidly repair degraded ports in strategic locations presents U.S. adversaries with a more complex targeting problem while ensuring agile strategic logistics, namely the ability to discharge strategic sealift vessels at a time and place preferred by logistics planners.

The PIER JCTD was planned to develop, demonstrate, and transition robust, rapid, innovative repair capabilities for pilings, decking, and berthing facilities (pier-side/dockside mooring and fender system solutions only). The program was designed to result in a minimally capable, militarily strategic port. For the purposes of this JCTD, a minimally capable military strategic port is defined as one that will provide the ability to safely moor and offload/onload a non-combatant, strategic sealift vessel, including Large Medium Speed Roll-on/Roll-off vessels (LMSR), conducting operations via the stern ramp, side ramp and/or ship-board cranes as well as dedicated container vessels when employed in conjunction with a suitable crane ship.

The was conducted in four spirals with each of the spirals addressing a particular aspect of pier repair. Spiral 1 of the focused on adapting and demonstrating commercial off-the-shelf (COTS) pile jacketing technology as a capability complementary with current military engineering practices. Pile jackets are a pile repair technique used to restore pile capacity. Spiral 2 focused on development and demonstration of pre-engineered mechanical repair kits for degraded timber pier repairs. Spiral 3 designed, developed, and demonstrated an air-transportable, modular system to provide a roadway across the top of structurally inadequate pier sections facilitating vehicular and supply offload. Finally, Spiral 4 designed, developed, and demonstrated expedient hardware and methods to interface between the LMSR vessel hull and mooring lines and a rapidly repaired pier.

This report describes the activities conducted in PIER Spiral 1. The remaining three spirals will be addressed in subsequent reports.

1.2 Objective

PIER Spiral 1 addressed expedient repair of timber and concrete marine piles. The objective of the spiral was to identify and adapt a COTS pile jacket technology to restore axial capacity of the damaged or degraded piles. Structurally competent piles are required to support the operational loads from tracked and wheeled vehicles on the structure and, if necessary, the Pier Over-Decking System (PODS) of PIER JCTD Spiral 3. Repaired piles can provide capacity in an expeditious manner. The PIER technical team identified pile jackets as a method to restore pile capacity without the requirements for traditional pile installation methods. Installing new piles is not feasible because pile installation techniques require large construction equipment and would not meet the project objectives.

Evaluation of COTS technologies provided cost and time savings, meeting further project objectives. A reduction in development and testing costs resulted from Spiral 1 leveraging existing commercial experience and testing.

1.3 Approach

The approach for identifying and adapting the technologies was as follows. First, the PIER technical team identified and quantified the baseline technical requirements to be met by the pile jacketing technology. Second, market research was conducted through a formal Request for Information issued through the ERDC legal and contracting authorities. Third, a Request for Proposal was extended to interested vendors to demonstrate their pile jacketing technologies at an ERDC test site in a dry, controlled environment. Using the developed technical requirements, three proposals for demonstration candidate pile jacketing technologies were selected from a total of six vendor responses. These six technologies were representative of the expedient technologies available in the commercial market at the time. After evaluating these three technologies in a dry, controlled environment, the fourth step involved a further down-select to a single candidate technology to demonstrate in a Technical Demonstration (TD). The TD provided an opportunity for the PIER Integrated Management Team and other stakeholders to provide feedback and input. Feedback was incorporated into the training documents and technology by working with the pile jacket vendor. Fifth, the candidate pile jacket technology and associated tactics, techniques, and procedures (TTPs) were evaluated for military utility at a Limited Operational Utility Assessment (LOUA). Finally, Spiral 1 will be evaluated as part of a full Operational Utility Assessment with the other spirals of the PIER JCTD scheduled for Fiscal Year 2019.

2 Technical Requirements

2.1 Background

Damage to marine piles is related to a number of factors determined by the exposure conditions. These exposure conditions along the length of the pile can be categorized into three principal zones: submerged zone, slash zone, and atmospheric zone. The submerged zone refers to the part of the pile that remains continuously below the water surface during all tidal and surf conditions. Above the submerged zone is the splash zone, a region of the pile that is subjected to repeated wetting and drying in the course of tidal fluctuations and wave action. A simple definition of the splash zone is the area lying between the maximum and minimum water levels reached by the waves. This zone is particularly vulnerable to a variety of deterioration mechanisms because of repeated wetting and drying action. The atmospheric zone is that portion of the pile above the splash zone. Table 1 presents a summary of expected pile damage types for timber and concrete piles.

Table 1. Expected Marine Pile Damage

Mechanism	Type of Piles	Exposure Zone
Marine Organisms	Timber	Primarily in splash zone
Wood decay	Timber	Primarily in atmospheric zone
Frost attack	Concrete	Primarily in splash zone
Chemical attack	Concrete	Primarily in splash zone
Impact	Concrete or timber	Any zone

2.2 Pile Jacket Technical Evaluation Requirements

2.2.1 Criteria for Down Select

The term down-select is used in this report to describe the decision-making process leading to the selection of a particular method from the options investigated. The criteria used for the selection of the pile jacketing methods investigated are listed below. Discussion of how each pile jacket method meets the criteria is in more detail in Chapter 4.

The evaluation was divided into two criteria: 1) technical factors and 2) cost. The technical factors criteria were further divided into sub-factors. The technical sub-factors in order of importance were:

1) Ability to restore structural capacity;
2) Speed and ease of installation;

3) Low logistical requirements for tools and equipment;
4) Time from installation to capacity restoration;
5) Adaptability to piles of different sizes and shapes;
6) Ability to perform in seawater and freshwater applications;
7) Shelf life

The following sections provide greater detail about the criteria.

2.2.2 Restoration of Pile Capacity

The primary criterion for all evaluated pile methods was the ability to restore the axial pile capacity. This criterion was evaluated as a pass/fail. No explicit credit was given in the evaluation for increasing the pile capacity. Each method was evaluated based on supporting tests included with the technical information.

2.2.3 Speed and Ease of Installation

Pile jacketing methods were evaluated on how quickly a pile could be installed and the training or expertise required by the installers. The pile jacket methods were evaluated on the number and complexity of steps required to install. In addition, the equipment used to install the piles was evaluated. Methods using equipment intrinsic to underwater construction units were favored over those with additional equipment.

2.2.4 Time from Installation to Capacity Restoration

The time from installation of the pile jacket to the time all materials cured was evaluated.

2.2.5 Adaptability to Pile Sizes and Shapes

The pile jackets were evaluated on their ability to adapt to piles of various sizes and shapes. Pile jackets with hard shells have limited flexibility. These shells are less able to adapt between pile shapes and sizes without compromising the speed of installation or capacity requirements. Adaptability of pile jackets improves opportunities to field-fit pile jackets. Adaptable and flexible pile jackets do not require storing or shipping per-sized pile wraps of different shapes and dimensions.

2.2.6 Ability to Perform in Freshwater and Seawater Applications

The pile jackets must have the ability to be installed in both freshwater and seawater applications.

2.2.7 Shelf Life and Storage

The shelf life of each component for each pile jacket method was considered. Each system was evaluated based on the shelf life of individual components of the system. In addition, pile jackets which use the same wrap for many pile sizes eliminates the need to store pile wraps of different sizes simplifying storage requirements.

2.2.8 Cost

The final criterion considered was the cost of the product. The costs were compared to typical ranges for pile jackets.

2.3 Required Military Unit Capabilities and Equipment

Spiral 1 assumed the military unit charged with installing pile jackets is capable of underwater construction and thus has training, equipment, and skills related to construction and repair of structures in a marine environment. Foremost, the unit must have dive capabilities. Beyond this basic requirement, it is assumed that the team has access to all the equipment in the Table of Allowances (TOA) for the underwater construction team. Any equipment or tools required to install the pile jackets beyond the TOA will be provided in the pile jacket kits.

3 Market Research and Product Evaluation

3.1 Pile Jackets

3.1.1 Pile Jacket Background

Pile jackets are used to repair and protect piles. In this report the term pile jacket refers to the entire system or method. The pile jacket system requires multiple components to achieve the desired result.

Marine piles are designed to function as columns carrying axial compressive forces. Bending moments in piles are secondary and do not dominate the pile capacity except in the case where piles are used as fenders to resist contact forces from a moored vessel.

Spiral 1 focuses on pile jacket repair (i.e., capacity restoration) of timber and concrete piles. Two components must be in place to restore pile capacity: a wrap and an annular filler material. The purpose of the wrap is to provide lateral confinement to the filler material which is emplaced in the annular space between the pile and wrap. The effective confinement provided by the wrap allows the compressive load in the retrofitted pile to be safely resisted by the composite pile/jacket system. For purposes of this study, the objective was to restore the pile to its original working load capacity.

Other components common to jackets include those components which aide in installation and components to increase the service life of the pile and/or repair.

3.1.2 Pile Jacket Components

3.1.2.1 Pile Wraps

Pile jackets are typically made from high density polyethylene (HDPE) and fibers encased in polymers or resins. Carbon fiber and fiberglass are common fibers used in pile jackets. The polymers and resins are either pre-cured, which encases the fibers during manufacture, or the wraps are cured after installation. Pre-cured methods create laminated sheets or shells. Fibers can also be impregnated with water activated resin. The pre-impregnated wraps are cured after being exposed to water during installation.

The wraps must be connected following installation around the pile. The two major forms of connection are epoxied overlaps and mechanical connections.

3.1.2.2 Annular Space Fill

Grouts are the most common fill materials for the annular space. The grouting materials are either a Portland cement binder or an epoxy binder. The grout is either pumped into the annular space through a port installed through the wrap or placed through the top of the jacket using a tremie method.

3.1.2.3 Pile Wrap Spacers

Pile jacket spacers make installation easier by keeping a consistent annular space on all sides of the pile. Keeping the jacket centered on the pile reduces eccentricities reduces eccentricities potentially impacting efficacy of the repair. The spacers vary between the methods but commonly consist of plastic angles or wooden blocks.

3.1.2.4 Bottom Seals

A bottom seal is installed to prevent the grout filler from falling out of the base of the pile jacket during filling. In most applications, the pile jacket is embedded into the mudline to protect the entire pile length. The soil which fills the annulus at the base of the jacket by embedment forms a seal preventing leaks or blowouts. Spiral 1 repairs are expected to target discrete lengths of pile damage making the use of an expedient bottom seal a requirement. Sealing the bottom of different shaped piles is one of the greatest challenges of pile jacketing. The bottom seals demonstrated during Spiral 1 consisted of appended formwork, plastic skirts, and foam (both pre-formed and polyurethane soaked oakum).

3.1.2.5 Extension of Service Life

Components and methods to extend the long-term service life of the pile are removing marine growth and sealing the pile with the pile wrap. Removing marine growth by cleaning the pile thoroughly prevents further long-term damage. Sealing the piles protects the pile and jacket from further damage or deterioration. Where possible, unnecessary steps and components were removed for Spiral 1. The only pile cleaning requirement for Spiral 1 was to remove any loose material from the piles with scrapers or water pressure. This level of cleaning ensures the pile jacket repair is in solid contact with the pile. Deep cleaning to remove all marine growth was unnecessary to extend the service life of the piles. The goals of the expedient expeditionary repair for Spiral 1 required only a 90 to 180 day service life.

3.1.2.6 Flexural Strength

The pile repair methods evaluated during the market research allow for rebar to be installed prior to installing the jacket. Adding rebar increases the pile capacity. Adding rebar was not considered for Spiral 1 because the focus was on restoring capacity up to the original pile capacity. Thus, installing rebar was not needed to meet this requirement.

3.2 Product Evaluation

Spiral 1 received six responses to a Request for Proposal to demonstrate pile jacket technologies. The responses were evaluated on the criteria listed in Chapter 2. The six respondents were:

A) Structural Assurance
B) University of Illinois - Champagne-Urbana
C) QuakeWrap® - PileMedic® PileMedic was the only product selected for extensive testing!
D) PileJax™
E) Five Star® Products
F) Simpson Strong-Tie

A brief description of each technology is presented in the following sections.

3.2.1 Structural Assurance – CDG Pile Jacket System

The CDG Pile System utilizes pre-cured fiber reinforced composite jackets. The jackets are pre-formed around steel mandrels in a controlled manufacturing facility in order to obtain their designed diameter and length. Once cured the jackets are slit lengthwise to allow placement around existing circular piles. It can be used with both timber and concrete piles.

3.2.2 University of Illinois Champagne- Urbana – Shape Memory Alloys

The proposed technology involves wrapping the piles with pre-stressed spiral made of unique metallic material known as Shape Memory Alloys (SMA). SMA spirals can be easily pre-stressed in the field using temperature (flame torch or electrical resistivity). The high active" confinement pressure applied on the piles by the pre-stressed spirals will restore both strength and ductility of the damaged/deteriorated piles.

Tests conducted on behalf of the vendor have indicated that the proposed "active" confinement using SMAs is superior to conventional "passive" confinement technique using fiber reinforced polymer (FRP) sheets. It can be used with both timber and concrete piles.

3.2.3 QuakeWrap® - PileMedic®

PileMedic® is a rapid structural repair system for marine piles, bridge piles, timber piles, and bridge columns. It features FRP laminate sheets manufactured with specially-designed equipment. Sheets of carbon or glass fabric up to 5-ft wide are saturated with resin and passed through a press that applies uniform heat and pressure to produce the laminate. One of the salient features of the system is that the FRP is supplied in rolls, which allows the user to cut the FRP wrap to the required length, allowing it to be adapted to fit piles of various cross-sectional shapes. The wraps are bonded with a water-resistant epoxy to form a shell which provides confinement to a grout placed in the annular space between the wrap and the pile. It can be used with both timber and concrete piles.

3.2.4 PileJax™

The engineered PileJax™ system provides a complete repair method. The proprietary systems are adaptable and suitable for installation onto timber and concrete (and steel) pile infrastructure in freshwater and saltwater environments.

Manufactured from lightweight glass fiber reinforced polymer materials, the PileJax™ jackets can be maneuvered into position by one or two persons. This jacket type also provides ease of maneuverability in tight and limited underside workspaces both above and below waterline. The speed and ease of installation is enabled by the proprietary Joinlox axial joint which provides a simple and fast jacketing method to install onto mid-pile/splash zone pile positions in a matter of minutes. The PileJax™ jackets are versatile and fully adaptable and compatible with a range of epoxy and cementitious grouts that can be pumped directly into the annular space created by the PileJax™ jackets via pumping ports incorporated into the jackets. This method ensures fast and reliable encapsulation of the damaged pile to provide protection and strength.

3.2.5 FiveStar™ – PileForm™ Fiberglass Reinforced Plastic

Five Star™ PileForm™ F FRP pile rehabilitation jackets meet and exceed marine engineering specifications for use in hostile marine environments where exposure to ice, floating debris, chemical pollution, oils, acids, salt water and ctidal action may occur. Five Star® PileForm™ F jackets are available in translucent or may be gel coated to any specified color.

PileForm™ F fiberglass pile jackets are manufactured in 1-ft to 20-ft long sections with wall thickness up to 1/2 in as required; custom sizes outside these ranges are available.

3.2.6 Simpson Strong-Tie – F70X

Each FX-70 high-strength fiberglass interlocking jacket is custom-made to the precise specifications of the repair project. Hand-made and assembled in the U.S., the FX-70 tongue-and-groove seamed jacket provides a corrosion-resistant protective shell and is available in round, square, H-pile and octagonal shapes. Panels and custom shapes are also available for additional applications such as pile foundations and seawalls.

3.3 First Down-Select of Pile Jacket Technology

The six proposals were evaluated by a team of engineers. Three technologies met the technical and cost criteria. The three pile jacket methods selected for technical testing were: PileJax™, PileMedic®, and Simpson Strong-Tie.

3.4 Pile Jacket Vendor Exhibitions

The three pile jacket methods advanced from the market research phase were invited to exhibit their technologies to the Spiral 1 team. Each vendor was asked to install their technologies on three piles. One of the three piles was a 10-ft-tall, 10-in-square reinforced concrete pile. The concrete pile was cast with the middle 4 ft of concrete missing. This simulated complete deterioration of the concrete leaving only exposed rebar. The other two piles were nominal 8-in-diameter round timber piles, the first timber pile was cut into two stubs. The two stubs were separated representing an extreme case of complete deterioration. The second timber pile was tapered into an hourglass shape representing a typical deterioration profile near the waterline.

The vendors installed their repairs in the dry (instead of partially submerged). There was no time limit for the repair methods, and the vendors interacted with the PIER technical team during installation.

3.5 Second Down-select of Pile Jacket Methods

Following vendor exhibitions, the Spiral 1 team selected PileMedic® to return for a technical demonstration. The primary reason this vendor was selected was because this jacket had the greatest adaptability to piles of different shapes and sizes. The FRP laminate rolls were also more compact than larger shell methods and thus more amenable to shipping on military 463L pallets.

PileMedic® also met the criteria for structural capacity restoration, speed and ease of installation; time from installation to reaching capacity, adaptability to freshwater and seawater environments, and shelf life. As a result of the demonstrations, the Spiral 1 technical team requested that PileMedic® improve their method sealing the bottom of the repair (improved skirt) and provide improved spacers for enforcing the annular space between the pile and wrap.

4 Technical Demonstration

4.1 Purpose

A TD was held at ERDC in Vicksburg, Mississippi on 26 Oct 2016 to demonstrate the state of COTS technology for expedient pile repair to the PIER Integration Management Team and other interested stakeholders. To demonstrate the technology, divers from the ERDC Coastal Hydraulics Laboratory (CHL) installed the PileMedic® product per the draft TTPs on three piles in a simulated marine environment. In addition, the TD included an axial load test showing the capacity of a jacketed pile.

The TD also served as an opportunity to develop training methods; evaluate tactics, techniques, and procedures (TTPs); and solicit feedback from soldiers and sailors with experience in underwater construction.

4.2 Demonstration Layout

The Spiral 1 TD was conducted in a concrete basin/sump facility in a hanger belonging to the CHL. The top of each pile was secured to a steel rack. The base of each pile rested on a concrete-filled drum. The TD used a similar three pile setup as the vendor exhibitions: two hour-glassed 8-in-diameter timber piles were provided. A third pile, consisting of a 10-in-square reinforced concrete pile with a section of missing concrete, was provided. The basin was partially filled with water covering a portion of the damaged section. The water depth was sufficient to preclude divers from standing on the bottom of the sump while effecting repairs.

4.3 Training

The steps involved in completing a pile repair using PileMedic® pile jackets are summarized in the following TTPs:

1. Clean the surface of the pile using scrapers or pressure wash to remove marine growth. This was not required for the TD test piles, because they were already clean.

2. Install spacers around the pile to separate pile jacket from the pile creating annulus for inserting grout.

3. Measure pile jacket and cut jacket. Calculate length required for a double wrap of pile plus 8 to 10 in extra.

4. Spread underwater epoxy on measured and cut pile jacket. The epoxy is the structural connection allowing the FRP laminate to develop the hoop or confining stress around the pile. Epoxy is not applied to the first wrap portion of FRP laminate in contact with pile. It is placed on the second wrap portion leaving room for the divers' hands to hold edge during pile wrap process.

5. Wrap the pile jacket around the pile. Divers and a surface support person work in tandem to wrap the pile jacket around the pile. Zip ties or straps are used every 6 in to 12 in to hold the jacket diameter in place as the epoxy cures.

6. Install bottom seal and skirt at the bottom of the pile jacket to prevent grout from leaking out or blowing out once pumped into the pile jacket annulus. During TD, divers used semi-rigid foam placed inside around the bottom of the pile jacket to help form a seal.

7. Mix and pump grout into pile jacket. During TD, mixing was accomplished using a bucket and power drill method. Pumping of the grout was accomplished using a manually operated grout pump.

8. Quality assurance / quality control of the repair is performed by divers tapping and/or shining a flashlight through the FRP laminate to check for voids in the grout.

9. Curing time of the grout is dependent on choice of grout and environmental conditions.

Training followed a crawl, walk, run approach. The ERDC divers had limited to no construction diving experience and had never installed pile jackets prior to the TD. Training began with the crawl phase two days before the TD. The dive team learned about the pile jacket and watched Quakewrap® representatives install jackets on three piles in the dry on a rack made for dry-side training (Figure 1). Next the ERDC dive team installed jackets on the dry piles under the supervision of the Quakewrap® representatives. For the walk phase of the training, the ERDC divers installed the pile jackets on a rack in the water using the same three pile setup as they would for the TD. The rack was placed in the sump, which was flooded to simulate field conditions (Figure 2). The learning curve for handling the FRP laminate wrap in the water was steep. After practicing and modifying the approach, the ERDC dive team learned to handle the FRP laminates and wrap the piles efficiently. After completing two days of training and practicing with the FRP laminates in the sump, the ERDC divers were competent to place the wraps during the TD.

Figure 1. Dry training rack

Figure 2. ERDC divers train on wrap installation in the flooded sump

4.4 Equipment and Materials

The technology demonstrated consisted of a kitted solution that included the pile wrap, underwater resin, spacers, skirts, Portland cement grout, and group pumps. The components of PileMedic® product are illustrated in Figure 3.

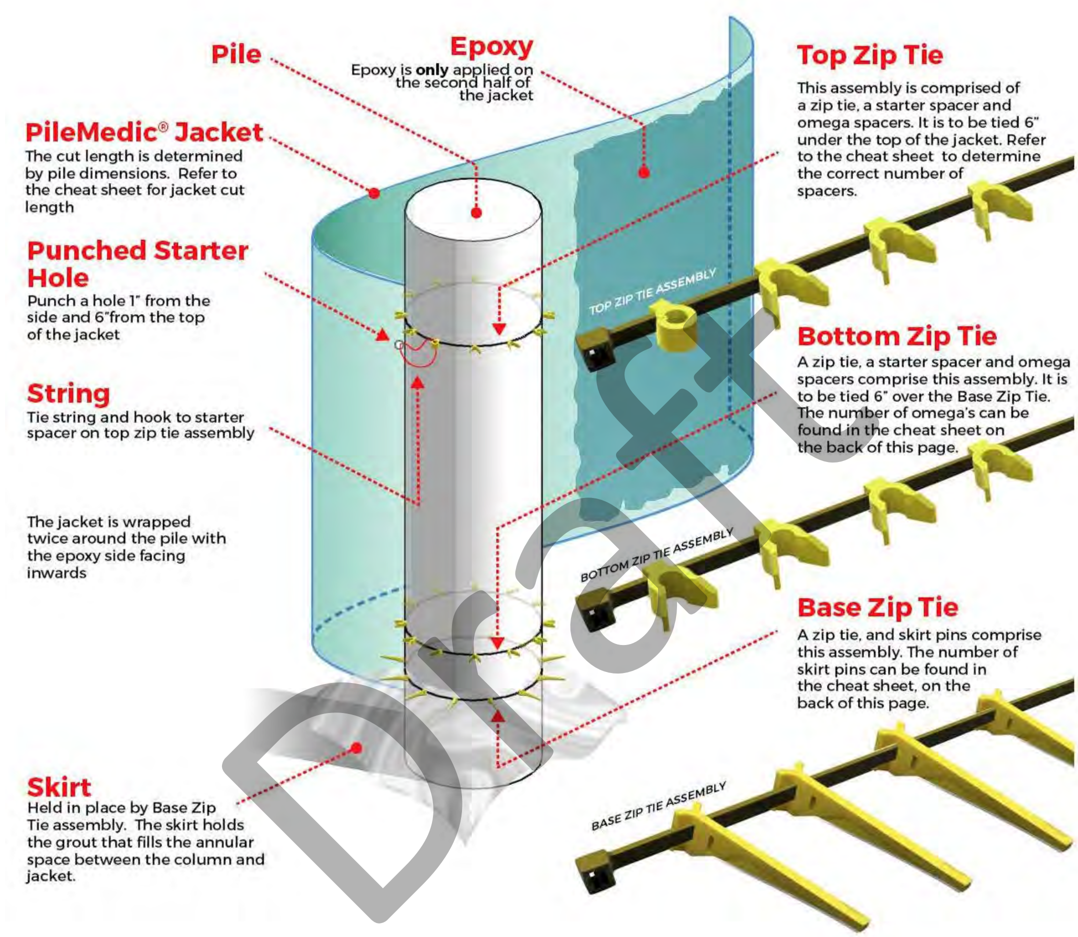

Figure 3. PileMedic® wrap system components

The primary component of the kit consisted of the patented PileMedic® technology solution for timber and concrete pile restoration developed and manufactured by QuakeWrap, Inc. of Tucson, Arizona. PileMedic® includes PileMedic® Fiber Reinforced Polymer (FRP) laminate sheets, QuakeBond® Underwater Epoxy Resin, Spacers, and Rigid Foam Base Insert and Skirt. The PileMedic® solution is a commercial-off-the-shelf (COTS) product that was modified by the manufacturer to better meet the needs of the military. Specifically, each PileMedic® kit included the following components:

- Roll of PileMedic® PLG60.60 FRP Laminate Sheet
- QuakeBond® 220UR Underwater Resin (epoxy) cartridges
- Underwater grout additive to minimize washout underwater
- Foam for sealing
- Skirt for sealing base of the repair
- Gloves for safety in handling epoxy
- String
- Static mixers for the epoxy cartridges
- Putty knives
- Starter spacers
- Corner spacers
- Skirt pins
- Omega spacers
- Marker
- Measuring tape
- Zip ties
- Duct tape
- Shrink wrap

Additionally, a PileMedic® tool kit was supplied with the following components to enable the repair process:

- A pneumatic-powered cartridge gun for epoxy cartridges
- Electric drill
- Shears
- Vise grip
- Mixing paddle
- A manual epoxy cartridge gun

The PileMedic® PLG60.60 FRP Laminate Sheets are 0.026 in thick and are packaged in 4 ft by 150 ft rolls as shown in Figure 4. The FRP bidirectional glass laminate contains orthogonal fibers in two directions (longitudinal and transverse to the roll). The sheets are wrapped around the pile two or more times to create a mutiple-ply impervious shell providing confinement to the filler material which is subsequently placed in the annular space between the pile and the liner. A significant advantage of the rolled FRP material is that it can be universally applied to piles of various cross-sectional shapes (round, square, rectangular, octagonal, etc.) with minimal impact on installation technique. Also, the FRP can be cut to desired lengths to wrap piles of various sizes. When the length of the repair exceeds 4 ft, the pile jacket segments are overlapped a minimum of 4 in to create a double or triple wrap to extend the repair to as much as approximately 11 ft in length.

Figure 4. FRP standard roll (4 ft by 150 ft)

The QuakeBond® 220UR Underwater Resin, shown in Figure 5, is a two-component, high-strength, structural epoxy for underwater application. It is used to bond the PileMedic® PLG60.60 FRP Laminate Sheet to itself to create an impervious shell. It is also used in double and triple wraps to form an overlapped watertight joint. The epoxy can be mixed and dispensed onto the laminate sheet either through use of a manual or pneumatic epoxy cartridge dispenser (Figure 6).

Figure 5. Two-part epoxy adhesive used to bond FRP wraps

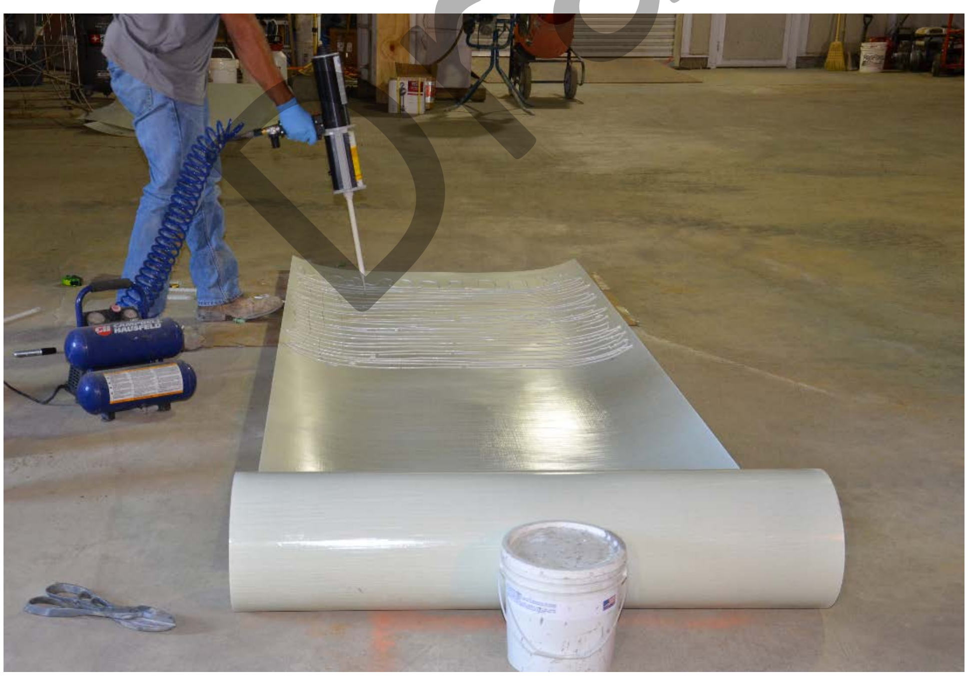

Figure 6. Applying epoxy to wrap using pneumatic dispenser gun

Spacers are placed on piles to create a uniform annulus for grouting (Figure 7). The annular spacer size can be adjusted to optimize the volume of grout required for the repair. Different spacers were provided for round versus rectangular (and square) column cross-sections. This duplicity was later found to be unnecessary, and a single spacer could be designed to accommodate both circular and rectangular cross-sections. A semi-rigid foam insert and polyurethane skirt (Figure 8) are installed at the bottom of the pile jacket to prevent grout from leaking or blowing out. This skirt system was shown in later trials to be a source of grout leakage and was modified to improve grout retention. Zip ties are placed around the PileMedic® PLG60.60 FRP Laminate Sheet before grout is pumped into the form and remain in place as the grout cures.

Figure 7. Annular spacers are placed on piles to ensure jacket standoff from pile

Figure 8. FRP jacket lifted to reveal foam insert and skirt

The PileMedic® system can use Portland cement grout or epoxy resin grout as fill. For the demonstration, a readily available pre-packaged commercial Portland cement grout (Quikrete Commercial Grade Grout) was used (Figure 9). This material was mixed with tap water according to the Quickcrete's specifications and pumped into the annular space between the pile and the FRP liner using a tremie method (grout is pumped into the top and the annular opening and allowed to settle into the annular space from the bottom upwards). Later demonstrations and assessment would reveal that this method can result in voids within the grout column. The grout was mixed in 5-gal buckets using a hand-held air-powered drill motor to power a small mixer paddle.

Figure 9. A commercial, non-shrink grout product was used

4.5 Installation during the TD

The ERDC dive team began the TD by wrapping 1.5-in-long plastic spacers around the first 8-in-diameter circular timber pile. For the square concrete pile, ½-in-long spacers were placed at the corners.

While this was taking place, topside support personnel measured and cut the pile jacket FRP laminate to the proper length. The required length to properly wrap a cylindrical timber pile for repair calls for a double wrap of the pile plus 10 in. extra FRP laminate. The equation to calculate the pile jacket length needed for the 8-in-diameter timber pile with 1.5-in. spacers in place is $[(8 + 3) * \pi * 2)] + 10 = 80$ in. pile jacket length required. Next came the application of the two-component QuakeBond™ 220UR Underwater Epoxy to the pile jacket using a small portable air compressor to mix and dispense the underwater epoxy.

The prepared pile jacket was then transferred to the divers and placed around the pile as shown in Figure 10. Once the pile was wrapped, it was secured in place with zip ties to allow the epoxy to cure.

Figure 10. Divers place wrap on pile

Next, the divers installed a bottom seal and skirt at the bottom of the pile jacket to prevent grout from leaking or blowing out. During the TD, the divers used semi-rigid foam placed inside the bottom of the pile jacket to help form the bottom seal instead of oakum line which was used in practice the day before. These steps were repeated for the 10 in by 10 in concrete pile and the remaining timber pile. Approximately 20 minutes was required per pile to prepare the pile jacket to receive grout.

While each pile in the TD was wrapped, topside support personnel began mixing the commercially available cementitious non-shrink grout using a hand drill, potable water, buckets, and an anti-washout additive. A concrete hand pump was then used (Figure 11) to pump the grout through a hose to fill the annular space around each pile (Figure 12). Hand pumping of the grout into the three pile jackets began at the 1-hour mark into the TD. As the grout filled each pile jacket, water was displaced out the top of the pile jacket. Pumping of grout into each pile jacket was stopped once the grout reached the top of the jackets. Shortly after grout had been placed in the pile jacket surrounding the concrete pile, a leak from the bottom seal developed. Divers had to re-do the bottom seal and conduct an additional grout filling evolution. TD repairs on the three test piles were declared complete at two hours and 24 minutes into the demonstration.

Figure 11. Hand pump used for grouting during the TD

Figure 12. Placing grout in prepared jacket

4.6 Findings

The primary findings from the TD were:

- The bottom seals (foam and skirt) need improvement. The divers had difficulty installing the skirts and sealing the base of the piles to prevent leakage of grout. After continued practice, sealing the round timber piles became easier. Difficulty sealing the annular space between square concrete piles and round FRP laminate jacket led to multiple grout blowouts.

- Construction divers with no experience with the system can be trained in a period of three days or less to install the PileMedic® system.

- The pile jackets were installed at a rate of one per hour. This informed the planning factor for the LOUA.

- The axial load test demonstrated the axial capacity restoration for a jacketed pile was achieved within 48 hours from installation.

5 Component Testing

5.1 Background

This chapter summarizes the testing and results completed to validate the restoration of axial capacity and investigation of the flexural capacity of jacketed piles. The Spiral 1 Technical Team identified the need to validate the axial capacity restoration published by the manufacturer. In addition, the Spiral 1 team identified the need to study the flexural capacity of the pile repairs. The main reason flexural tests were included along with axial tests is that, typically, the axial response of the column is largely governed by the eccentricity of the load, which causes flexural loading in the columns. Tests reported in the recent literature (Menkulasi, Baghi, & Farzana, 2017) (Mohammadi, Gull, Taghinezhad, & Azizna, 2014), (Yang, Sneed, Saiidi, Belarbi, & Eshani, 2015) displayed pure axial capacity restoration, but many of the failures occurred in the end-regions due to support conditions rather than column capacity. Tests on flexural capacity were performed to further demonstrate the repair capabilities. Large-eccentricity axial loading was considered, but dismissed due to safety concerns and potential damage to the loading actuator caused by large bending moments.

These technical tests were conducted on the ERDC GSL's Structural Test Floor located in Building 6000 at the ERDC Vicksburg site. The following section details the portions of the testing setup including the test frame and supports, test specimens and their specific installation, and instrumentation.

5.2 Test Specimens

Two different types of piles were tested for this program. One set of piles was constructed of concrete; the other of timber. Each of these is described in this section.

5.2.1 Timber Piles

The timber pile under consideration in this test series was a 10-ft long, 8-in. diameter round Southern Yellow Pine pile. These piles have been treated with Chromated Copper Arsenate Type C (CCA-C) to slow degradation and are intended for Use Category UC5C (Marine use in Southern waters). Four variants of timber piles were used: control, tapered, dry-retrofitted, and wet-retrofitted.

The control timber tests were used to verify the capacity of an 8-in.-diameter round pile with constant cross section. The capacity was compared to the design capacity calculated from the *National Design Specification for Wood Construction* (American Wood Council, 2015).

The tapered pile test determined the capacity of an 8-in.-diameter round column that had been tapered to a diameter of 5 in. (Figure 13). The taper is approximately 36 in. long and is in the center of the pile. This taper is intended to represent in situ timber section loss due to mechanical or biological deterioration.

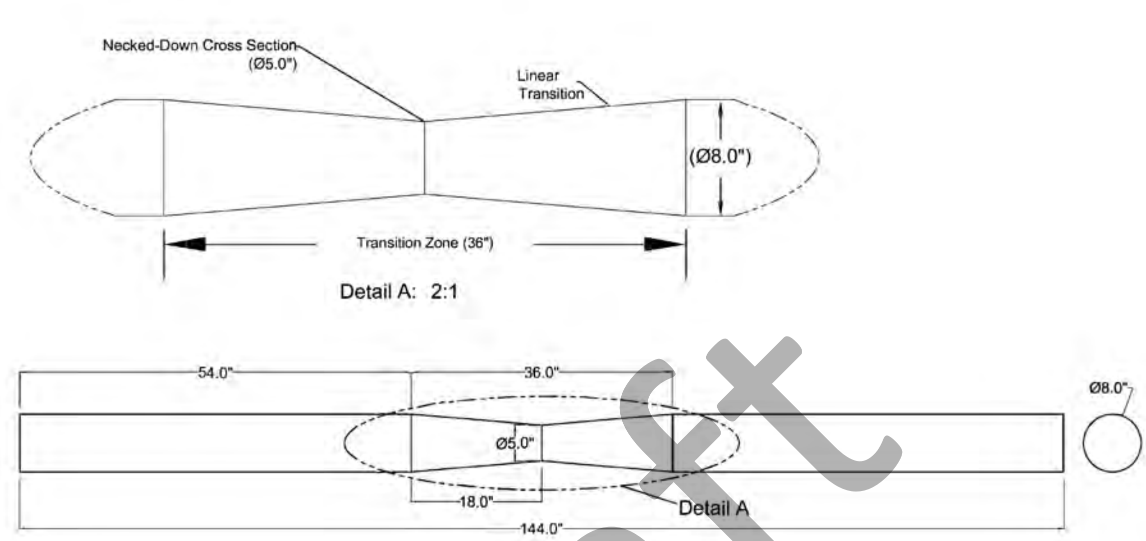

Figure 13. Schematic of tapered timber pile

Selected tapered piles were retrofitted through the area of reduced cross section. This retrofit mimics rapid field retrofit of pier columns. One set of tapered columns was retrofitted under dry conditions. These dry repairs mimic retrofits of above-water piles. The other set of tapered piles was retrofitted while fully submerged under water. These wet repairs mimic retrofits of below-water piles.

5.2.2 Concrete Piles

The concrete piles tested in this test series consisted of a 10-ft long, 10-in. x 10-in. rectangular pile. The design 28-day unconfined concrete compressive strength (f'c) for the concrete was 5,000 psi. These columns are longitudinally reinforced with four No. 8 rebar and transversely reinforced with No. 4 stirrups at 12 in. on center. All reinforcing bars were Grade 60. Figure 14 shows the rebar layout for the concrete piles.

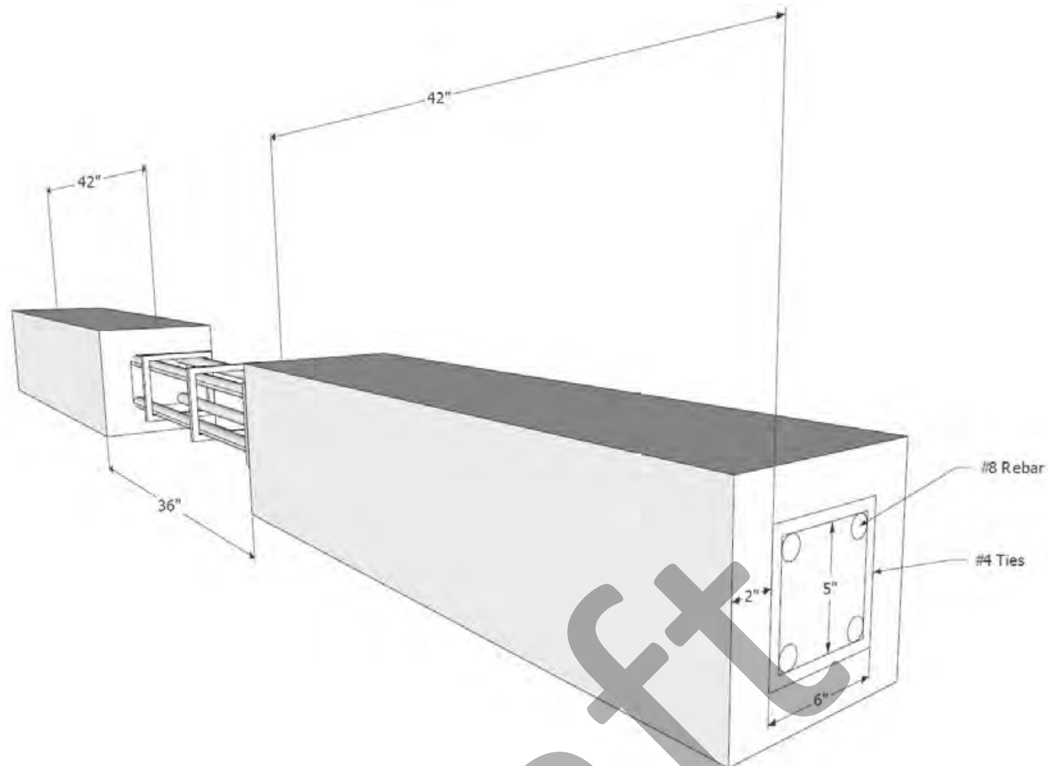

Figure 14. Schematic of concrete pile prepared for retrofit

Three variants of concrete piles were used: control, dry-retrofitted, and wet-retrofitted. The control test will verify the capacity of a 10-in. x 10-in. square column that is 10-ft in length. The capacity was compared to the design capacity calculated from The American Concrete Institute (ACI) ACI 318-14 *Building Code Requirements for Structural Concrete* (The American Concrete Institute, 2014).

The retrofits were performed on columns that are missing 36 in. of concrete at their center as shown in Figure 14. This represents an area that has experienced severe damage to the concrete, and the damaged concrete has been removed to prepare for retrofit. The reinforcing bars are continuous through this section representing reinforcing bars that have been cleaned and are in good condition. Like the timber columns, one set of columns was retrofitted under dry conditions, mimicking retrofits of above-water pier columns, and the other set of columns was retrofitted while fully submerged under water mimicking retrofits of below-water pier columns.

5.3 Test Frame and Load Supports

5.3.1 Test Frame

The loading frame on the GSL Structural Test Floor is a system of large structural steel I-beams capable of resisting at least 600,000 lbf from a hydraulic actuator. The base of the system is made of four separate L-shaped supports made of steel I-beams with internal stiffeners and diagonal bracing. The supports can be moved into various configurations using an overhead crane. Figure 15 shows an I-beam support being moved into position for lowering onto the strong floor. High-strength steel threaded bars are welded to the base of each beam so that the support can be fastened to the strong floor. The rods are secured by installing nuts under the strong floor, as shown in Figure 16.

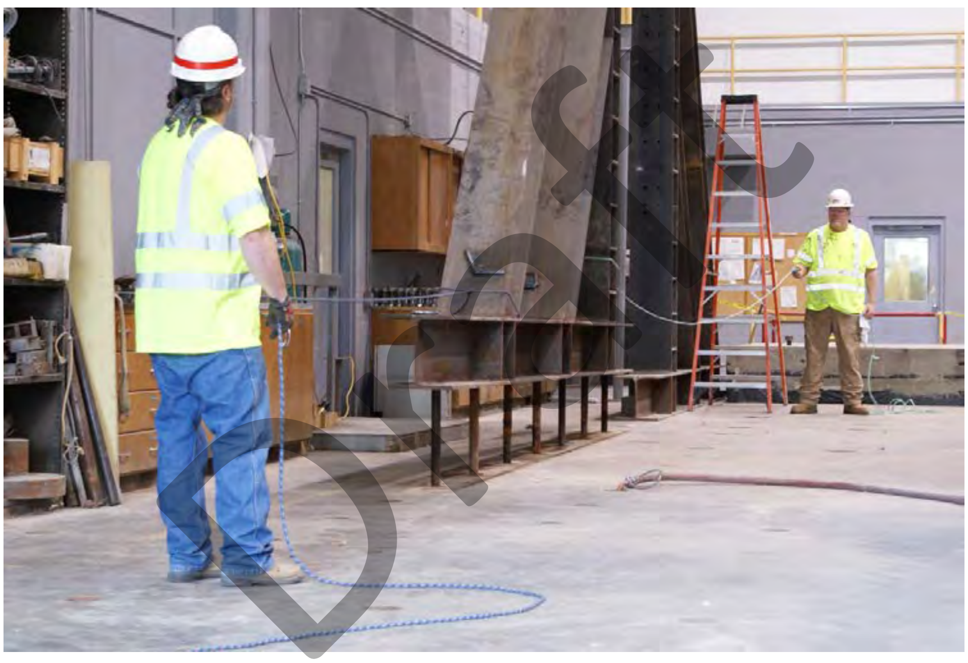

Figure 15. Placing of I-beam supports with threaded bars protruding into strong floor

Figure 16. Tightening of nuts and securing the support to the strong floor

The supports are connected to each other by two steel beams (stabilizing beams) bolted to the very top of the supports, as shown in Figure 17, and two larger beams running perpendicular to the stabilizing beams (loading beams) bolted mid-way down the support height. The hydraulic actuator is attached to one final beam which connects the two loading beams as shown in Figure 18.

5.3.2 Base Loading Support

A movable bearing surface was required to adjust the columns and beams to assure they were properly aligned and had uniform loading applied by the actuator. A 2-in.-thick by 10-ft by 8-ft steel plate was used as the base for this series of tests. Enlarged holes allowed for adjustment of the base plate on the test floor. The base plate was secured to the strong floor using similar methods as the test frame. Figure 19 shows the base plate installed on the strong floor. A “knife-edge” support, fabricated of hardened steel, was welded at the midpoint of the plate to serve as a pivot point. An initial eccentricity was built in for two reasons: first, to induce a bending moment along with the axial load and secondly, to ensure failure occurred in a known direction for safety reasons. The knife is square bar stock 2-in. wide by 12-in. in length. One side of the edge was machined flat, as shown in Figure 20, so that when it was welded to the base plate the vertical height of the knife-edge was 2 in. This knife-edge prevents translation of the column bottom during testing while still allowing for rotation.

Figure 17. Stabilizer beams on top of the supports

Figure 18. Loading beams installed with actuator

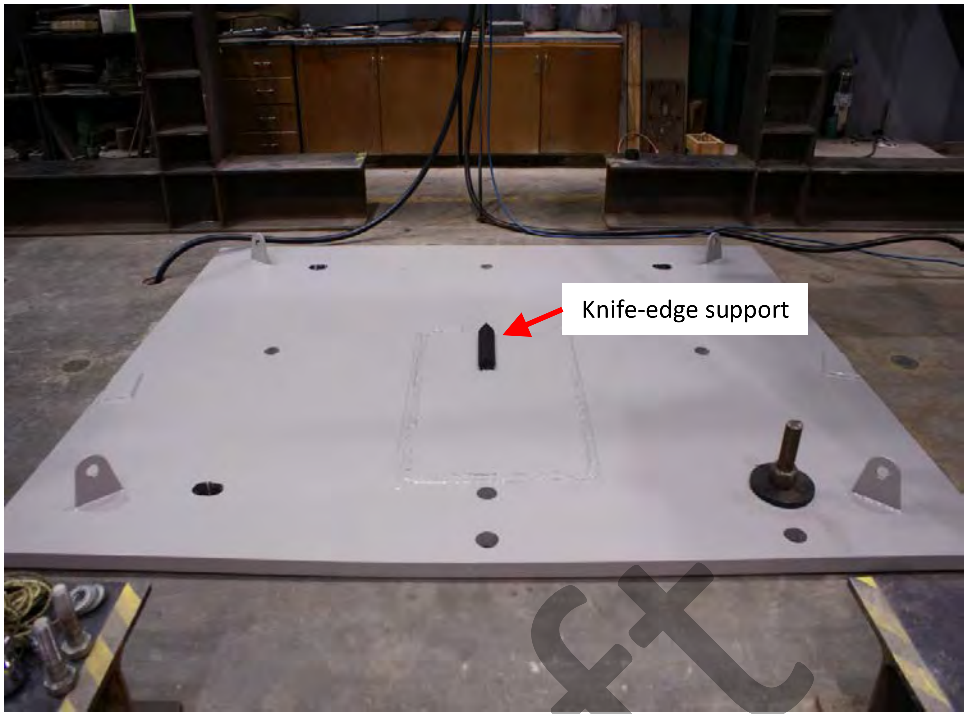

Figure 19. Base plate with knife-edge support attached to strong floor

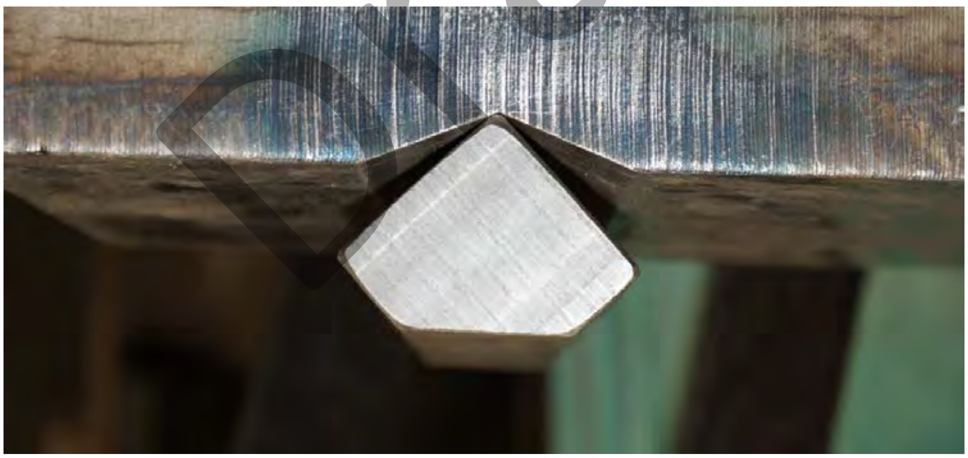

Figure 20. Knife-edge support and channel on bottom base plate

5.3.3 Hydraulic Actuator Assembly

The timber and concrete piles were tested to failure as a column in axial compression (with eccentricity to induce a bending moment) or as a beam in 4-point bending (placing the section of the beam between the load points in a state of zero shear and constant bending moment). The compression or bending load was applied via an MTS 243.90T Hydraulic Actuator with a 600,000 lbf compression capacity and a 20-in. maximum stroke length. As shown in Figure 21, the actuator was attached to the steel frame discussed in Section 5.3.1. A load pin and load pin clevis were used to transfer load from the actuator to the top column end cap. The clevis eye was threaded into the actuator ram, shown in Figure 22, and connected to the clevis with an instrumented load pin. The clevis only allows rotation about the axis of load pin and is oriented to allow rotation in the same axis as the column rotation/rocking about the knife-edge support, limiting buckling to a predetermined plane to protect the testing frame and other equipment should sudden, catastrophic failure occur.

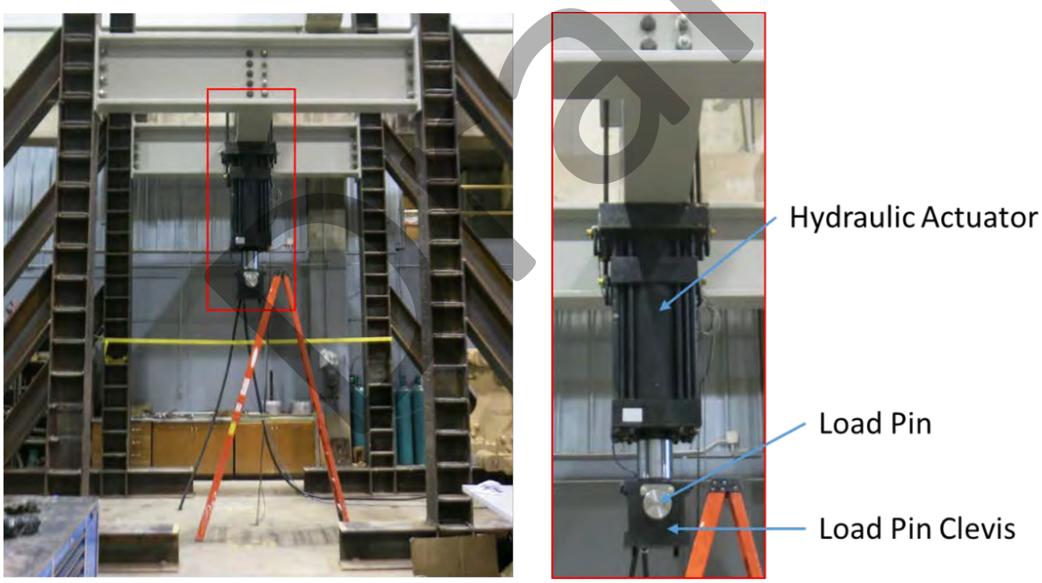

Figure 21. Hydraulic actuator assembly installed on test frame

Figure 22. Load pin clevis eye threaded into hydraulic actuator end

5.3.4 Column Test Setup

An overall view of the typical column test setup with an installed pile is shown in Figure 23. To ensure proper load transfer through the pile cross-section from the actuator, a top and bottom column cap were manufactured. The top of the column was held in a steel end cap with a 2-in.-thick base and 4-in.-tall sides and was bolted to the load pin clevis and actuator, as shown in Figure 24. The load pin allowed for the top of the column to rotate about one axis only, i.e., in the plane of buckling failure of the column.

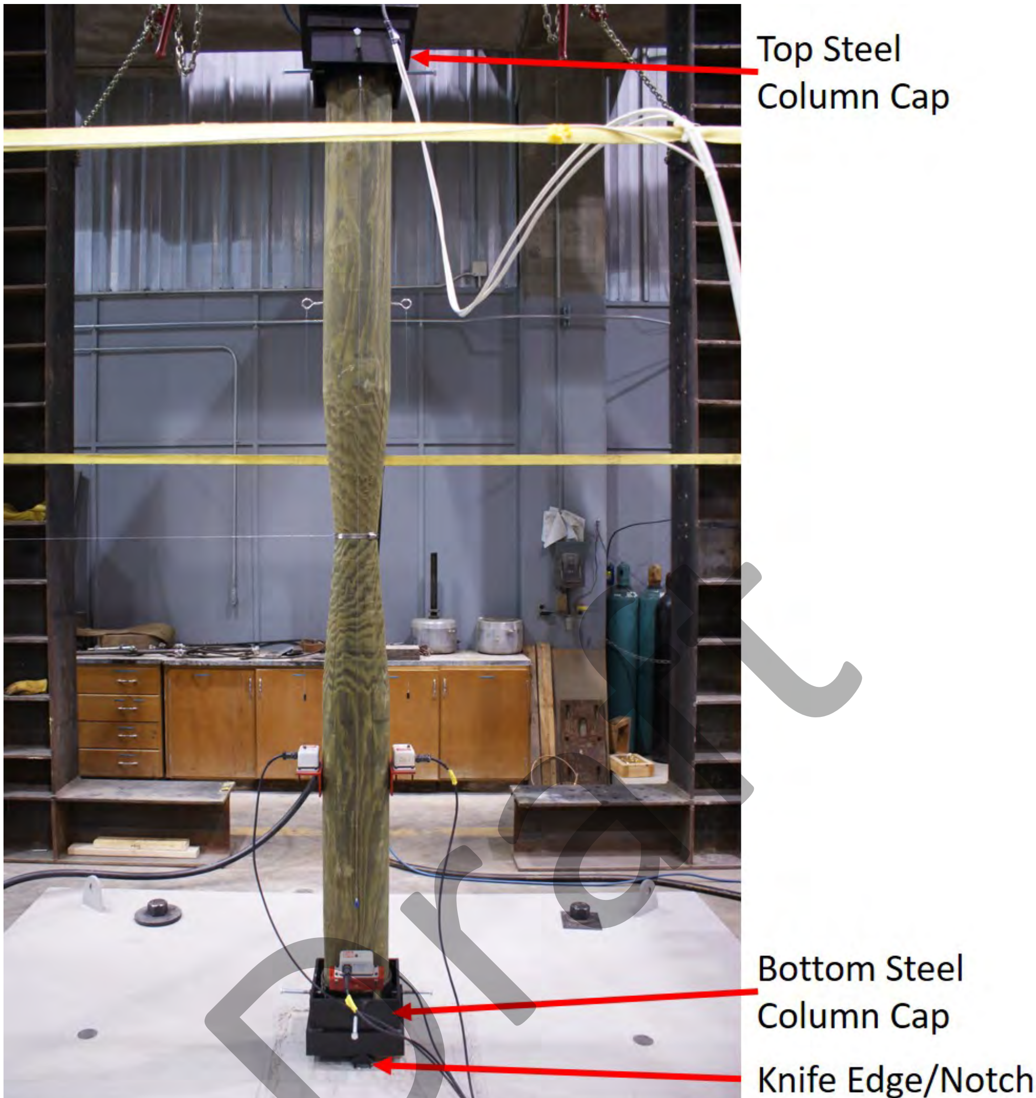

Figure 23. Overall view of column test setup with timber column installed

Figure 24. Upper column end cap for concrete column installed beneath load pin clevis and actuator

The bottom of the column was held in a similar steel end cap with a 3-in.-thick base and 4-in. sides as shown Figure 25. It has a notch on the underside that allowed the column to rock along the knife-edge welded to the base plate. The notch is offset 0.9 in. from center, as shown in Figure 26, which is based on the minimum allowable column eccentricity from ACI 318-14. This value of eccentricity was used for both the concrete and timber columns as a reasonable minimum eccentricity for pier columns.

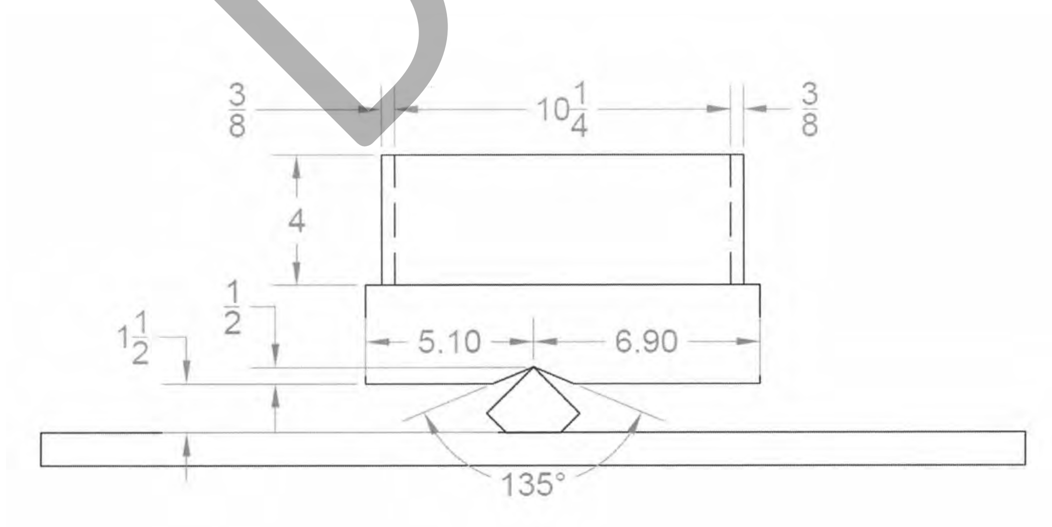

Figure 25. Drawing of column bottom steel end cap and knife-edge support

Figure 26: Knife-edge notch in the bottom base plate

The column end caps utilized for the concrete piers were used on the timber piers as well. However, the round shape of the timbers required a steel collar, seen in Figure 27 in each cap to eliminate pier movement and to hinder uneven crushing of the ends of the piers. These collars fit inside of the column end cap and are 4-in. thick with an 8.25-in.-diameter hole to receive the timber column end.

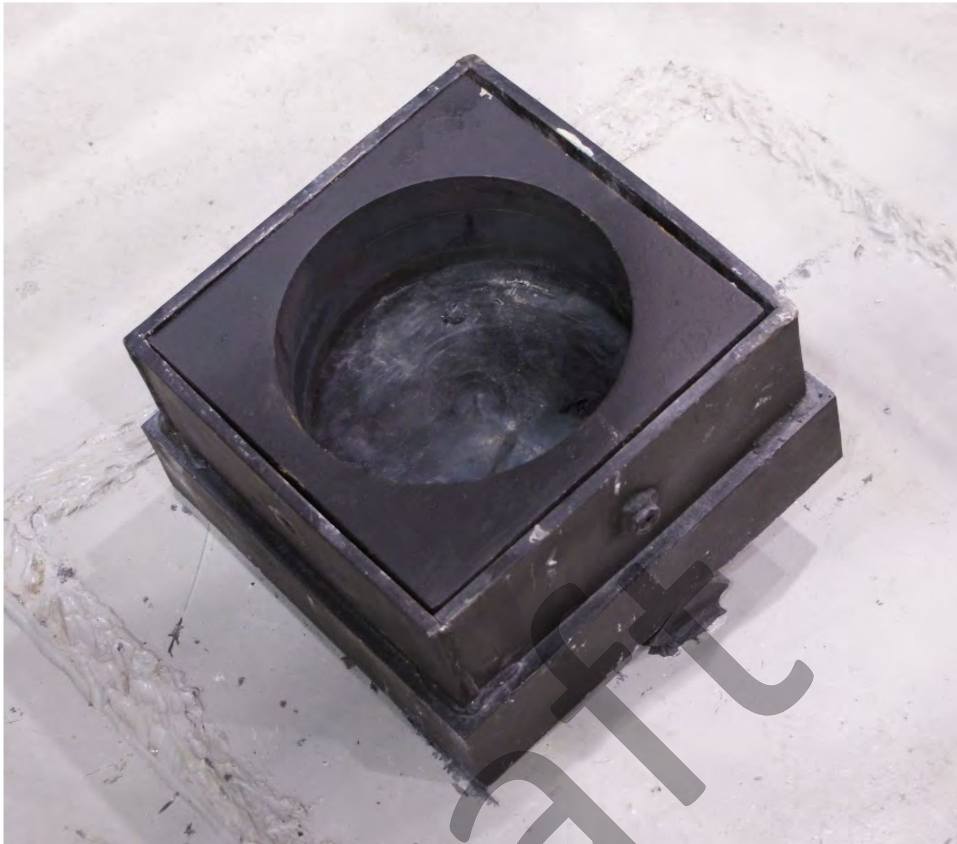

Figure 27. Timber column end cap

5.3.5 Beam Test Setup

The overall beam testing setup is shown in Figure 28. The beam testing utilizes a 4-point bending loading setup. All loading points utilized rollers at the supports to minimize any axial restraint resulting in axial loads. A load transfer beam, shown in Figure 29, has loading points approximately 58 in. apart. This distance between the rollers was sufficient to place the loading points on either side of the retrofit/damaged sections of the beam. This setup enforces constant bending moment between the loading points. The ends of the beam were supported by rollers on steel pedestals as shown for the timber beams in Figure 30 and concrete beams in Figure 31.

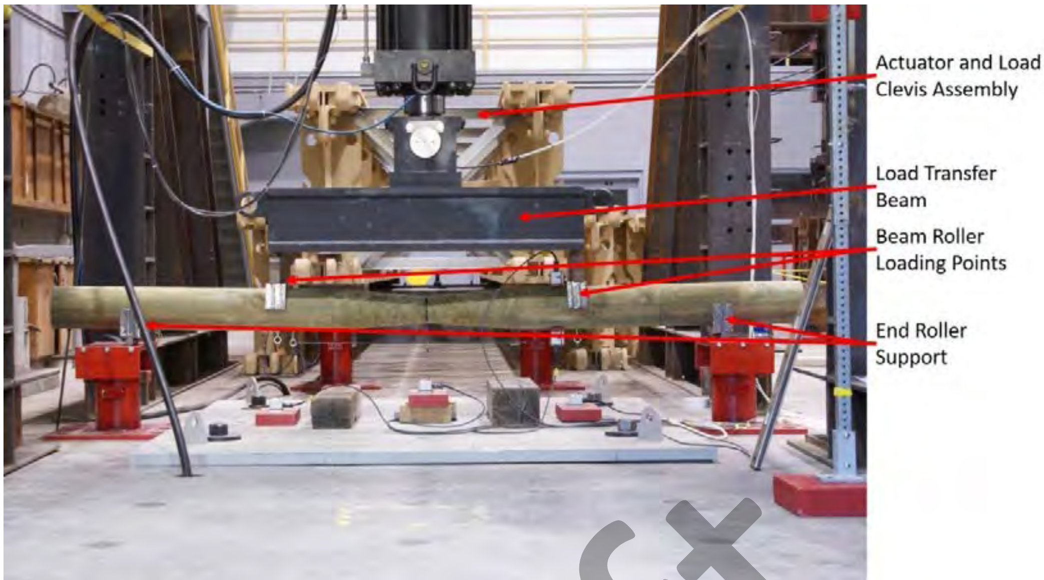

Figure 28. Overall view of flexural testing setup

Figure 29. Load transfer beam with typical roller supports

Figure 30. End roller support for timber beams

Figure 31. End roller support for concrete beams

5.3.6 Instrumentation

A biaxial load pin was used to record forces imparted to the test piles in the vertical and horizontal directions. The load pin connected the clevis eye on the hydraulic actuator to the clevis on the loading beam. The ability of the clevis to rotate about the load pin enforced equal load distribution to the two loading points.

Up to five UniMeasure PA Series linear position transducers with a 20-in. extension range, referred to herein as string potentiometers, were utilized per test. For concrete test specimens, the gauges were mounted to 2-in. steel angles which were screwed to wood blocks and glued to the test specimen using epoxy resin. For timber test specimens, the 2-in. steel angles were screwed directly to the pier itself. Light gauge stainless steel wire connected the potentiometers to screw–in eyelets to measure deflection in the test specimens.

In the column testing of the concrete and timber piers, gauges were installed on the north – south – east – west "faces" along the axis of loading and near the center of the column perpendicular to the axis of loading. A diagram showing the locations of the four string potentiometers is in Figure 32. An example of the string potentiometer locations is shown in Figure 33. The north and south string potentiometers were attached at the ends of the column and measured the shortening of the entire column. The east and west string potentiometers were attached just outside the damaged/retrofitted region and oriented along the direction of failure (perpendicular to the knife-edge). These measured the shortening of the "damaged" section of the column. By measuring the lengthening/shortening of the column on opposite faces, possible bending forces could be measured and accounted for in the data analysis.

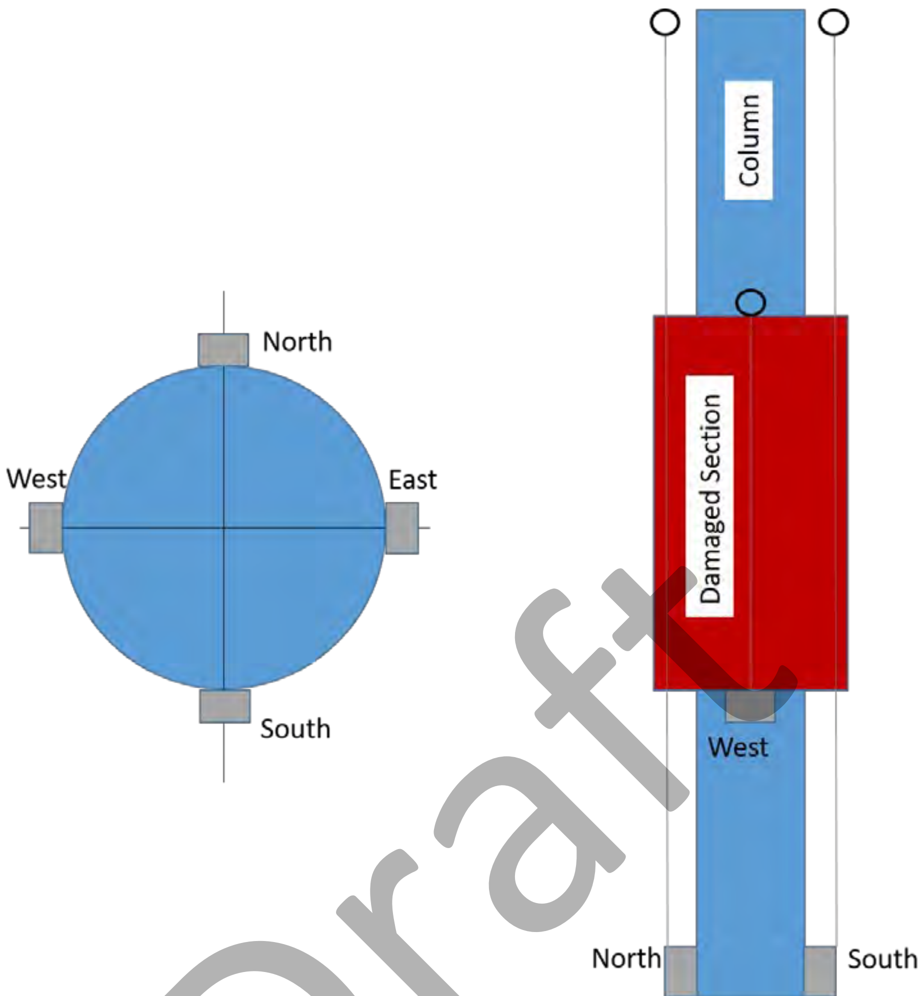

Figure 32. Diagram of string potentiometer locations for axial load testing

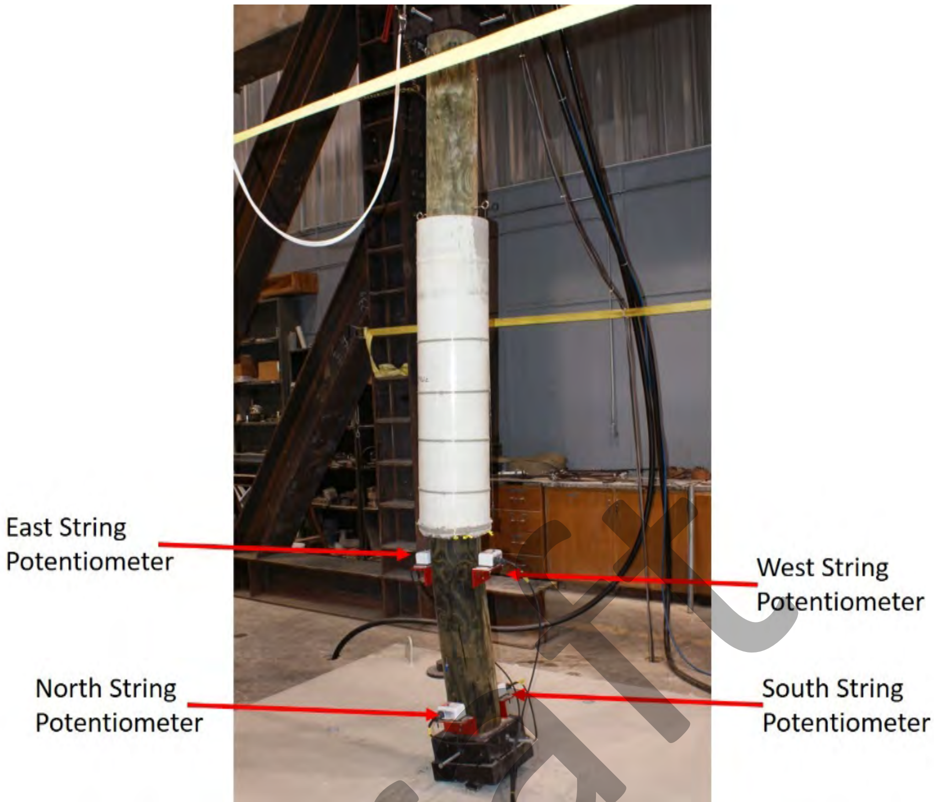

Figure 33. Example of string potentiometer locations for axial load testing

For the flexural load testing of the concrete and timber piers, a diagram of the string potentiometer locations is shown in Figure 34. An example of the string potentiometer locations installed on a flexural load test specimen is shown in Figure 35. Two potentiometers were installed on the top and bottom of the beam, just outside the damaged section, to measure lengthening/shortening along the outer tensile/compressive fibers of the beam, and three gauges were installed on the bottom of the beam to measure vertical deflection, with one underneath each of the loading points and center of beam.

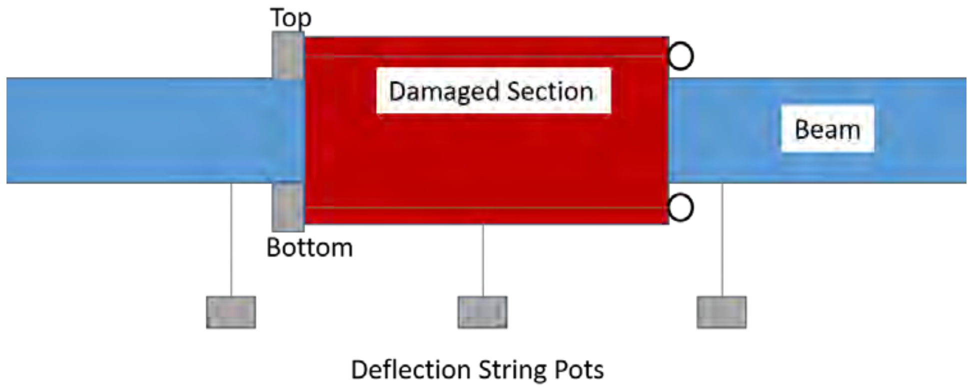

Figure 34. Diagram of string potentiometer locations for flexural load testing

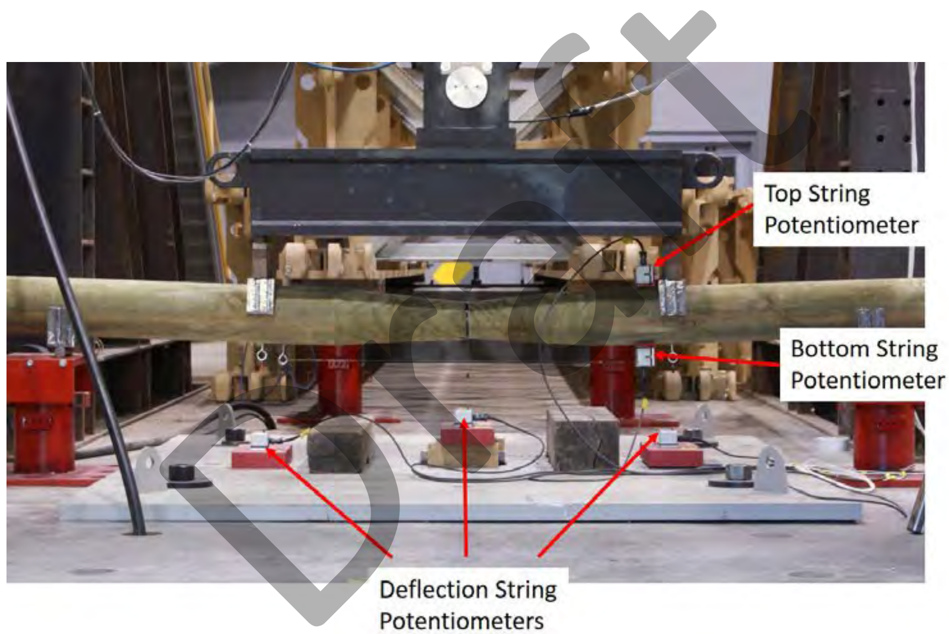

Figure 35. Example of string potentiometer locations for flexural load testing

Data acquisition was performed by using a National Instruments SCXI-1001 chassis controlled by National Instruments™ LabVIEW SignalExpress software. The acquisition system recorded data from the two load pin channels, up to five string potentiometers, and load and displacement measurements from the hydraulic actuator. All data were recorded at a rate of 100 Hz.

5.4 Loading Results

This section presents the test data and photos from 13 axial column and 13 flexural beam bending tests on timber and concrete samples. Test data is typically shown in average axial stress vs strain, for the column tests, and bending moment vs beam curvature, for the beam tests.

The test naming convention is as follows: X-Y-#, where the “X” represents the specimen material (“T” for timber or “C” for concrete), the “Y” represents the damaged condition of the specimen (“C” for control, “T” for tapered/damaged, non-retrofitted, “RD” for a retrofit applied over the damaged section while the specimen was dry, or “RW” for a retrofit applied over the damaged section while the specimen was wet), and the “#” represents the test number of the specimen type. For example, “T-T-2” is the second test of a timber specimen with a tapered/damaged, non-retrofitted section.

5.4.1 Axial Column Performance

The axial column performance was based on two factors: overall strength compared to undamaged columns and stiffness of the damaged/retrofitted region. By comparing the overall strength, one can determine whether or not a retrofit works sufficiently to replace the “lost” strength when the pile is damaged. When comparing the stiffness of the sections, one can better understand how the section will react under loading.

In order to compare the stiffness of the retrofitted region between samples, two sets of data were collected. The longitudinal string potentiometers measured global axial deflection of the column, while the retrofit string potentiometers measured axial deflection and bending across the damaged/retrofitted area of the column. The axial deflection of the column was measured across a gauge length of approximately 9 ft. using the longitudinal string potentiometers attached to the north and south sides of the column. These data provide the average axial strain across the length of the column. The axial deformation and bending of the damaged/retrofitted region were measured across a gauge length of approximately 58 in. The average of these two gauges’ data provides the average axial strain across the length of the damaged/retrofitted region. The difference of the two gauges provides the bending of the column. The stress in the damaged region was assumed to have acted across the area equivalent to the area of the undamaged region. Since the stiffness of a column is equivalent mathematically to a spring stiffness, the relationship of springs in series was used to determine the stiffness of the undamaged/non-retrofitted region. Since the data gathered included the overall change in length and the damaged region change in length, the undamaged region change in length could be calculated, using the relationship shown in equation 1. This data shows how the damaged/retrofitted section performs compared to the undamaged portion.

$$x_{total} = x_{damaged} + x_{undamaged} \quad (1)$$

A total of 13 tests were conducted using axial loading: 12 with timber piles and 1 with concrete piles. A table summary of the results with a comparison to the columns' respective design capacities and control column capacities is shown in Table 2. Note that values from concrete columns are not included in the summary table. This is due to the columns failing due to local crushing/rebar pullout rather than in axial/flexural failure.

Table 2. Summary Results from Column Testing of Timber Piles

Test Name	Material	Test Type	Max Average Axial Stress, psi	Strength Diff. vs. Control	Strength Diff. vs. Design
T-C-1	Timber	Control	1,710	--	50% greater
T-C-2	Timber	Control	1,638	--	44% greater
T-C-3	Timber	Control	1,512	--	33% greater
T-T-1	Timber	Tapered	1,620	0%	42% greater
T-T-1-OFF	Timber	Tapered	936	42% less	18% less
T-T-2	Timber	Tapered	756	53% less	34% less
T-T-3	Timber	Tapered	1,494	8% less	31% greater
T-T-4	Timber	Tapered	972	40% less	15% less
T-RD-1	Timber	Tapered with Dry Retrofit	2,178	34% greater	91% greater
T-RD-1-OFF	Timber	Tapered with Dry Retrofit	2,304	42% greater	102% greater
T-RW-1	Timber	Tapered with Wet Retrofit	1,872	16% greater	64% greater
T-RW-2	Timber	Tapered with Wet Retrofit	1,512	7% less	33% greater

5.4.1.1 Timber Piles

There were 12 timber column tests conducted. Three tests had no retrofit with no taper (control), five tests had no retrofit with a tapered ("damaged") middle section, two tests had a retrofit over a dry timber with a tapered middle section, and two tests had a retrofit over a wet timber with a tapered middle section. For these tests, the maximum applied stress will be compared to the design maximum allowable stress of 1,140 psi. Calculations are shown in Appendix A.

Specimens T-C-1, T-C-2, and T-C-3 were the control timber tests. A typical specimen before and after testing is shown in Figure 36.

Figure 36. Typical timber control specimen; left: prior to testing, right: after failure

The stress vs strain comparisons for the tests are shown in Figure 37. The average stress in the columns was 1,800 psi. There was very little deviation in maximum stress (plus/minus 50 psi) for all the tests. The second loading line on T-C-3 is due to recording a cycle of loading and unloading prior to loading to failure.

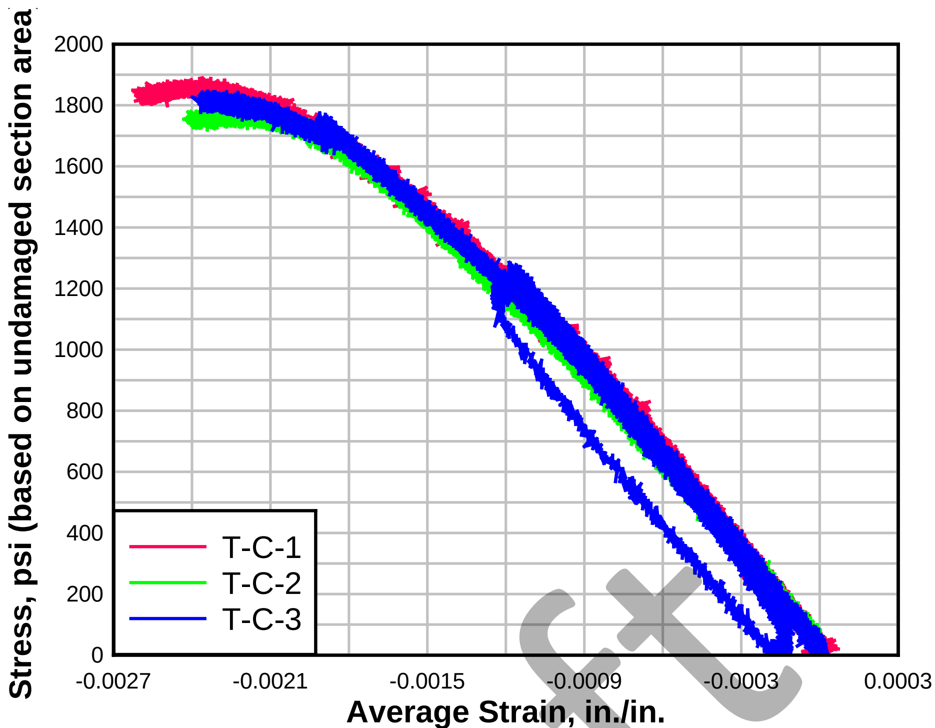

Figure 37. Stress versus strain data for timber control column tests

Specimens T-T-1, T-T-2, T-T-3, T-T-4 and T-T-1 (offset) were the five "damaged", non-retrofitted timber tests. A typical specimen before and after testing is shown in Figure 38.

The stress vs strain comparisons for the tests are shown in Figure 39 (T-T-1), Figure 40 (T-T-2), Figure 41 (T-T-3), Figure 42 (T-T-4), and Figure 43 (T-T-1 Offset). Generally, the undamaged region was stiffer than the damaged region, as would be expected. The range of maximum stress in the timber pile was from 750 psi to 1650 psi. This large range is expected due to the organic nature of the timber resulting in naturally-occurring variability. The average stress, based on undamaged cross-section, was 1150 psi, an approximately 35% reduction in strength from the control tests, but nearly the same value as the design maximum capacity. Note that the data shows positive strain in tests T-T-3, T-T-4, and T-T-5. Theoretically, this is not possible. The positive strain is likely due to the alignment of the string potentiometers and the calculations used to determine the strain in the undamaged region. It is likely that when the column begins to fail and crack, the displacements measured across the damaged region are larger than the displacements along the length of the column, as they have to travel "around" the crack.

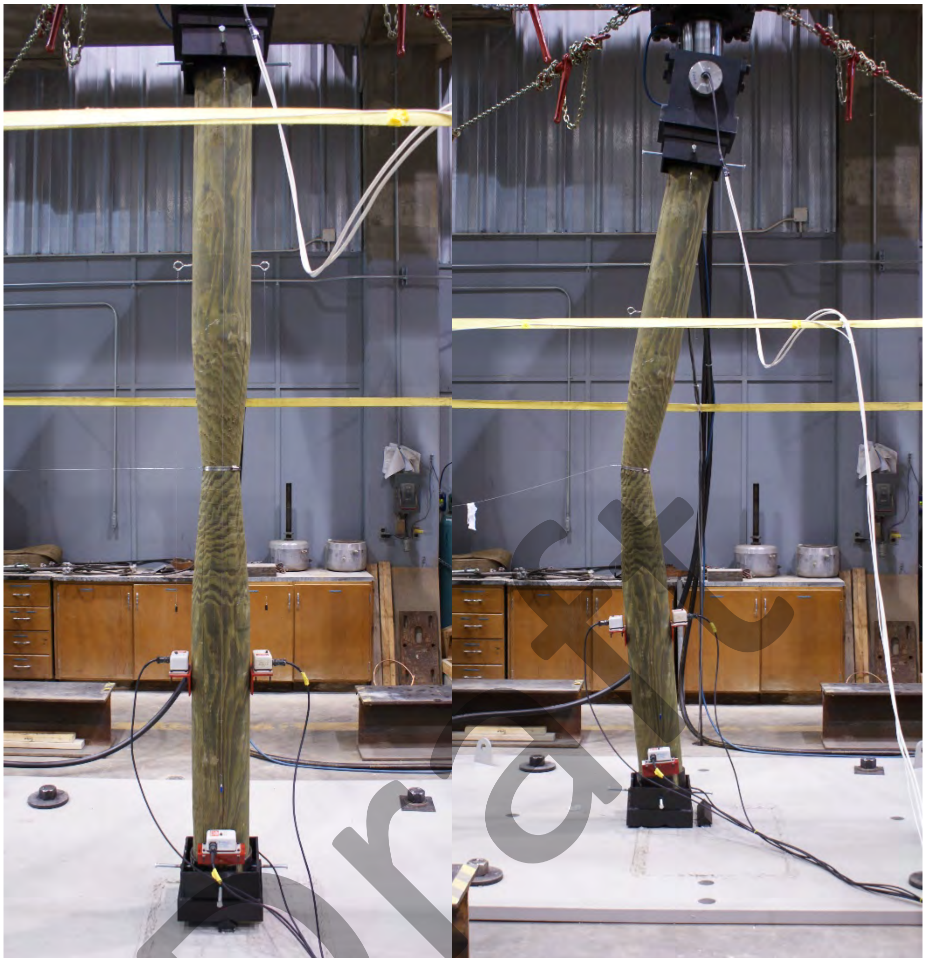

Figure 38. Typical necked-down, non-retrofitted timber specimen; left: before testing, right: after failure

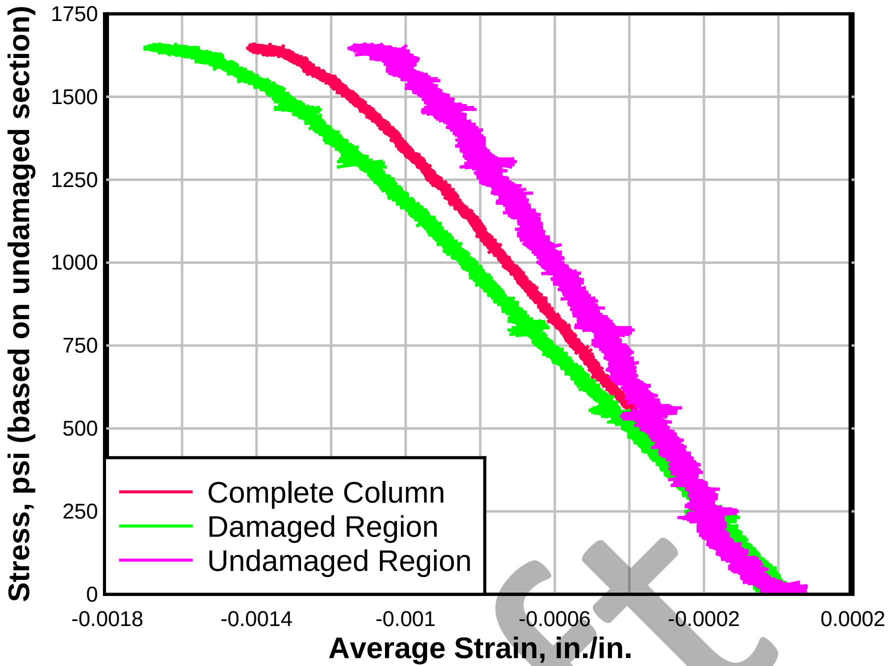

Figure 39. T-T-1 stress versus strain data

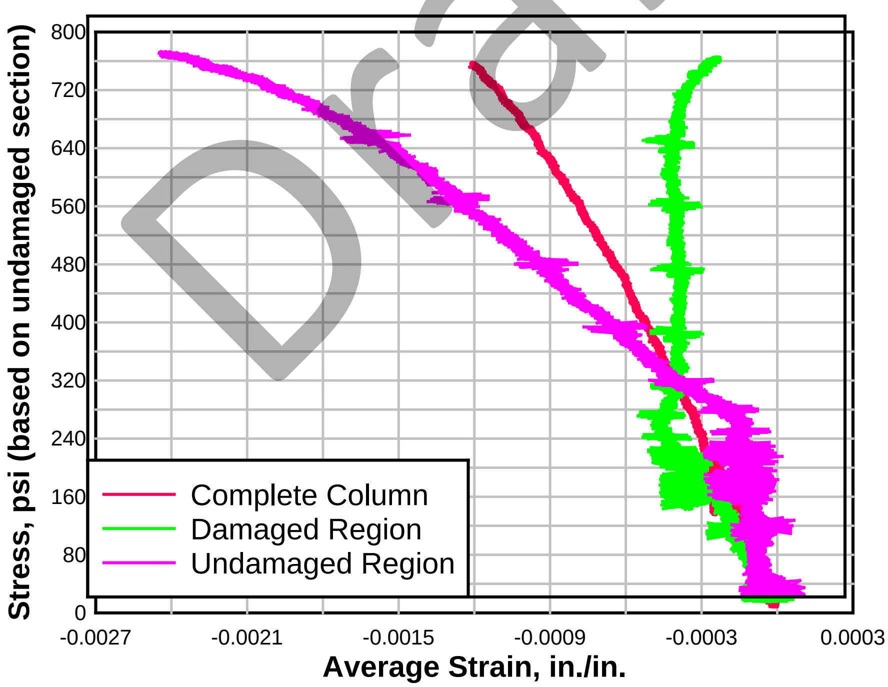

Figure 40. T-T-2 stress versus strain data

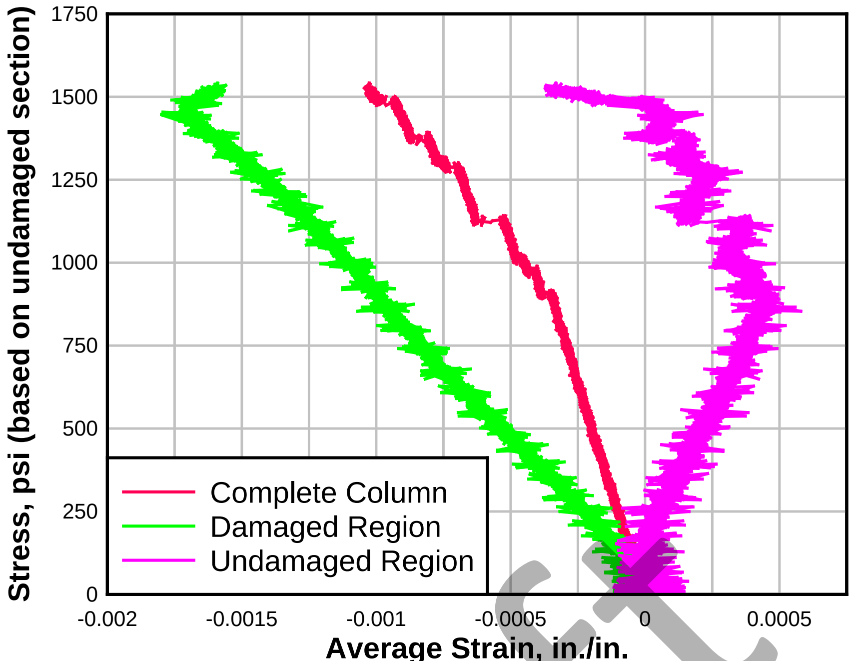

Figure 41. T-T-3 stress versus strain data

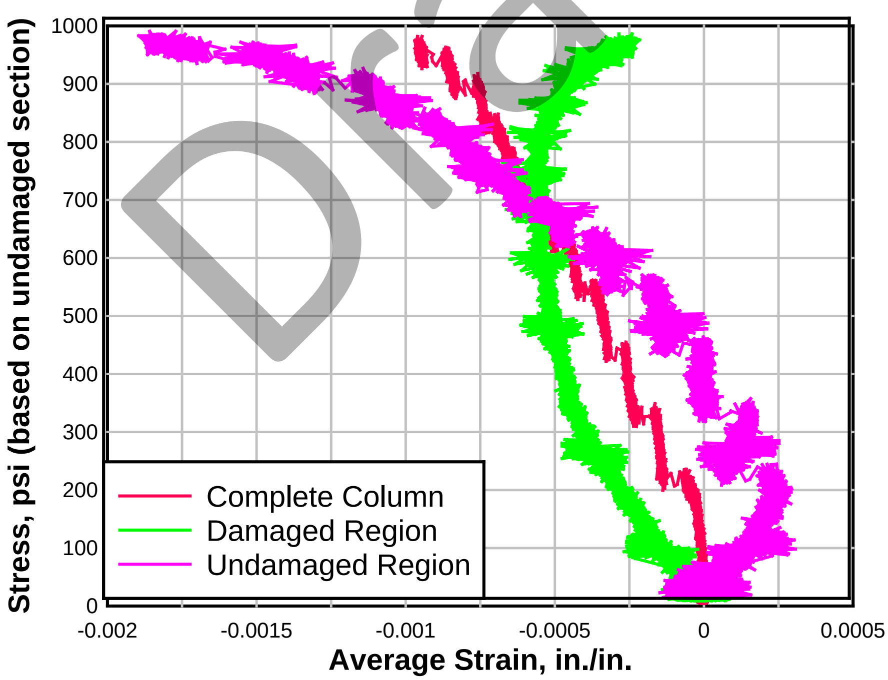

Figure 42. T-T-4 stress versus strain data

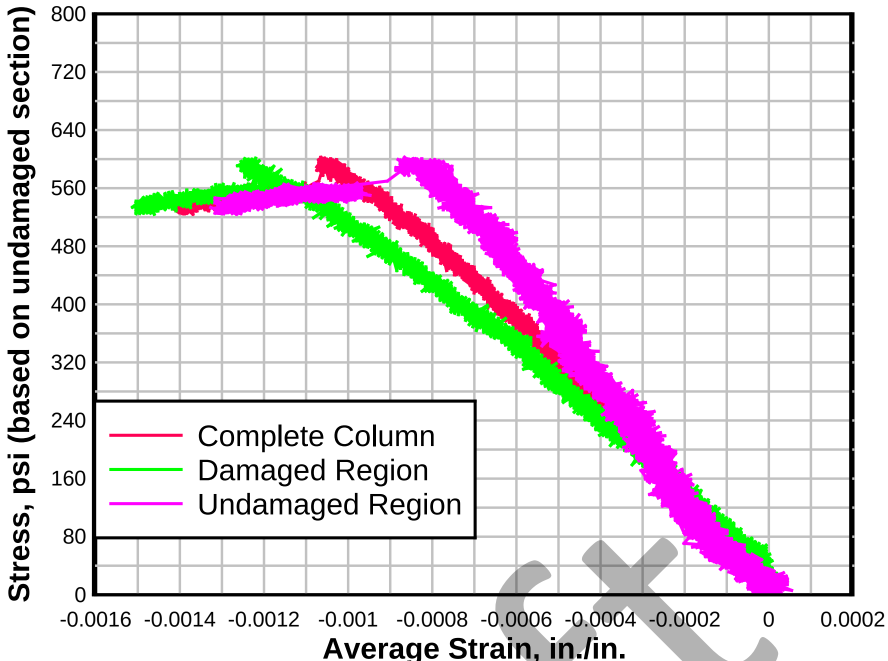

Figure 43. T-T-1 Offset stress versus strain data

Specimens T-RD-1 and T-RD-1 (Offset) were the retrofitted dry timber tests. A typical specimen before and after testing is shown in Figure 44.

Figure 44. Typical retrofitted, dry timber specimen; left: before testing, right: after failure

The stress vs strain comparisons for the tests are shown in Figure 45 (T-RD-1) and Figure 46 (T-RD-1 Offset). The average stress, based on undamaged cross-section, was 2,200 psi, an approximately 95% increase in strength based on the design strength, as well as an approximately 22% increase in strength based on control specimens.

Specimens T-RW-1, and T-RW-2 were the retrofitted wet timber tests. A typical specimen before and after testing is shown in Figure 47.

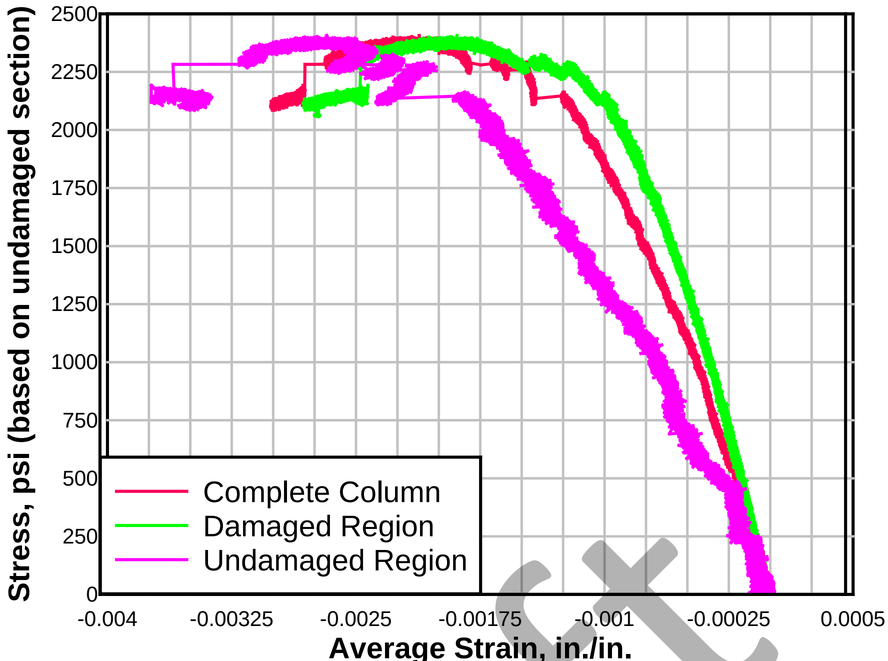

Figure 45. T-RD-1 stress versus strain data

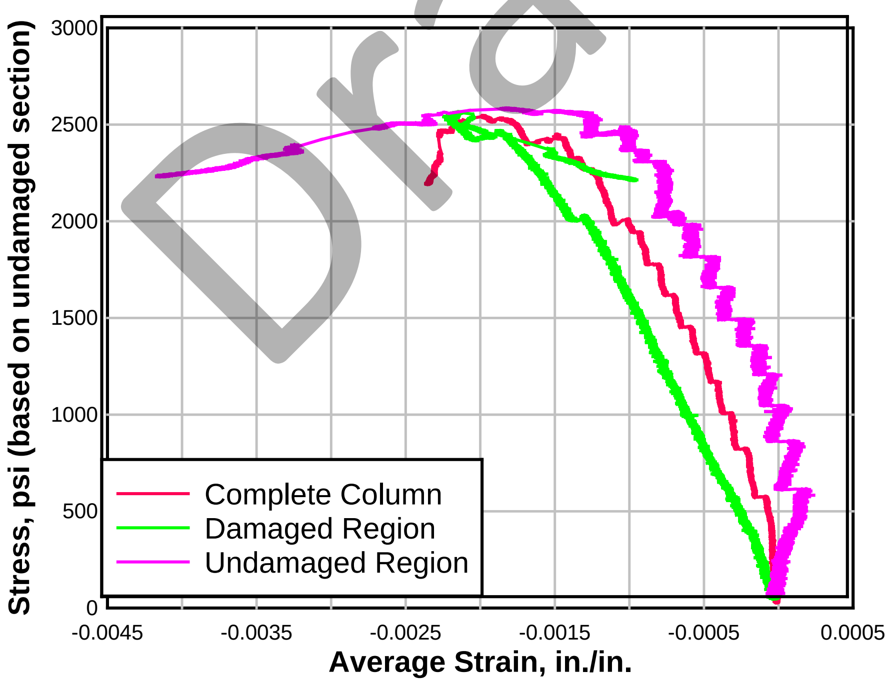

Figure 46. T-RD-1 Offset stress versus strain data

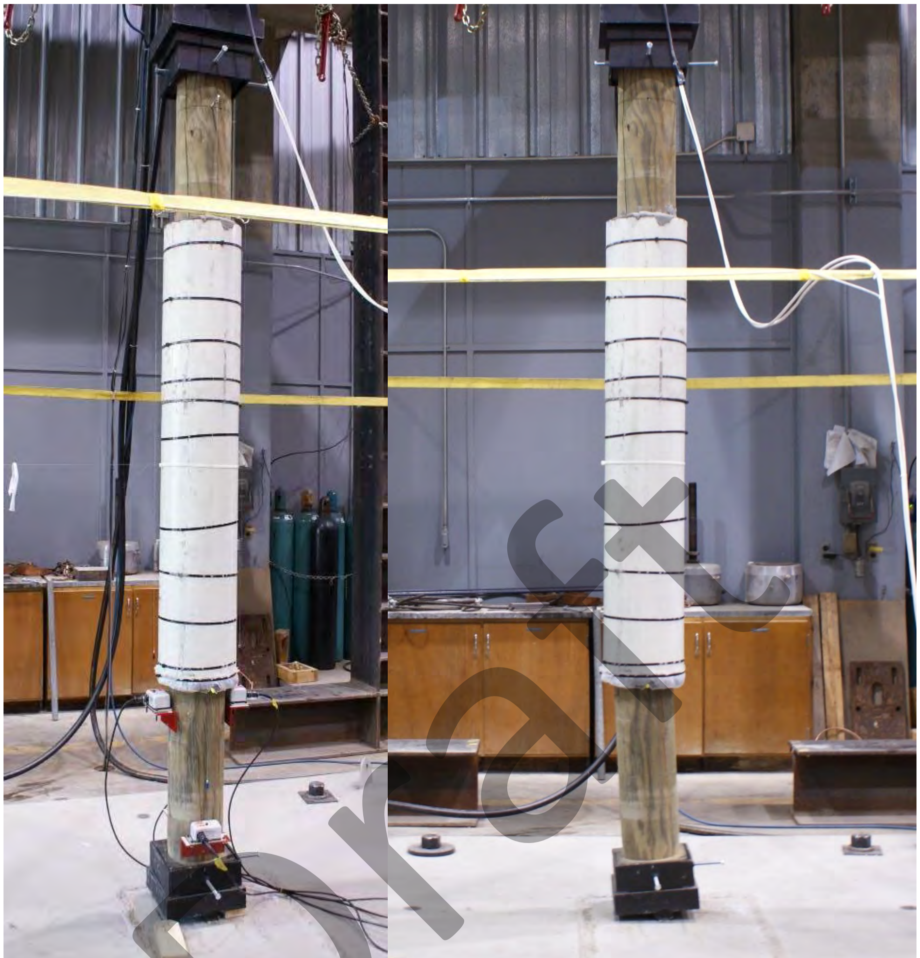

Figure 47. Typical wet-retrofitted timber specimen; left: prior to testing, right: after failure

The stress vs strain comparisons for the timber, wet-retrofitted tests are shown in Figure 48 and Figure 49. The average stress, based on undamaged cross-section, was 1,800 psi, an approximately 45% increase in strength compared to the design strength, as well as nearly the same strength compared to the average control strength.

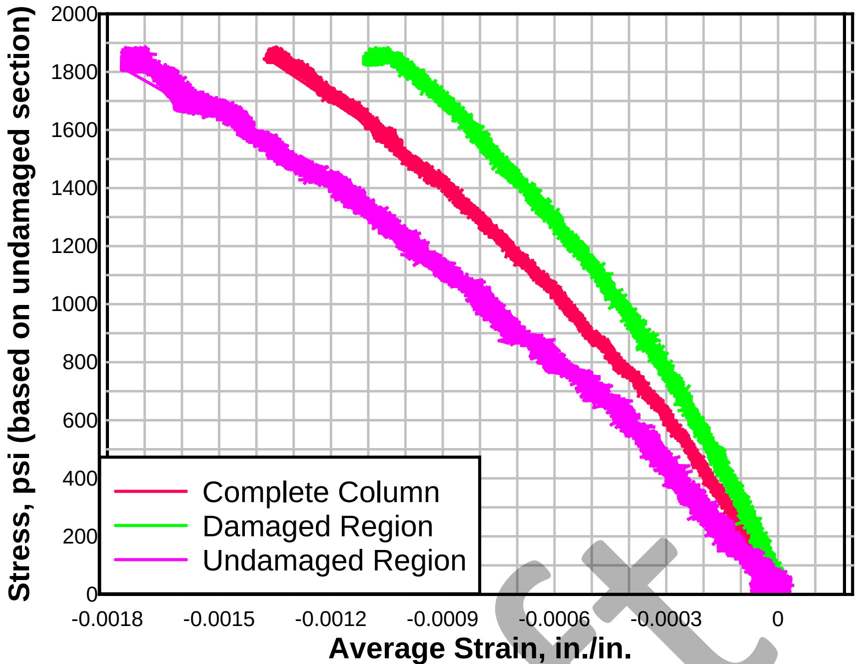

Figure 48. T-RW-1 stress vs strain data

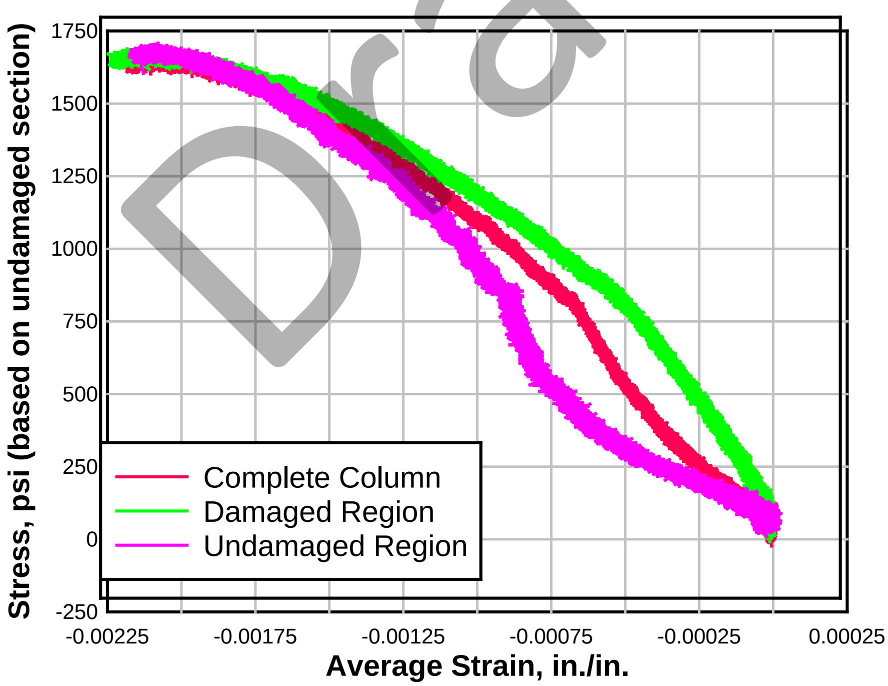

Figure 49. T-RW-2 stress versus strain data

5.4.1.2 Concrete Columns

There were two concrete column tests performed. The tests consisted of one with a concrete control column and one with a concrete dry-retrofitted column. The axial stress at failure of both tests was around 2500 psi, well below the expected failure stress of over 5000 psi. This was due to the end crushing and/or rebar pullout in the end region. The remaining scheduled concrete columns were tested using a 4-point beam bending test. The photos of the tests and test data are shown in Figure 50 and Figure 51 for test C-C-1 and Figure 52 and Figure 53 for test C-RD-1. Note that the data shows positive strain in test C-C-1. Theoretically, this is not possible. As was the case for the timber columns (Section 5.4.1.1), this result is an artifact of testing method at failure conditions.

Figure 50. C-C-1; left: prior to testing, right: end crushing of column after load testing

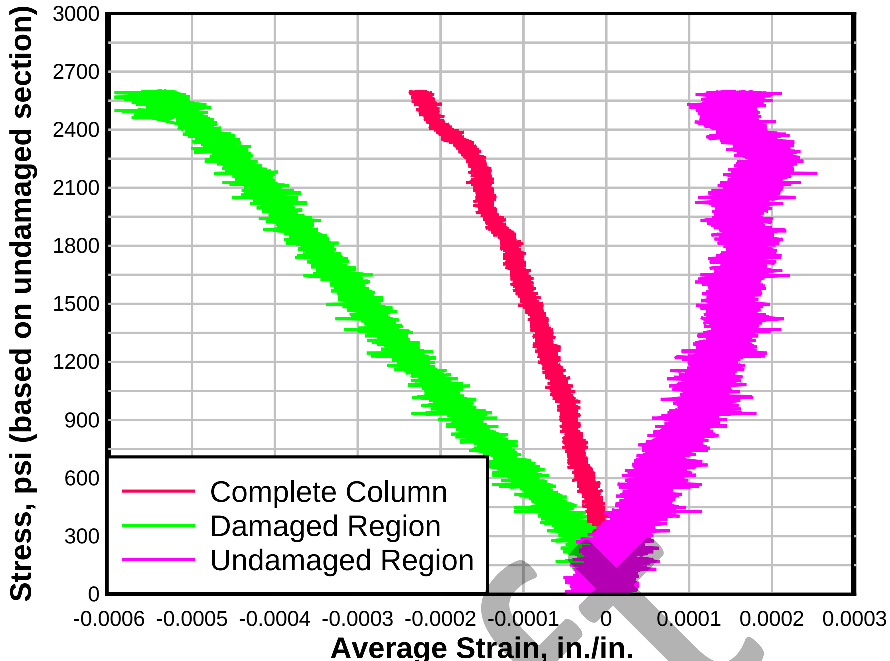

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Figure 51. C-C-1 stress versus strain data

Figure 52. C-RD-1; left: prior to testing, right: end crushing of column after load testing

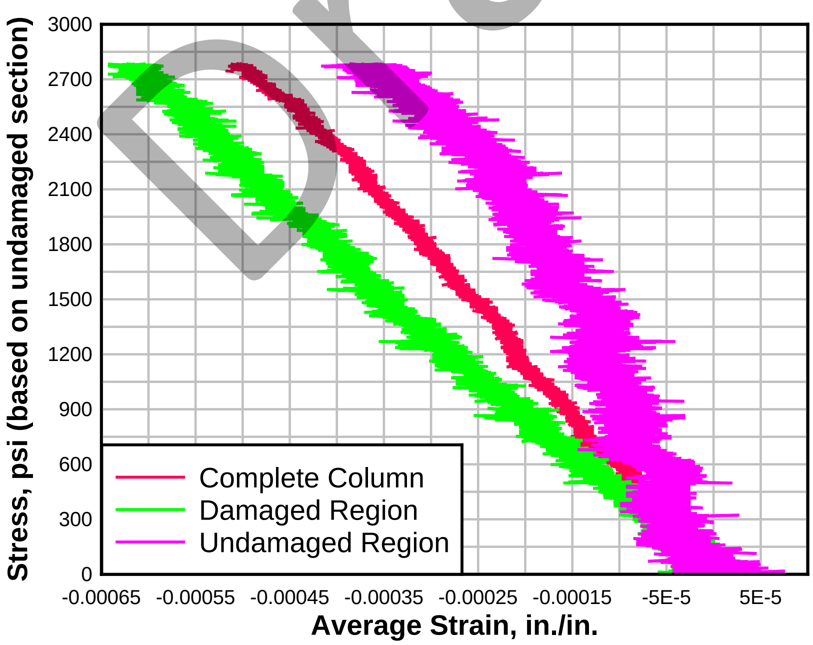

Figure 53. C-RD-1 stress versus strain data

5.4.2 Flexural Performance

A change was made in the testing procedure for the remaining specimens due to the appearance of end cracking in the concrete columns. A four-point bending test was used which provided a constant bending moment in the repair section of the piles. The only occurrences of shear forces were in the ends of the section outside of the repair. Since, in all cases, the column testing showed failures in flexure rather than pure compression, it was determined that a pure flexure test would provide sufficient results to understand the restorative effects of the pile repairs in comparison to the undamaged design values

A total of 13 tests were conducted using four-point bending: 8 with timber piles and 5 with concrete piles. A table summary of the results with a comparison to the beams' respective design capacities and control beam capacities is shown in Table 3.

Table 3. Results from Flexural Testing of Piles

Test Name	Material	Test Type	Max Applied Moment, lbf-in	Strength Diff. vs. Control	Strength Diff. vs. Design
T-C-4	Timber	Control	350,000	--	81% greater
T-C-5	Timber	Control	200,000	--	4% greater
T-C-6	Timber	Control	240,000	--	24% greater
T-T-5	Timber	Tapered	80,000	70% less	-59%
T-T-6	Timber	Tapered	65,000	75% less	-66%
T-RD-2	Timber	Tapered with Dry Retrofit	240,000	9% less	24% greater
T-RW-3	Timber	Tapered with Wet Retrofit	220,000	16% less	14% greater
T-RW-4	Timber	Tapered with Wet Retrofit	360,000	37% greater	87% greater
C-C-2	Concrete	Control	615,000	--	34% greater
C-RD-2	Concrete	Dry Retrofit	700,000	14% greater	52% greater
C-RD-2 B	Concrete	Dry Retrofit	800,000	30% greater	74% greater
C-RD-3	Concrete	Dry Retrofit	700,000	14% greater	52% greater
C-RW-2	Concrete	Wet Retrofit	870,000	41% greater	89% greater

5.4.2.1 Timber flexural tests

There were a total of eight timber flexural tests. Each of the four types of timber piles (control, tapered, dry-retrofitted, and wet-retrofitted) were tested. For these tests, the maximum calculated moment will be compared to the design maximum moment capacity, 192,960 lbf-in. Calculations are shown in Appendix A.

Specimens T-C-4, T-C-5, and T-C-6 were the control timber specimens for the 4-point bending tests. The typical specimen before and after testing is shown in Figure 54 and Figure 55.

Figure 54. Typical timber control specimen prior to flexural testing

Figure 55. Typical timber control specimen after flexural testing

The moment versus curvature comparisons for the timber control tests is shown in Figure 56. The average moment capacity for the timber beams was 260,000 lbf-in, which is a 36% increase in strength compared to the design moment capacity. The wide spread in capacity is due to the organic nature of the timber causing natural variability. It is difficult to estimate the strength and have similar results due to the non-homogenous nature of the timber cross-sections. Therefore, the design moment capacity has several factors to account for the impact of this non-homogenous nature, and, ultimately, a lower design capacity than expected.

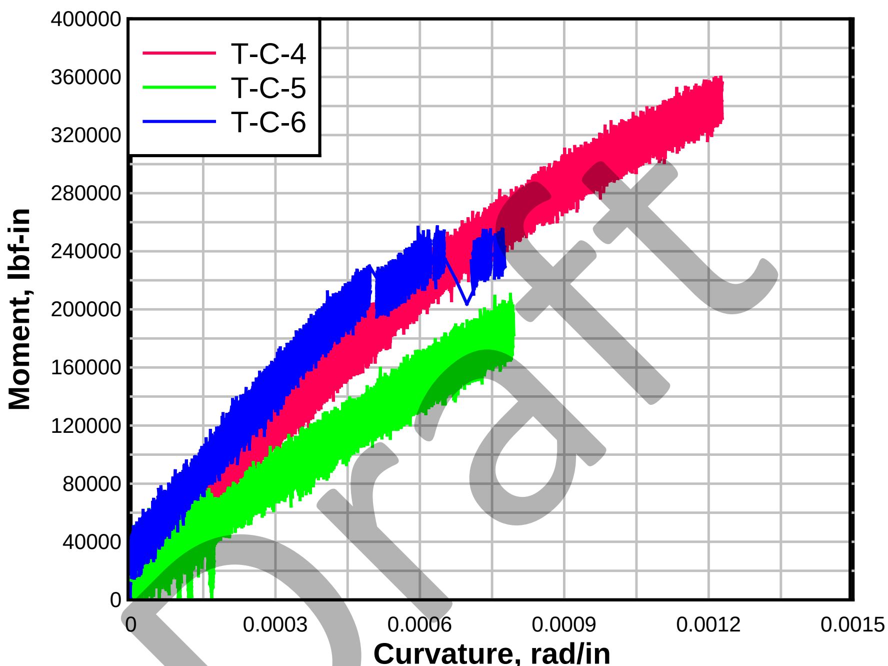

Figure 56. Timber control specimen moment versus curvature data.

Specimens T-T-5 and T-T-6 were the tapered timber specimens for the 4-point bending tests. The typical specimen before and after testing is shown in Figure 57 and Figure 58, respectively.

The moment versus curvature comparisons for the tapered timber tests areshown in Figure 59. The average moment capacity for the tapered timber beams was 72,500 lbf-in, an approximately 63% decrease in capacity compared to the design strength, as well as an approximately 72% decrease in capacity compared to the control beams.

Figure 57. Typical tapered timber specimen prior to flexural testing

Figure 58. Typical tapered timber specimen after flexural testing

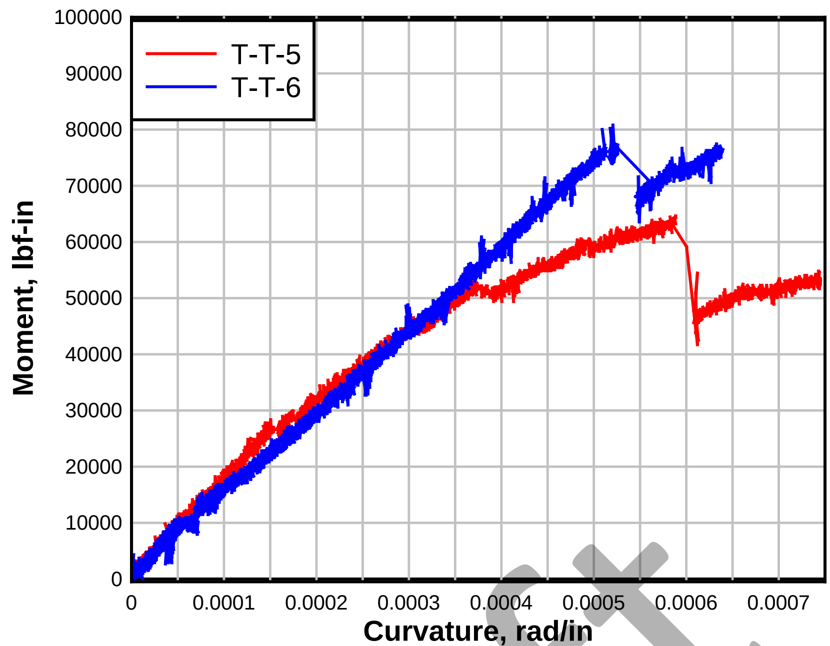

Figure 59. Tapered timber specimens moment versus curvature data

Specimen T-RD-2 was the damaged and dry-retrofitted timber specimen for the 4-point flexural bending tests. The typical specimen before and after testing is shown in Figure 60 and Figure 61.

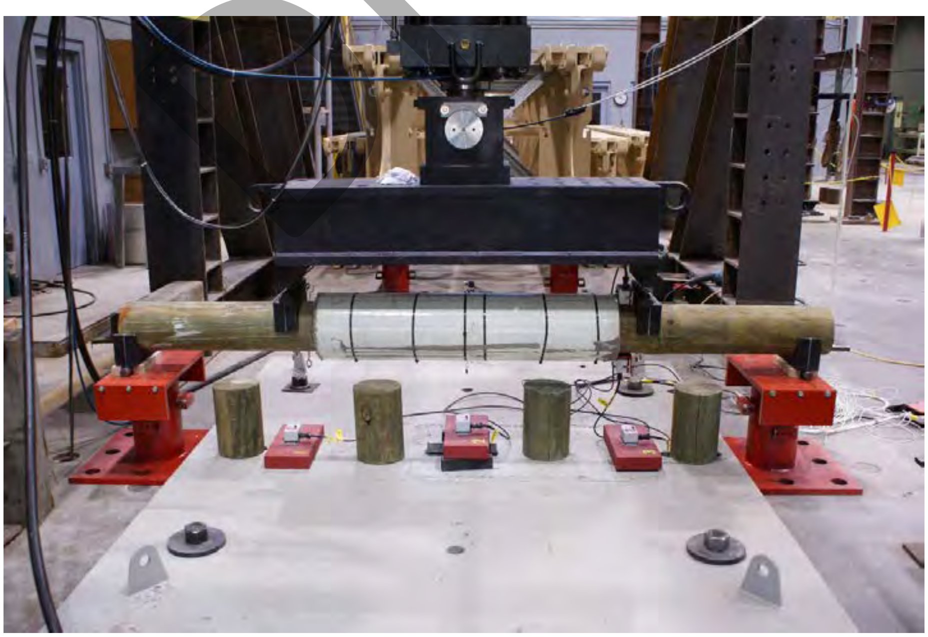

Figure 60. T-RD-2 timber specimen prior to flexural testing

Figure 61. T-RD-2 timber specimen failure after flexural testing

The moment versus curvature data for the damaged and dry-retrofitted test are shown in Figure 62. The moment capacity for the beam was 240,000 lbf-in, an approximately 24% increase in capacity compared to the design strength. It is important to note that the failure of the beam occurred at the edge of the repair between the repair and the loading location.

Specimens T-RW-3 and T-RW-4 were the damaged and wet-retrofitted timber specimens used for the 4-point bending tests. The typical specimen before testing is shown in Figure 63, and the after test photos of T-RW-3 and T-RW-4 are shown in Figure 64 and Figure 65, respectively.

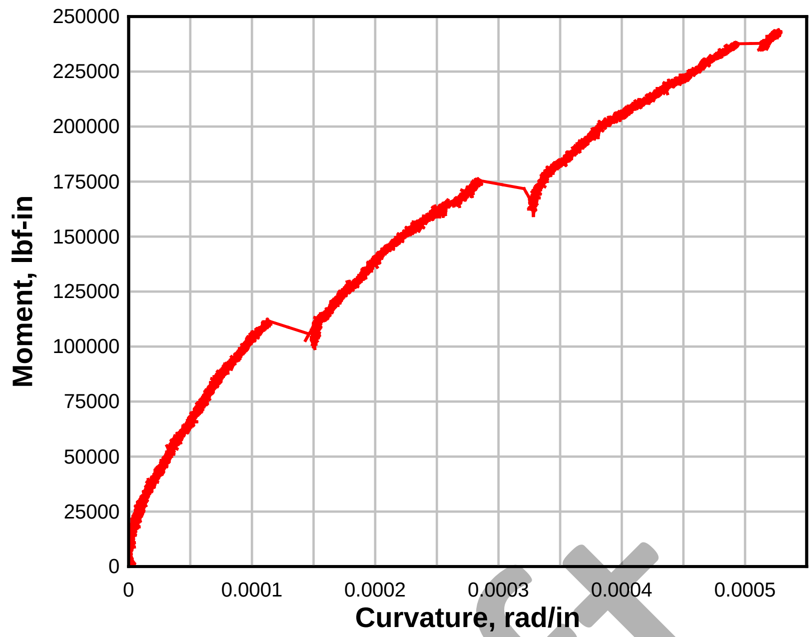

Figure 62. Tapered and dry-retrofitted timber moment versus curvature data

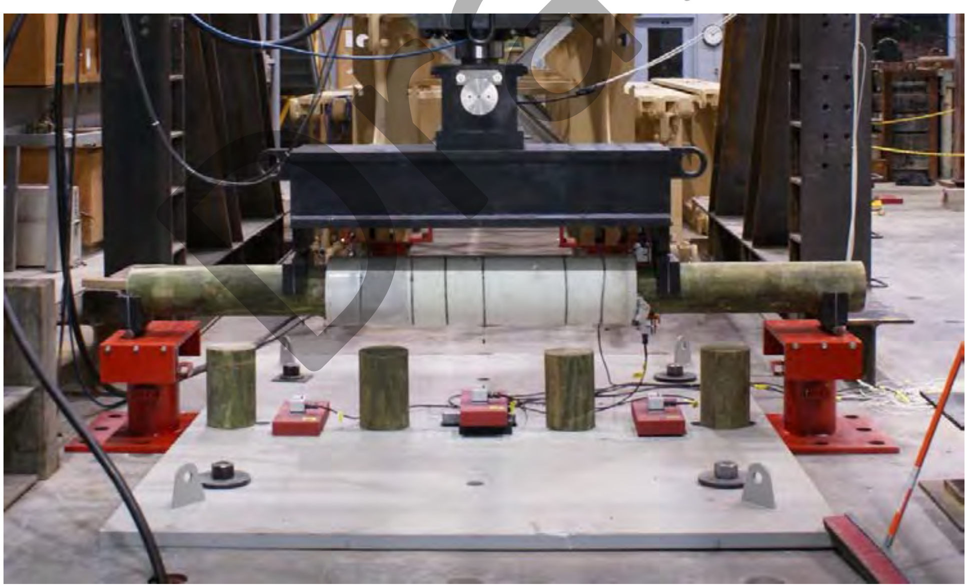

Figure 63. Typical tapered and wet-retrofitted specimen prior to flexural testing

Figure 64. Point of failure for T-RW-3

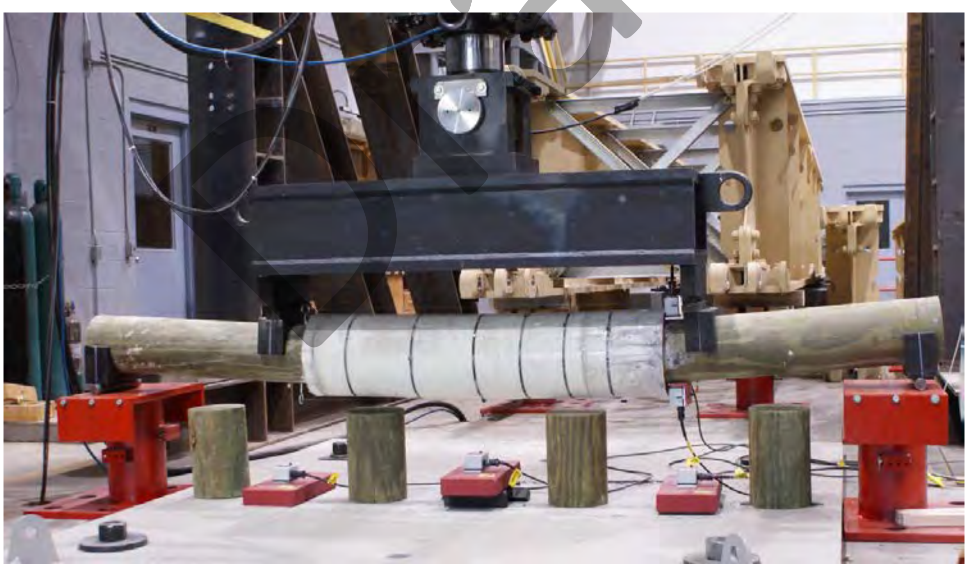

Figure 65. Post-test view of T-RW-4

The moment versus curvature data for the damaged and wet-retrofitted timber tests is shown in Figure 66. The average moment capacity for the beams was 290,000 lbf-in, an approximately 50% increase in capacity compared to the design moment capacity. It is important to note that the failure of T-RW-3 occurred at the edge of the repair between the repair and the loading location, whereas the failure in T-RW-4 occurred in the repaired region, which led to the much more ductile failure of the beam.

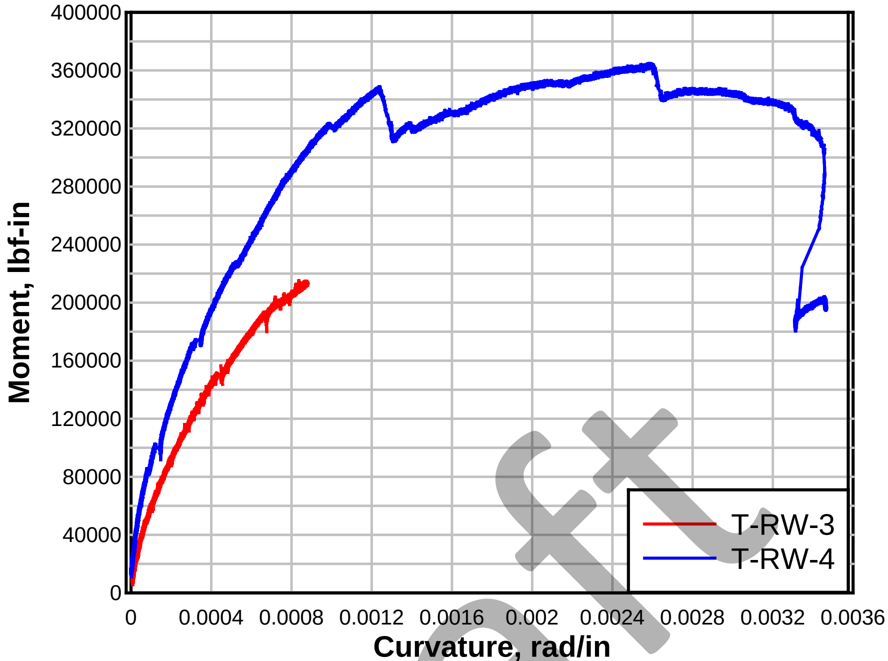

Figure 66. Moment versus curvature data, tapered and wet-retrofitted timber specimens.

5.4.3 Concrete Beams

There were a total of five concrete beam tests. Each of the three types of concrete piles (control, dry-retrofitted, and wet-retrofitted) were tested. Prior to testing, the far ends of the concrete beams were wrapped with SikaWrap® Hex and epoxied to concrete. This application was done to prevent any premature end pullout and/or crushing. For these tests, the maximum calculated moment will be compared to the factored ACI 318-14 design maximum moment capacity in pure bending, approximately 460,000 lbf-in. Calculations were done in Microsoft® Excel using an interaction diagram shown in Appendix B.

Specimen C-C-2 was the control, undamaged concrete pile specimen for the 4-point bending tests. The moment versus curvature data for the control test are shown in Figure 67. The moment capacity for the tested beam was 615,000 lbf-in, an approximately 34% increase in strength compared to the factored design capacity.

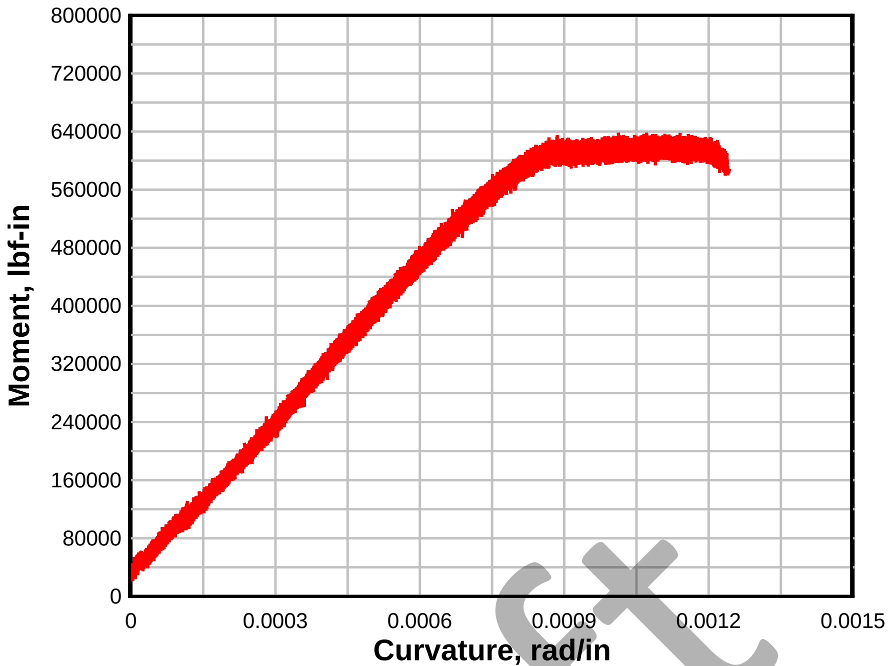

Figure 67. C-C-2 moment versus curvature data

Specimens C-RD-2, C-RD-2 B, and C-RD-3 were the damaged and dry-retrofitted concrete specimens used for the 4-point flexural bending tests. The typical specimen before and after testing is shown in Figure 68 and Figure 69. It is important to note that the failure of the beams occurred at the edge of the repair between the repair and the loading location, as shown in Figure 70.

The moment versus curvature data for C-RD-2 and C-RD-3 is shown in Figure 71. The moment versus center deflection data for all the damaged and dry-retrofitted concrete beam tests is shown in Figure 72. The average moment capacity for the beams was 740,000 lbf-in, an approximately 67% increase in capacity compared to the factored ACI 318-14 design moment capacity, as well as an approximately 20% increase in capacity compared to the control beam capacity. In test C-RD-2, one end of the beam sheared off and fell off the support, as shown in Figure 73. The repair and loading sections of the beam were checked for failures, and none were observed. A second test on the same beam (C-RD-2 B) with supports moved 6 in. in on each end was performed. No string potentiometers were installed for test C-RD-2 B; therefore, there is no data for moment versus curvature for this test. For comparison, a data set of applied moment versus center deflection from all three tests is presented.

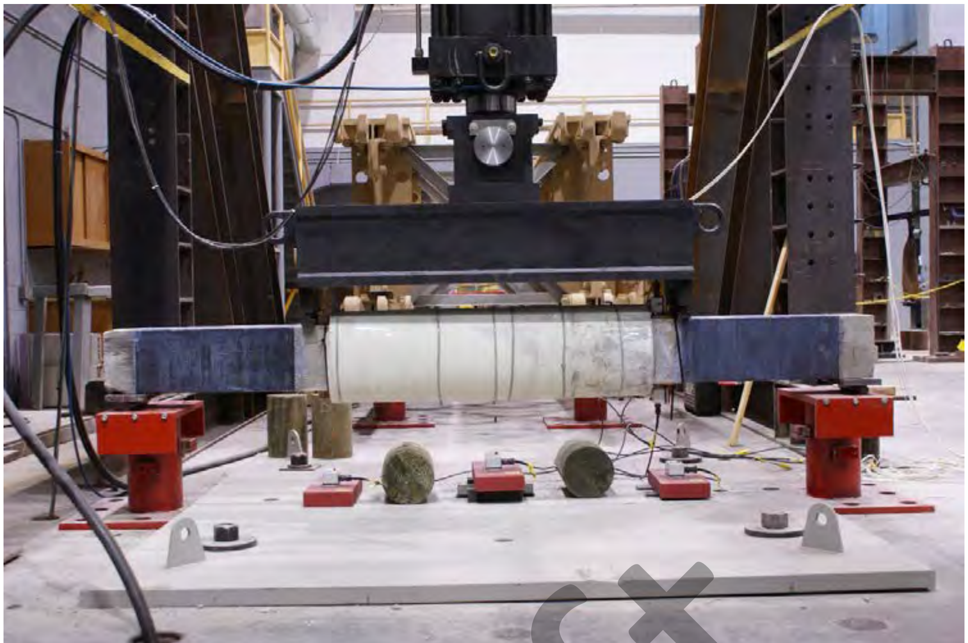

Figure 68. Damaged and dry-retrofitted concrete specimen prior to flexural testing

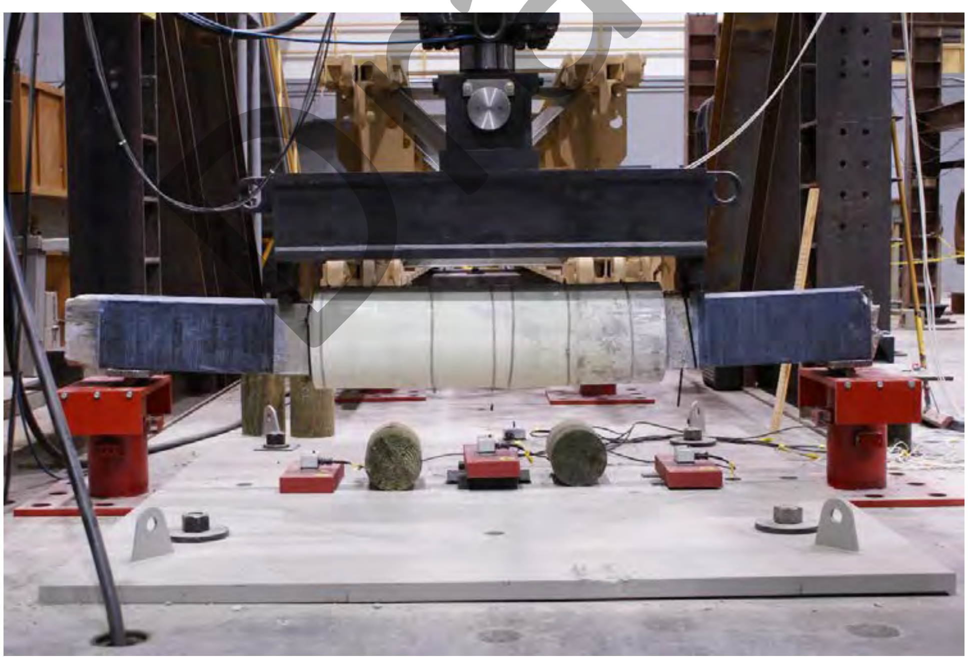

Figure 69. Damaged and dry-retrofitted concrete specimen after flexural testing

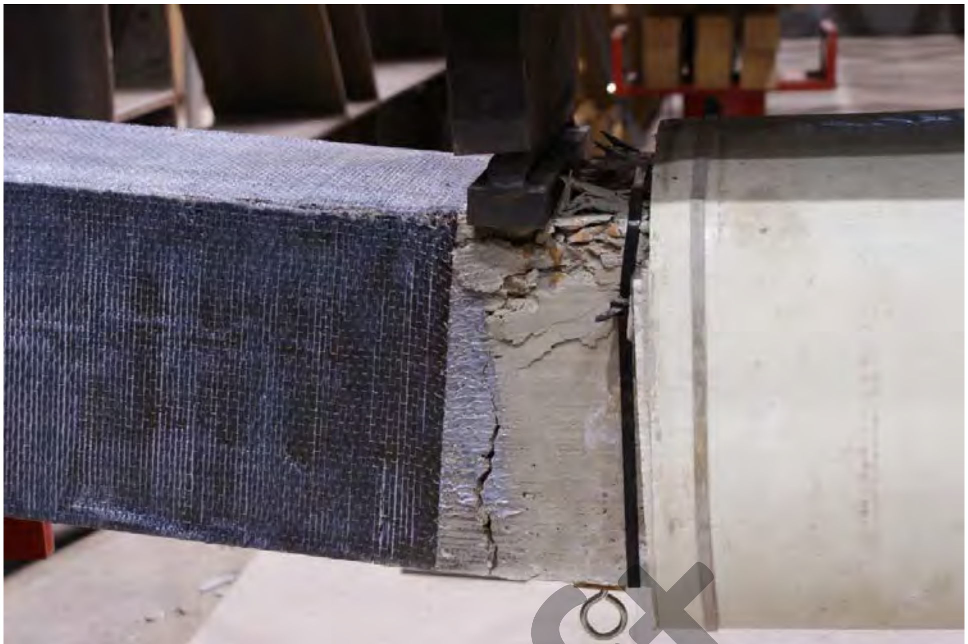

Figure 70. Typical failure location of dry-retrofitted concrete specimen in flexural test

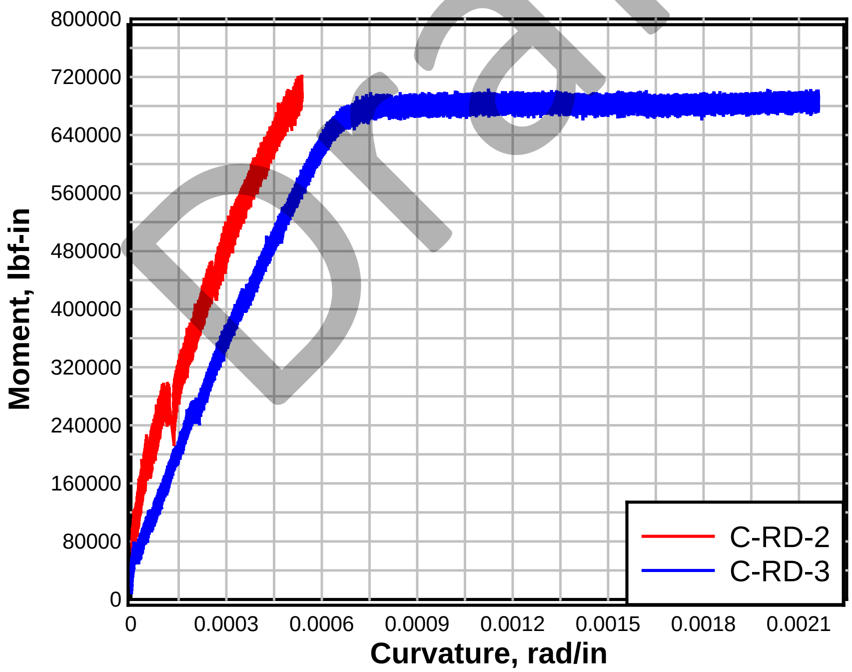

Figure 71. Damaged and dry-retrofitted concrete specimen moment versus curvature data

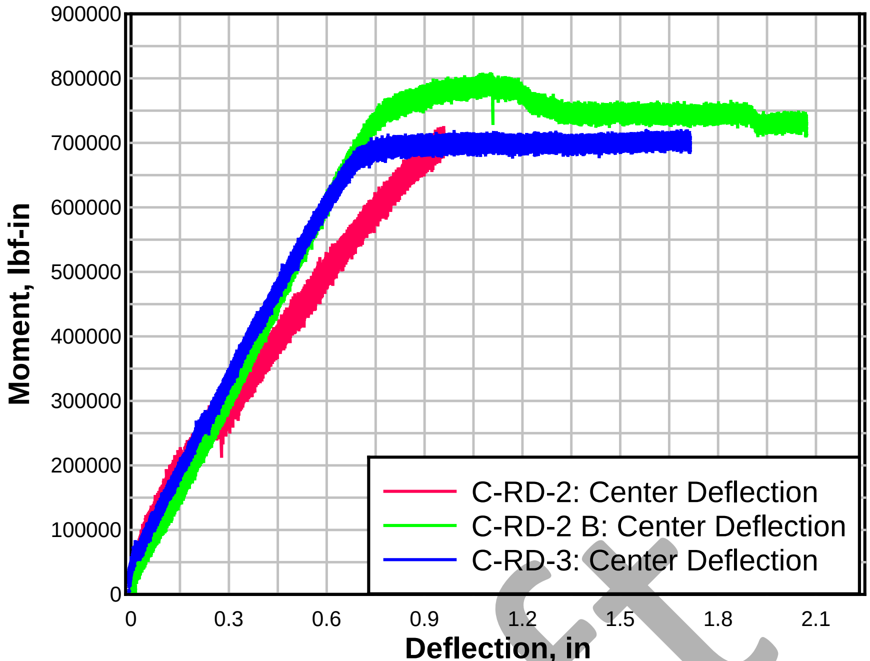

Figure 72. Damaged and dry-retrofitted concrete specimen moment versus center deflection

Figure 73: Failure of C-RD-2 beam end in shear

Specimen C-RW-3 was the damaged and wet-retrofitted concrete specimen for the 4-point bending tests. The specimen before and after testing is shown in Figure 74 and Figure 75. It is important to note that the failure of the beams occurred at the edge of the repair between the repair and the loading location, as shown in Figure 76.

Figure 74. C-RW-2 concrete specimen prior to flexural test

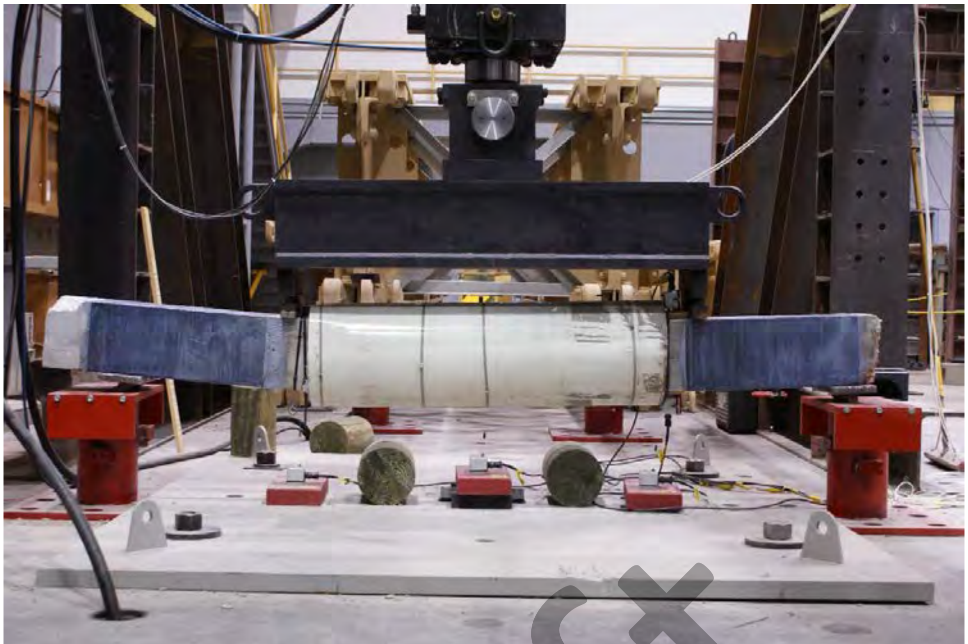

Figure 75. C-RW-2 concrete specimen failure after flexural test

Figure 76. Failure location of C-RW-2 beam

The moment versus curvature data for the damaged and wet-retrofitted concrete beam test is shown in Figure 77. The moment capacity for the beam was 870,000 lbf-in, an approximately 89% increase in capacity compared the ACI 318-14 design strength, as well as a 41% increase in capacity compared to the control beam.

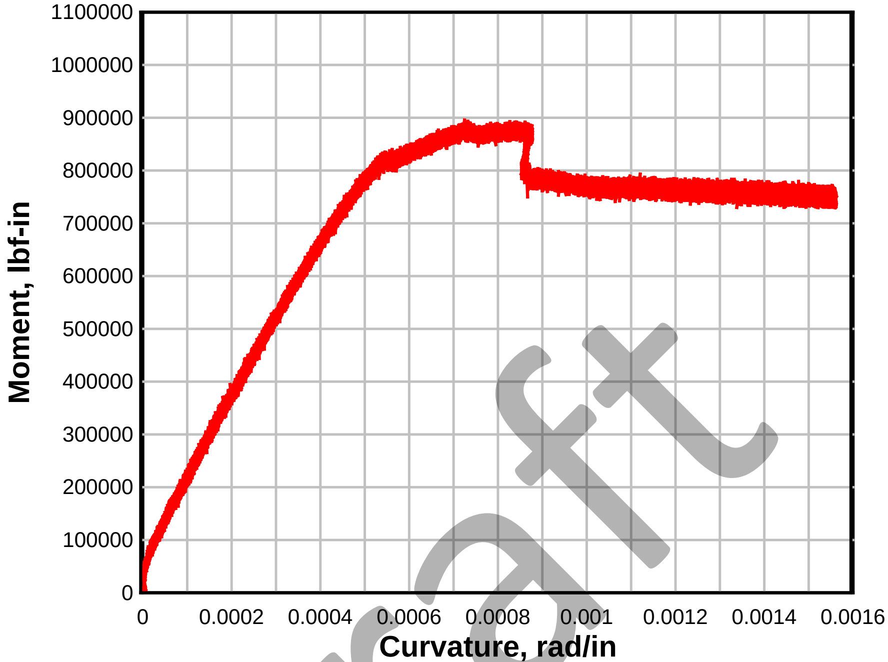

Figure 77. C-RW-2 moment versus curvature data

5.5 Analysis

The primary goal of this testing was to determine whether a damaged pile could have most, if not all, of its pre-damaged strength restored via retrofit. Previous published results (Menkulasi, Baghi, & Farzana, 2017) (Mohammadi, Gull, Taghinezhad, & Azizna, 2014), (Yang, Sneed, Saiidi, Belarbi, & Eshani, 2015) concluded that a proper repair using FRP and grout could restore all or nearly all of the axial strength of the damaged pile and can exceed the maximum allowable design strength.

The results from this test series support the previous research, and compare very well with the previous results. This research also shows that proper repairs to timber piles and concrete piles can restore the pile design strength, even with eccentric loading.

The results of the timber pile axial load tests are reproduced in Figure 78. For the timber piles in column testing, the capacity of the undamaged pile was approximately 1,620 psi, which exceeds the design maximum capacity of 1,140 psi. Damaged timber piles without retrofits had an average capacity of 1,155 psi, which was above the design capacity. However, two tests had a capacity of near the control pile capacity averaging 1,500 psi, while the other 3 averaged just under 900 psi. Therefore, it can be stated that the average damaged pile cannot reliably meet the specified design capacity. However, when a repair/retrofit is placed on the damaged column pile, the capacity is increased to at or above the control pile strength and design capacity. When a repair wasplaced on the damaged section, the capacity of the timber column was an average of 1,950 psi, or an increase of approximately 70% over the design capacity, as well as a 20% increase over the control column strength. It appears that the repair placed on a dry timber pile has a higher capacity than one placed on a wet pile, but more testing but more testing is is necessary to verify this result as statistically significant.

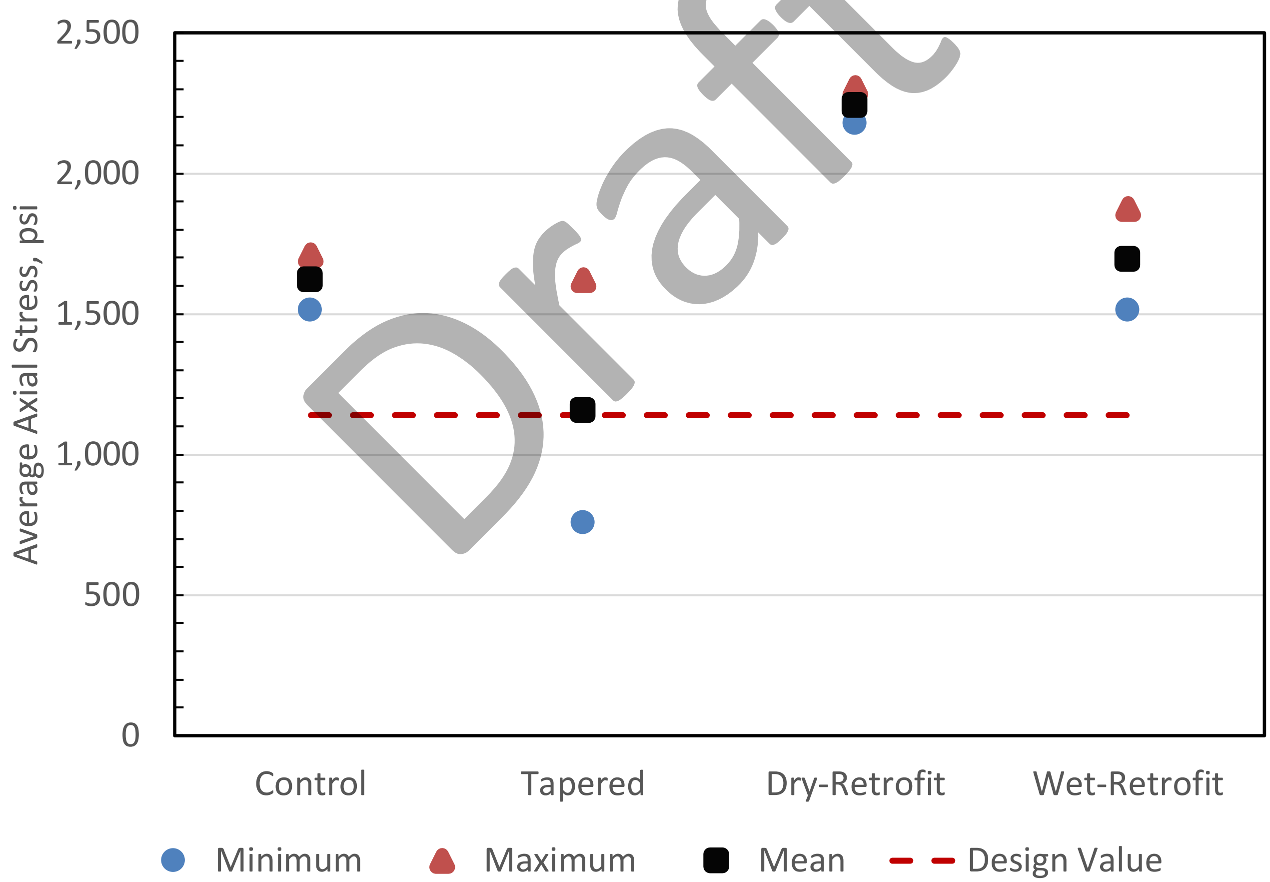

Figure 78. Timber pile axial load test comparison

The concrete and timber piles tested under flexural beam loading conditions performed similarly to those tested under column loading conditions. Figure 79 presents the results for the timber pile bending tests. The damaged timber piles without retrofits did not meet the design capacity, as they were on average 50% below the design moment capacity of 143,000 lbf-in. However, the retrofitted timber piles had an ultimate capacity above the design moment capacity, averaging a 92% increase.

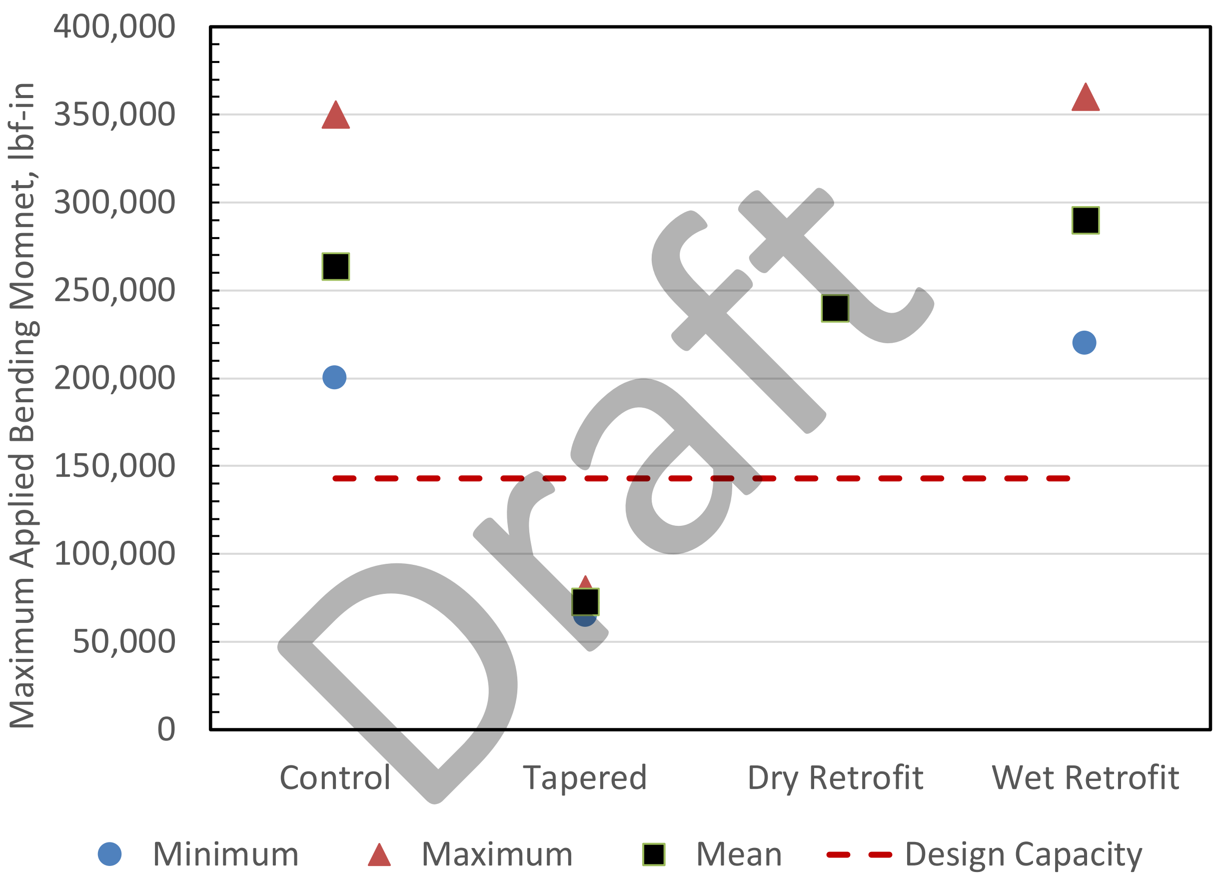

Figure 79. Timber pile flexural bending moment comparison

For the concrete piles (Figure 80), all capacities had an average 67% increase in strength over the factored ACI design moment capacity of approximately 460,000 lbf-in. The retrofits were able to increase the capacity of the beam by an average of 25% compared to the control beam capacity. Although no piers are under flexural beam loading conditions like that done in this testing series, the flexural beam loading tests do show that the original capacity can be restored by a retrofit.

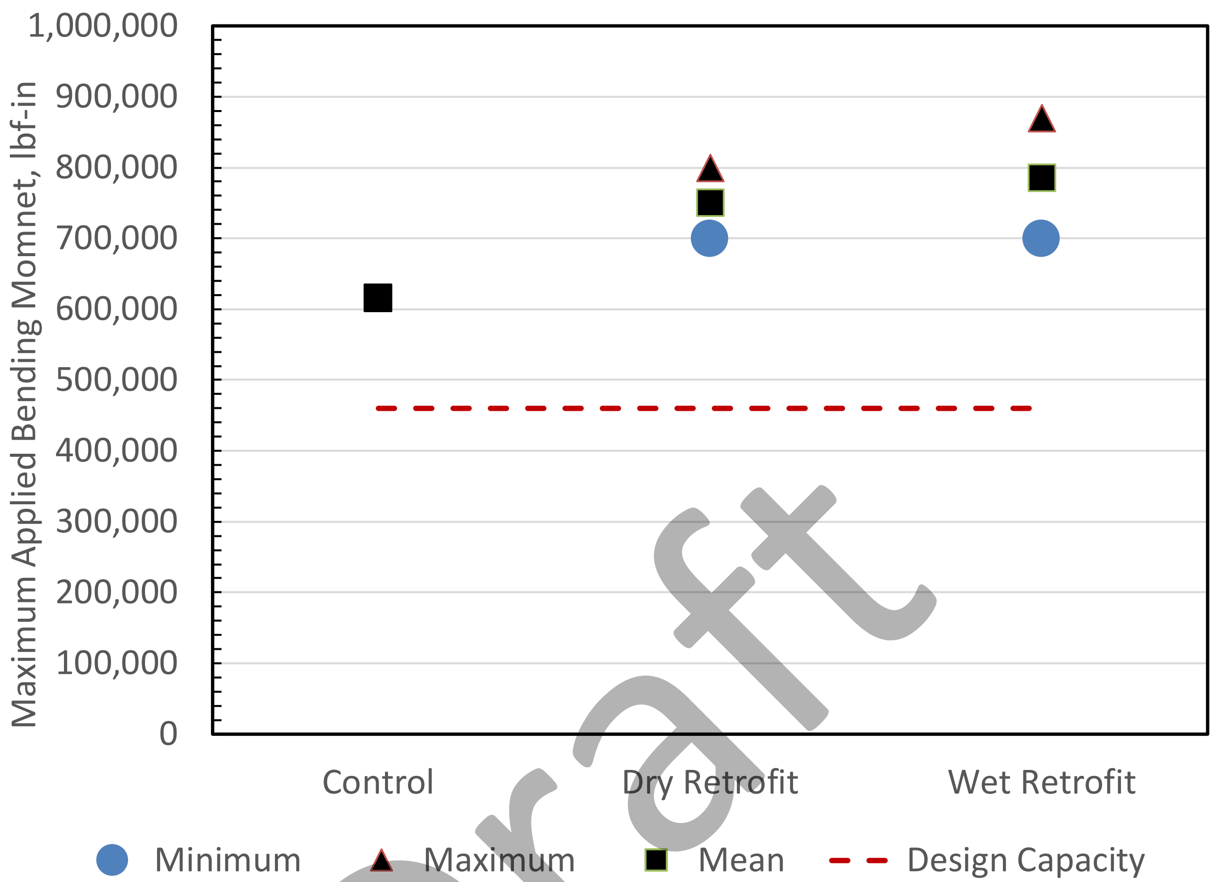

Figure 80. Concrete pile flexural bending moment comparison

It is important to note that in all tests, the tapered specimens without repairs failed in the damaged region; however, the tapered specimens with repairs did not fail in the damaged region, with the exception of one concrete beam. The failure location was pushed to the undamaged portion of the specimen, generally near the edge of the repair. The relocation of the failure region outside the damaged area demonstrates that the repair can recover the original design capacity and may be capable of increasing the strength of the pile in the repair region to greater than the capacity of the undamaged pile.

6 Limited Operational Utility Assessment

6.1 Purpose

The purpose of a JCTD operational utility assessment is to determine how the assessed products affect the resolution of an operational problem and fulfill operational desired capabilities. It assesses the level of operational utility according to the Concept of Operations (CONOPs) and Tactics, Techniques, and Procedure (TTPs); and provides post-JCTD transition, CONOPs and TTP, and Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities and Policy (DOTMLPF-P) recommendations (Defense Acquisition University, 2018).

The PIER Spiral 1 technologies were evaluated to assess their operational effectiveness, suitability, and overall utility when used by trained military construction units to accomplish repairs to damaged and degraded concrete and timber piles at Limited Operational Utility Assessment 1 (LOUA1) conducted at Wharf Victor 3 at Joint Base Pearl Harbor – Pearl City Annex, Hawaii. The LOUA was limited only in the sense that it evaluated the products of a single spiral of the JCTD, not the full suite of PIER JCTD spiral-developed products.

6.2 Technology Description

The PileMedic® kits as described in Section 4.4 were employed for the LOUA. Two types of grout pumps were employed. The first, an AIRPLACO HGA-530 pump, was powered by compressed air (Figure 81). The portable HGA-530 has a 30-gal mixer, 8-gal hopper, and 5-HP compressed air motor powered by an external air compressor. The pump features an air cylinder system, ball-check manifold, pressure gauge, and wide hopper for easy loading. The second pump type was a manually-operated AIRPLACO Handy-Grout HG-9 Pump shown in Figure 82. The HG-9 has a 5-gal hopper and 15 cu ft/hr production capacity. The pump has a self-priming manifold, an in-line pressure gauge, and does not require a power source.

Figure 81. Air-powered grout pump

Figure 82. Manual grout pump used at LOUA 1

6.3 Warfighter Teams

An Army dive team and a Navy dive team were assembled for the LOUA. The Army dive team consisted of personnel from the 7th Engineer Dive Detachment, 84 Engineer Battalion, 130th Theater Engineer Brigade based at Schofield Barracks, HI. The Navy team was a composite team consisting of personnel from Underwater Construction Team 1 (UCT 1), based at Joint Expeditionary Base Little Creek-Fort Story, VA, Mobile Diving Salvage Unit 1 (MDSU-1), based at Joint Base Pearl Harbor-Hickam, HI, and UCT 2, based at Port Huenume, CA.

6.4 Venue

The LOUA was conducted on the Victor 3 wharf at Joint Base Pearl Harbor-Hickam – Pearl City Annex, Hawaii. Victor 3 is located on the southeast end of the Pearl City Peninsula along the East Loch parallel to the shoreline. The Army team worked on the North end of the wharf, and the Navy team worked on the South end.

The wharf, constructed in 1943, was approximately 455 ft long and 40 ft wide. Water depth beneath the wharf ranged from 1.0 to 38.1 ft with a tidal variation of 1.8 ft. The wharf is support by 18-in-square concrete piles which were spaced at 10 ft on center. The concrete piles exhibited open and closed corrosion spalling and/or widespread cracking. The wharf was faced with 16-in-diameter timber fender piles spaced at approximately 5 ft apart. Many of the timber piles were damaged and in poor condition. All piles exhibited some loss of cross-section due to weathering, and in some cases, the exterior reinforcing bars were exposed. Selected concrete structural piles and timber fender piles were utilized in the demonstration.

6.5 Tasks

Each of the Army and Navy teams repaired a total of 12 piles over the course of three days of assessment:

- Army team - 6 timber piles and 6 concrete piles
- Navy team - 5 timber piles and 7 concrete piles

Day 1, 27 February, assessed the time it took to conduct repairs on 4 piles, consisting of 2 single wrap repairs and 2 triple wrap repairs, while conducting repair steps in a parallel work order (i.e., clean 4 piles, wrap 4 piles, pour grout for 4 piles).

During the final training day and the first day of assessment, the Army team utilized the manual, hand-operated grout pump; and the Navy team utilized a pneumatic powered grout mixer and pump. On Day 2, 28 February, the teams swapped out grout pumps. Day 2 again assessed the time it took to conduct repairs on 4 piles, consisting of 2 single wrap repairs and 2 triple wrap repairs, while conducting repair steps in a parallel work order. On the last day of the assessment, 1 March, the two repair units began work in the afternoon, requiring them to work into the evening to assess the Pile Jacketing Repair Kit capability used at night.

6.6 Schedule

The PIER LOUA 1 operating window was 20 February 2017 through 3 March 2017. The master schedule for the event is presented in Table 4.

Table 4. LOUA Master Schedule

	WEEK 1				
	MONDAY 20-Feb	**TUESDAY 21-Feb**	**WEDNESDAY 22-Feb**	**THURSDAY 23-Feb**	**FRIDAY 24-Feb**
AM	Venue Preparation and Setup*	Training Rehearsal*	Classroom Orientation	Dive Station Setup	Wet Training
PM			Dry Training	Wet Training	
	WEEK 2				
	MONDAY 27-Feb	**TUESDAY 28-Feb**	**WEDNESDAY 1-Mar**	**THURSDAY 2-Mar**	**FRIDAY 3-Mar**
AM	**Assessment Day 1** x2 Single x2 Triple (USA/USN)	**Assessment Day 2** x2 Single x2 Triple (USA/USN)	*Rest*	After Action Report and Visitor's Day Preparation	**Visitor's Day**
PM			**Assessment Day 3:** x2 Single x2 Triple (USA/USN)		Clean-up and Shutdown
*PIER Integrated Management Team members only (no warfighters).					

6.7 Training

Personnel from ERDC and PileMedic® provided training to the Army and Navy teams that consisted of a classroom orientation, dry training on pile mockups, and wet training on Victor 3 timber and concrete piles. Training materials consisted of a PileMedic® User's Manual that was prepared for the event. The training materials are presented in Appendix C.

On the first day of training, a classroom orientation session was conducted to familiarize the warfighters with purpose and objectives of the LOUA and to introduce the pile jacketing TTPs developed by the technical management team. Immediately after the classroom session, instructors from the technical management team demonstrated the TTPs on a dry-side training mockup constructed by the ERDC team for that purpose. The warfighters were subsequently allowed to practice the TTPs on the dry training site with instructor guidance (Figure 83).

Figure 83. Dry-side training

On the second day of training, the warfighters trained in the water and applied the TTPs to piles from the Victor 3 wharf. A third and final day of wet training was conducted in the wet (Figure 84 through Figure 86) in which each of the Army and Navy dive teams completed repairs on two additional piles on Victor 3.

Figure 84. Divers prepare to enter the water

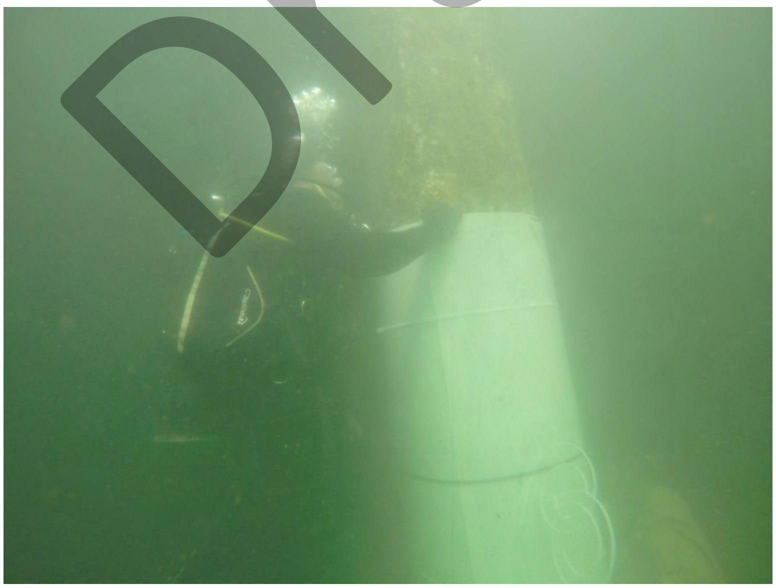

Figure 85. Underwater placement of jacket

Figure 86. Grout placement

6.8 Assessment Methodology

An independent assessor (IA) team was furnished by the JCTD Operational Manager (OM). This team consisted of assessors from the Space and Naval Warfare Systems Center Pacific (SCC PAC) Field Experimentation Team's (FET). The FET assessment team evaluated the Effectiveness, Suitability, and Mission Impact of the PIER Spiral 1 Pile Jacketing Repair Kit capability during employment and installment to repair damaged concrete and timber piles. The IA captured and reported on the warfighters' evaluation of the PIER technologies. Responsibilities included planning the assessment, developing the Assessment Execution Document (AED), developing data collection forms and questionnaires, collecting and analyzing data, and provided a report of the results (Donovan & Dubach, 2017).

The standard time to complete repairs to four piles, consisting of two piles requiring single wrap repair and two piles requiring triple wrap repair, was a 10-hour planning factor based on repair planning times developed by ERDC. This 10-hour planning factor was used as a baseline objective with the TTPs that were presented to the warfighters to identify problems and limitations observed during the LOUA. Three Critical Operational Issues (COIs), which are high-level questions to be answered during the assessment, were developed by the OM and IA to help focus the PIER JCTD effort. The COIs are as follows:

- **COI 1**. Do the PIER capabilities effectively rehabilitate a damaged or degraded pier?

- **COI 2**. Are the PIER capabilities suitable for use in the operational environment?
- **COI 3**. Do the PIER capabilities positively impact the capability to project forces and logistical support?

The IA team examined these COIs during LOUA 1 to determine if the Spiral 1 technical solution brought forward performed its intended function of providing an expedient Pile Jacketing Repair Kit capability. Additionally, these COIs had twelve accompanying objectives as outlined in Table 5. However, not all objectives were assessed at LOUA 1; only objectives 1.2, 2.2, 2.3, 2.4, 2.5, 2.6, and 3.1 were assessed. The specific Objectives, MOEs, MOSs, and MOPs that were addressed during the LOUA 1 event are provided and discussed in the Results and Annex B sections of the report.

Table 5. COIs and Objectives

COI 1: Do the PIER capabilities effectively rehabilitate a damaged or degraded pier?
Objective 1.1 Not assessed in this spiral.
Objective 1.2 Assess Pile Jacketing capability for expedient temporary repair of damaged concrete and timber piles.
Objective 1.3 Not assessed in this spiral.
Objective 1.4 Not assessed in this spiral.
Objective 1.5 Not assessed in this spiral.
COI 2: Are the PIER capabilities suitable for use in the operational environment?
Objective 2.1 Assess PILLAR damage assessment capabilities for reliability, availability, and maintainability.
Objective 2.2 Assess PIER equipment reliability, availability, and maintainability.
Objective 2.3 Assess PIER compatibility.
Objective 2.4 Assess PIER interoperability.
Objective 2.5 Assess PIER transportability, supportability, and storage.
Objective 2.6 Assess PIER training.
COI 3: Do the PIER capabilities positively impact the ability to project forces and logistical support?
Objective 3.1 Assess PIER capability to establish a minimally-capable military strategic port.

The various COIs have metrics expressed as measures of effectiveness (MOEs), measures of suitability (MOSs), or measures of performance (MOPs). Each of these are described in detail by Donovan and Dubach (2017) and are not detailed in this report. The IA gathered essential data elements to support the COIs, objectives, MOEs, MOSs, and MOPs during the assessment. The types of data collected and sources utilized by the IA to assess the LOUA 1 capabilities' effectiveness, suitability, and overall utility are the following:

- **Objective Data** was gathered by data collectors to address measures that required quantitative information (e.g., time).
- **Subjective Data** consisted of warfighter and data collector observations and comments, as well as survey ratings. Subjective data was collected via surveys, informal interviews with warfighters, and After Action Reviews.
- **Warfighter Surveys** (subjective) were completed at the end of the assessment to solicit feedback on the training received and to address the effectiveness, suitability, and mission impact of the PIER Pile Jacketing capability.
- **Warfighter Demographics Survey** (objective) was completed before warfighter training was held to baseline each participating warfighter's operational experience and possible exposure to the PIER technologies prior to LOUA 1.
- **Observation / Event Logs** (subjective) were completed daily to record pertinent information observed during each day of the assessment not captured on other forms.
- **After Action Reviews (AAR)** (subjective) with warfighters were conducted after each day's assessment and at the end of the LOUA event to capture comments and impressions.
- **Interviews** (subjective) were used to clarify information or solicit additional feedback.
- **Maintenance, Compatibility, and Interoperability Logs** (objective) were completed by data collectors to capture any maintenance, compatibility, and interoperability issues noted, the time the incident occurred, how long it took to repair/mitigate, and who conducted the repair.
- **Photographs** were taken during training and assessment periods to document the LOUA.

6.9 Findings Summary from the IA

The PIER JCTD Spiral 1 related equipment and material for repair of damaged or degraded piles using pile jacketing technology, along with proposed TTPs, are an improvement over current pile repair processes. The pile jacket repair kits demonstrated significant capabilities for an expedient and effective means to repair multiple damaged or degraded piles. Both Army and Navy repair teams were able to effectively apply the technology. The capabilities demonstrated during the LOUA will result in the re-opening of a damaged or degraded pier/wharf much sooner than current military construction capabilities.

The LOUA demonstrated that a standard 10-man Army Dive Detachment or 15-man UCT Detachment provides an adequate number of personnel to conduct expedient pile jacketing repair operations using the Pile Jacketing Repair Kit capability.

The PIER JCTD Spiral 1 training and training materials were assessed to be meaningful, helpful, and effective in preparing the repair teams to perform pile jacketing repairs. Three days training time was adequate for achieving user proficiency in performing pile jacketing repairs.

All pile jacketing repair kit equipment, materials, and support tools were interoperable and worked effectively together as a system. It was not anticipated that the pile jacketing repair kit capability will have interoperability issues with any of the other PIER JCTD spirals in development or with service specific survey, assessment, or repair systems.

All pile jacketing repair kit equipment and materials were acceptable and suitable for transportation by sea, air, and land transportation methods. All components of the fielded capability can be placed on standard cargo transportation pallets (463L). The weights of all Pile Jacketing Repair Kit equipment and material components delivered to the LOUA were deemed suitable and acceptable. The size of the repair kit package was scalable to meet mission requirements.

7 Summary, Conclusions, and Recommendations

7.1 Summary and Conclusions

PIER Spiral 1 focused on identifying and adapting a COTS pile jacketing technology to expediently repair concrete or timber marine piles supporting piers, wharfs, and other harbor structures. The materials and methods were investigated and modified to enable warfighters to expediently restore pile capacity. Spiral 1 assumed the military unit charged with installing pile jackets is capable of underwater construction and thus has training, equipment, and skills related to construction and repair of structures in a marine environment. Foremost, the unit must have dive capabilities. Beyond this basic requirement, it was assumed that the underwater construction team has access to all the equipment in their TOA. Any equipment or tools required to install the pile jackets beyond the TOA was provided in the pile jacket kits.

The PIER technical team identified and quantified the baseline technical requirements to be met by the pile jacketing technology. Market research was conducted through a formal Request for Information. Subsequently, a Request for Proposal was extended to interested vendors to demonstrate their pile jacketing technologies at a test site in a dry, controlled environment. Using the developed technical requirements, three proposals for candidate pile jacketing further evaluation were selected from a total of six vendor responses. After evaluating these three technologies in a controlled environment, a single candidate technology was selected for TD. The TD provided an opportunity to showcase the technology in a relevant environment, evaluated TTPs, and allowed stakeholders to provide feedback and input. Finally, the technology and associated TTPs were evaluated for military utility at a Limited Operational Utility Assessment (LOUA).

The Spiral 1 technical team selected PileMedic® product because the jacket had the greatest adaptability to piles of different shapes and sizes. The FRP laminate rolls are amenable to shipping on military 463L pallets. PileMedic® also met the criteria for structural capacity restoration; speed and ease of installation; time from installation to reaching capacity; adaptability to freshwater and seawater environments; and shelf life. As a result of technical testing, the Spiral 1 team requested that PileMedic® improve their method for sealing the bottom of the repair (improved skirt) and provide improved spacers to enforce the annular space between the pile and wrap.

The PileMedic® manufacturer worked with the technical team to modify the COTS product to better meet the needs of the military. The primary component of the Spiral 1 repair kit consisted of the patented PileMedic® technology solution for timber and concrete pile restoration developed and manufactured by QuakeWrap, Inc. PileMedic® includes PileMedic® Fiber Reinforced Polymer (FRP) laminate sheets, QuakeBond® Underwater Epoxy Resin, Spacers, and Rigid Foam Base Insert and Skirt.

The PileMedic® system can use Portland cement grout or epoxy resin grout as fill. A readily available pre-packaged commercial Portland cement grout was adopted for demonstration purposes. This material was mixed with potable water according to the manufacturer's specifications and pumped into the annular space between the pile and the FRP liner using the tremie method. The grout was mixed in 5-gal buckets using a handheld air-powered drill motor to power a small mixer paddle.

The Spiral 1 Technical Team identified the need to validate the axial capacity restoration published by the manufacturer. In addition, the Spiral 1 team identified the need to study the flexural capacity of the pile repairs. The main reason flexural tests were included along with axial tests is that, typically, the axial response of the column is largely governed by the eccentricity of the load, which causes flexural loading in the columns. These tests indicated that repairs made to timber and concrete piles restored all or nearly all the pile's original strength, and in all cases, exceeded the design capacity of a virgin pile. The repairs will likely force the failure zone outside the repair area, indicating the efficacy of the repair techniques and materials.

The PIER Spiral 1 technologies were evaluated to assess their operational effectiveness, suitability, and overall utility when used by trained military construction units to accomplish repairs to damaged and degraded concrete and timber piles at LOUA1 conducted at Wharf Victor 3 at Joint Base Pearl Harbor – Pearl City Annex, Hawaii. The LOUA was limited only in the sense that it evaluated the products of a Spiral 1, not the full suite of PIER JCTD spiral-developed products.

The Victor 3 wharf, constructed in 1943, was approximately 455 ft long and 40 ft wide. Water depth beneath the wharf ranged from 1.0 to 38.1 ft with a tidal variation of 1.8 ft. The wharf is support by 18-in-square concrete piles which were spaced at 10 ft on center. The concrete piles exhibited open and closed corrosion spalling and/or widespread cracking. The wharf was faced with 16-in-diameter timber fender piles spaced at approximately 5 ft apart. Many of the timber piles were damaged and in poor condition. All piles exhibited moderate to heavy weathering. Selected concrete structural piles and timber fender piles were utilized in the demonstration.

Both an Army dive team and a Navy dive team participated in the LOUA. The Army dive team consisted of personnel from the 7th Engineer Dive Detachment, 84 Engineer Battalion, 130th Theater Engineer Brigade based at Schofield Barracks, HI. The Navy team was a composite team consisting of personnel from Underwater Construction Team 1 (UCT 1), based at Joint Expeditionary Base Little Creek-Fort Story, VA, Mobile Diving Salvage Unit 1 (MDSU-1), based at Joint Base Pearl Harbor-Hickam, HI, and UCT 2, based at Port Huenume, CA. Each of the Army and Navy teams repaired a total of 12 piles over the course of three days of assessment.

The PIER JCTD Spiral 1 related equipment and material for repair of damaged or degraded piles using pile jacketing technology, along with proposed TTPs, were found to be an improvement over current pile repair processes. The pile jacket repair kits demonstrated significant capabilities for an expedient and effective means to repair multiple damaged or degraded piles. Both Army and Navy repair teams were able to effectively apply the technology. The capabilities demonstrated during the LOUA will result in the reopening of a damaged or degraded pier/wharf much sooner than current military construction capabilities.

The most common point of inconvenience during grouting was leakage of the grout around the skirt that seals the bottom of the annular space between the FRP and pile. This leakage results in clouding of the water in the vicinity of the repair and could lead to occurrence of voids in the grout.

The tremie method was used during the TD and LOUA to place grout in the annular space between the FRP sheet and the pile. This method was found to be inefficient and, on occasion, resulted in the formation of voids within the annulus. An improved grout placement method should be adopted that reduces diver involvement and decreases the potential for grout voids.

Round and square piles required different types of spacers to achieve annular spacing between the pile and FRP jacket. This increases the number of components required and unnecessarily complicates the kits.

The LOUA demonstrated that a standard 10-man Army Dive Detachment or 15-man UCT Detachment provides an adequate number of personnel to conduct expedient pile jacketing repair operations using the Pile Jacketing Repair Kit capability.

The PIER JCTD Spiral 1 training and training materials were assessed to be meaningful, helpful, and effective in preparing the repair teams to perform pile jacketing repairs. Three days training time was adequate for achieving user proficiency in performing pile jacketing repairs.

All pile jacketing repair kit equipment, materials, and support tools were interoperable and worked effectively together as a system. It is not anticipated that the pile jacketing repair kit capability will have interoperability issues with any of the other PIER JCTD spirals in development or with service specific survey, assessment, or repair systems.

All pile jacketing repair kit equipment and materials are acceptable and suitable for transportation by sea, air, and land transportation methods. All components of the fielded capability can be placed on standard cargo transportation pallets (463L). The weights of all Pile Jacketing Repair Kit equipment and material components delivered to the LOUA were deemed suitable and acceptable. The size of the repair kit package is scalable to meet mission requirements.

7.2 Recommendations for Improvement

It is recommended that the technical team work with the manufacturer to make the following evolutionary improvements to the Spiral 1 kits prior to the final OUA:

1. The bottom skirt of the system should be replaced with a thicker polyethylene sheet with internal string reinforcement. This system should be no less than 26 in. in length.

2. Abandon the tremie method of grout placement. Develop and test a self-tapping grout port that can be placed at the bottom of the FRP jacket. This port will allow grout to flow from the bottom of the repair toward the top during placement. An integral guillotine gate will be required with this port to allow grout to be pumped into the annular space while preventing it from flowing back out once the pumping tube is removed.

3. Develop and implement a common spacer for square and round piles to reduce the number of components and simplify the system. This spacer should be designed to accept rebar for reinforcement on wooden piles, if required.

8 References

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Mohammadi, A., Gull, J., Taghinezhad, R., & Azizna, A. (2014). *Assessment and Evaluation of Timber Piles Used in Nebraska for Retrofit and Rating.* Miami, FL.: Florida International University.

The American Concrete Institute. (2014). *ACI 318-14: Building Code Requirements for Structural Concrete.* Farmington Hills, Michigan: American Concrete Institute.

Yang, Y., Sneed, L., Saiidi, S., Belarbi, A., & Eshani, R. (2015). Emergency repair of an RC bridge column with fractured bars using externally bonded prefabricated thin CFRP laminates and CFRP strips. *Composite Structures Vol. 133*, 727-738.

Appendix A: Timber Pile Design Capacity Calculations

Reference: American Wood Council. 2015. "National Design Specification for Wood Construction." Leesburg, VA

<u>Assume Southern Pine Pile (Table 6A), where</u>:

$F_c = 1{,}200$ psi
$F_b = 2{,}400$ psi
$F_v = 110$ psi
$F_{Ct} = 250$ psi
$E = 1{,}500{,}000$ psi
$E_{min} = 790{,}000$ psi

<u>Adjustment Factors:</u>

Load Duration Factor, C_D, where:
$C_D = 1.6$ (chosen due to relatively rapid load application)

Temperature Factor, C_t, where:
$C_t = 1.0$ (temp. less than 100° F)

Untreated Factor, C_u,where:
$C_u = 1.0$ (lumber is treated)

Critical Section Factor, C_{cs}, where:
$C_{cs} = 1.0$ (pile not tapered for driving)

Single Pile Factor, C_{sp}, where:
$C_{sp} = 1.0$ (even though this is a single pile, this factor is unnecessary for laboratory test comparison)

Column Stability Factor, ℓ_e, where:
$\ell_e = 120 \text{ in.} + 10.5 \text{ in.} + 2.5 \text{ in.} = 133 \text{ in.}$

$F_c^* = 1{,}200\ (1.6) = 1{,}920$ psi

$$F_{cE}\frac{0.822(790{,}000)}{\left({}^{133}/_{8}\right)^2} = 2349.5$$

$$c = 0.85$$

$$C_p = \frac{1 + (F_{cE}/F_c^*)}{2c} - \sqrt{\left[\frac{1 + (F_{cE}/F_c^*)}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}}$$

$$C_p = \frac{1+(2349.5/1920)}{2(0.85)} - \sqrt{\left[\frac{1+(2349.5/1920)}{2(0.85)}\right]^2 - \frac{2349.5/1920}{0.85}}$$

$$C_p = 0.788$$

<u>Allowable Bearing Stress:</u>

$$F_c' = F_c^* C_p = 1{,}512.96 \text{ psi}$$

$$F_b' = F_b C_D C_t C_u C_F C_{sp} = 1.6(2{,}400 \text{ psi}) = 3{,}840 \text{ psi}$$

<u>Combined bi-axial bending and axial compression:</u>

$$e' = 0.9 \text{ in.}$$

$$\left(\frac{f_c}{F_c'}\right)^2 + \frac{f_c(6e_1/d_1)\left[1 + 0.234\left(f_c/F_{cE_1}\right)\right]}{F_{b_1}'\left[1 - (f_c/F_{cE2})\right]} \leq 1$$

<u>Using Goal Seek Feature in Excel, calculate allowable axial stress:</u>

$$f_{c,max} = 1{,}139.45 \text{ psi}$$

<u>Calculate allowable bending moment:</u>

$$A_t f_{c,max} = 57{,}275 \text{ lb}$$

$$f_b' = 3{,}840 \text{ psi}$$

For bending stress = $\sigma = \frac{M \cdot y}{I} = f_b'$

Solving for M => $M = \frac{f_b' \cdot I}{y}$

$y = 4$ in.

$$I = \frac{\pi d^4}{64} = \frac{\pi(8")^4}{64} = 201.1 \text{ in.}^4$$

$$M = \frac{3840 \text{ psi} \cdot 201.1 \text{ in.}^4}{4 \text{ in.}} = 192{,}960 \text{ lbf} - \text{in.}$$

Therefore:

Allowable axial stress in timber pile is 1,140 psi.

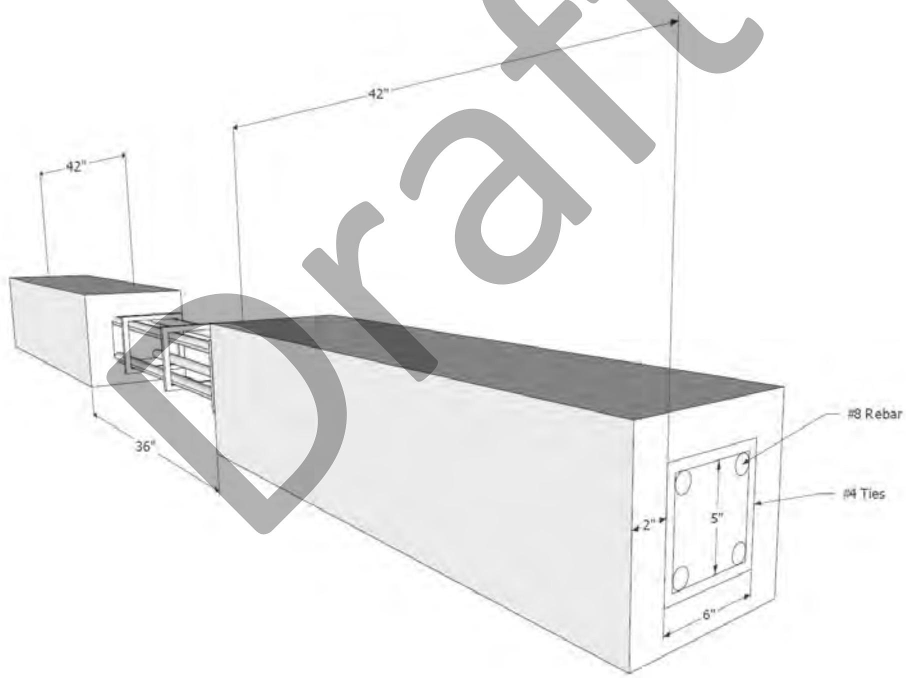
Allowable bending moment in timber beam is 192,960 lbf-in.

Appendix B: Concrete Pile Bending Capacity Calculations

Reference: The American Concrete Institute. 2014. *ACI 318-14: Building Code Requirements for Structural Concrete.* Farmington Hills, Michigan: American Concrete Institute.

<u>Interaction Diagram for Concrete Piles:</u>

Concrete Pile Description:



Pile Cross-Section: 10 in. by 10 in.

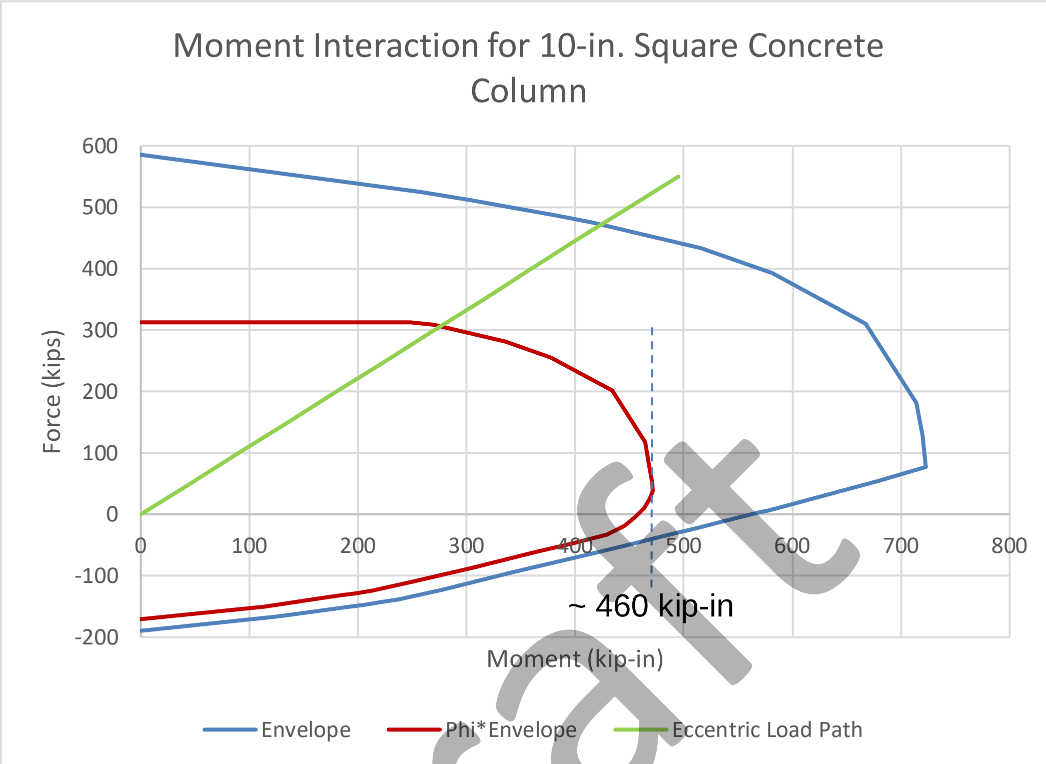
F'c = 5,000 psi

f_y = 60,000 psi

Four each No. 8 reinforcing bars axially

Stirrups consist of No. 4 reinforcing bars at 12 in. on center

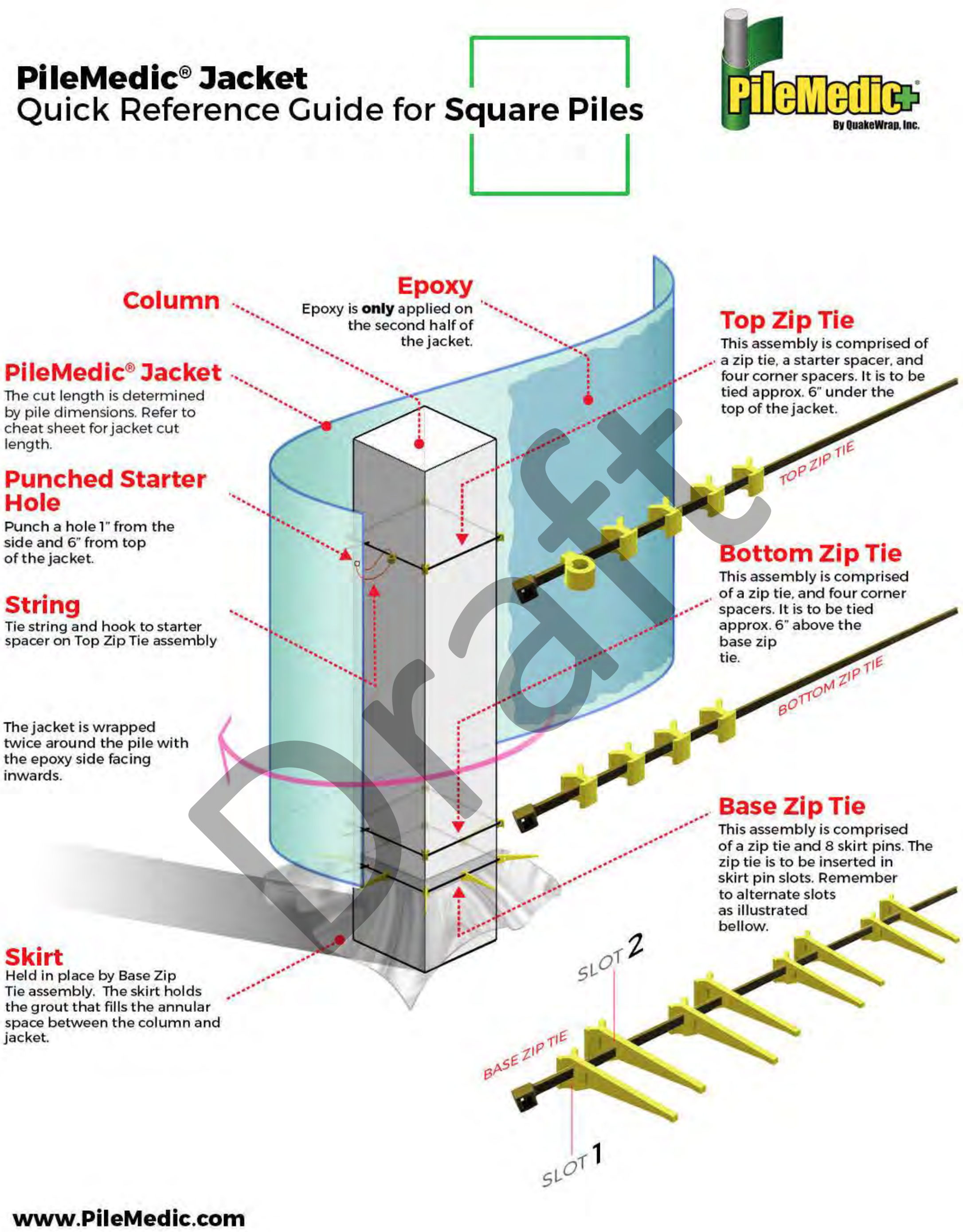
The
The
The



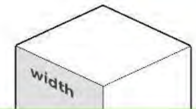
The interaction diagram envelope, shown above, represents the locus of all combinations of axial load and bending moment that cause failure in the 10-in.-square reinforced pile. The curve labeled "Phi*Envelope" incorporates a capacity reduction factor, Φ, which accounts for variability in materials and construction practices consistent with the ACI318-14 code.

From diagram above: Maximum factored bending moment in concrete pile is 460,000 lbf-in.

Appendix C: Training Manual


PileMedic® Jacket
Quick Reference Guide for Square Piles
PileMedic+
By QuakeWrap, Inc.
Column
Epoxy
Epoxy is only applied on the second half of the jacket.
Top Zip Tie
This assembly is comprised of a zip tie, a starter spacer, and four corner spacers. It is to be tied approx. 6" under the top of the jacket.
PileMedic® Jacket
The cut length is determined by pile dimensions. Refer to cheat sheet for jacket cut length.
TOP ZIP TIE
Punched Starter Hole
Punch a hole 1" from the side and 6" from top of the jacket.
Bottom Zip Tie
This assembly is comprised of a zip tie, and four corner spacers. It is to be tied approx. 6" above the base zip tie.
String
Tie string and hook to starter spacer on Top Zip Tie assembly
BOTTOM ZIP TIE
The jacket is wrapped twice around the pile with the epoxy side facing inwards.
Base Zip Tie
This assembly is comprised of a zip tie and 8 skirt pins. The zip tie is to be inserted in skirt pin slots. Remember to alternate slots as illustrated bellow.
SLOT 2
Skirt
Held in place by Base Zip Tie assembly. The skirt holds the grout that fills the annular space between the column and jacket.
BASE ZIP TIE
SLOT 1
www.PileMedic.com
Draft

PileMedic® Jacket
Dimension "Cheat Sheet" for **Square Piles**

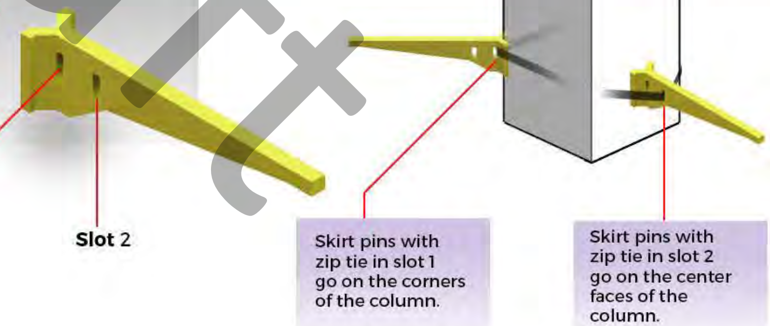


WIDTH (inches)	TOP ZIP TIE ASSEMBLY	BOTTOM ZIP TIE ASSEMBLY	BASE ZIP TIE ASSEMBLY	LENGTH TO CUT JACKET (INCHES)	GROUT VOLUME (FT^3) PER VERTICAL FOOT
8	4 Corner Spacers + 1 Starter Spacer	4 Corner Spacers	8 Skirt Pins	33	0.44
10	4 Corner Spacers + 1 Starter Spacer	4 Corner Spacers	8 Skirt Pins	38	0.66
12	4 Corner Spacers + 1 Starter Spacer	4 Corner Spacers	8 Skirt Pins	44	0.92
14	4 Corner Spacers + 1 Starter Spacer	4 Corner Spacers	8 Skirt Pins	49	1.23
16	4 Corner Spacers + 1 Starter Spacer	4 Corner Spacers	8 Skirt Pins	55	1.58
18	4 Corner Spacers + 1 Starter Spacer	4 Corner Spacers	8 Skirt Pins	61	1.97
20	4 Corner Spacers + 1 Starter Spacer	4 Corner Spacers	8 Skirt Pins	66	2.40

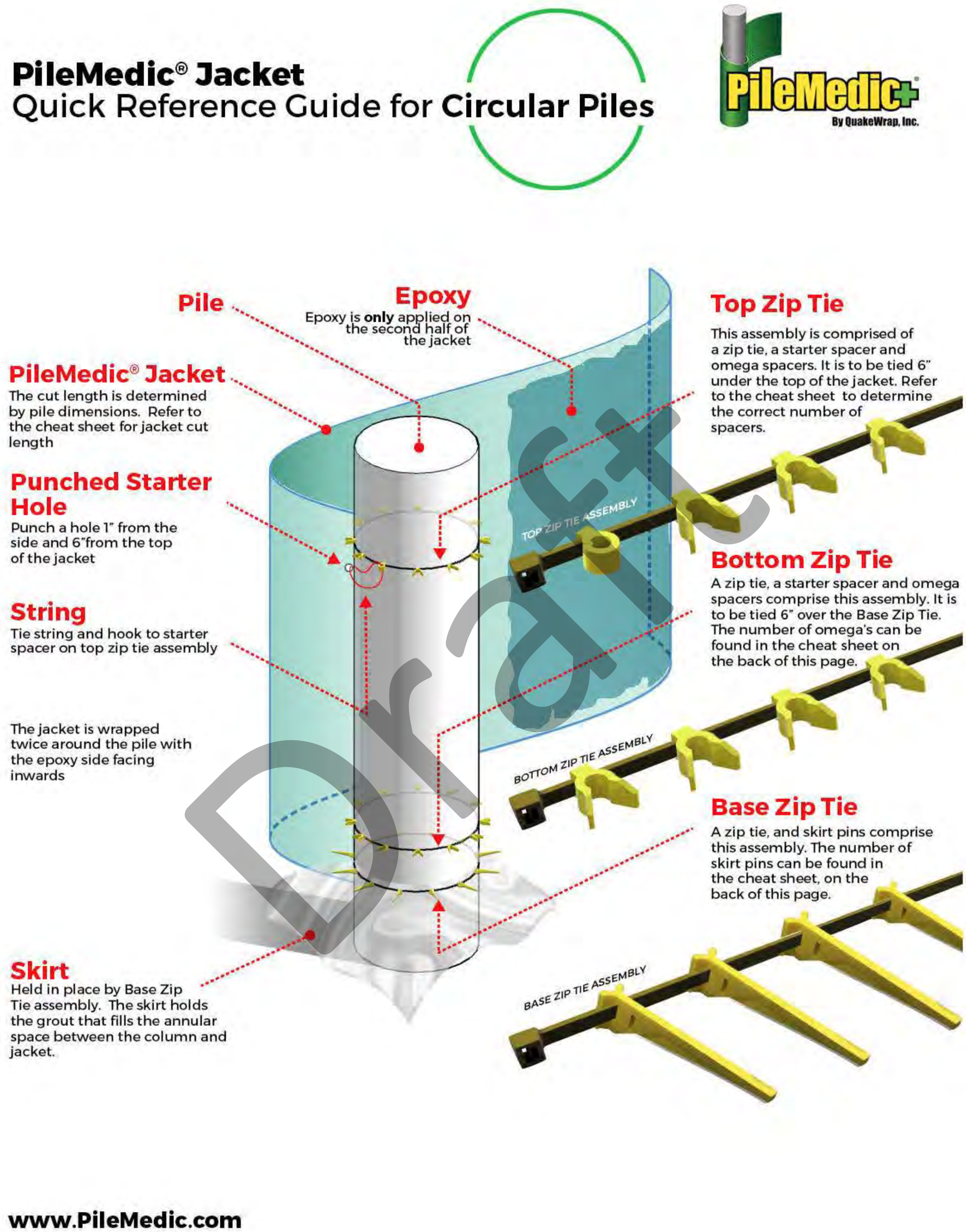
Corner Spacer
Used on the corners of the column.

Starter Spacer
Used for hooking jacket at the start of wrapping.

Skirt Pin
Used to pinch plastic skirt against pile and support the jacket.



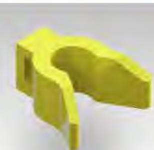
www.pilemedic.com


PileMedic® Jacket
Quick Reference Guide for Circular Piles
PileMedic+
By QuakeWrap, Inc.
Pile
Epoxy
Epoxy is only applied on the second half of the jacket
Top Zip Tie
This assembly is comprised of a zip tie, a starter spacer and omega spacers. It is to be tied 6" under the top of the jacket. Refer to the cheat sheet to determine the correct number of spacers.
PileMedic® Jacket
The cut length is determined by pile dimensions. Refer to the cheat sheet for jacket cut length
Punched Starter Hole
Punch a hole 1" from the side and 6"from the top of the jacket
TOP ZIP TIE ASSEMBLY
Bottom Zip Tie
A zip tie, a starter spacer and omega spacers comprise this assembly. It is to be tied 6" over the Base Zip Tie. The number of omega's can be found in the cheat sheet on the back of this page.
String
Tie string and hook to starter spacer on top zip tie assembly
The jacket is wrapped twice around the pile with the epoxy side facing inwards
BOTTOM ZIP TIE ASSEMBLY
Base Zip Tie
A zip tie, and skirt pins comprise this assembly. The number of skirt pins can be found in the cheat sheet, on the back of this page.
BASE ZIP TIE ASSEMBLY
Skirt
Held in place by Base Zip Tie assembly. The skirt holds the grout that fills the annular space between the column and jacket.
www.PileMedic.com

PileMedic® Jacket
Dimension “Cheat Sheet” for Circular Piles

Diameter (inches)	TOP ZIP TIE ASSEMBLY	BOTTOM ZIP TIE ASSEMBLY	BASE ZIP TIE ASSEMBLY	LENGTH TO CUT JACKET (INCHES)	GROUT VOLUME (FT^3) PER VERTICAL FOOT
8	4 Omega's + 1 Starter Spacer	4 Omega Spacers	4 Skirt Pins	58	0.31
10	5 Omega's + 1 Starter Spacer	5 Omega Spacers	5 Skirt Pins	71	0.38
12	6 Omega's + 1 Starter Spacer	6 Omega Spacers	6 Skirt Pins	83	0.44
14	7 Omega's + 1 Starter Spacer	7 Omega Spacers	7 Skirt Pins	96	0.51
16	8 Omega's + 1 Starter Spacer	8 Omega Spacers	8 Skirt Pins	108	0.57
18	9 Omega's + 1 Starter Spacer	9 Omega Spacers	9 Skirt Pins	121	0.64
20	10 Omega's + 1 Starter Spacer	10 Omega Spacers	10 Skirt Pins	134	0.70
22	11 Omega's + 1 Starter Spacer	11 Omega Spacers	11 Skirt Pins	146	0.77
24	12 Omega's + 1 Starter Spacer	12 Omega Spacers	12 Skirt Pins	159	0.83

Omega Spacer
Used on zip tie assemblies for circular piles.



Skirt Pin
Used to pinch plastic skirt against pile and to support the jacket.

Starter Spacer
Used for hooking jacket at the start of wrapping.

www.pilemedic.com

PileMedic® Step-by-Step Manual for Easy Installation

This manual will aid in the installation of the PileMedic® system.

Refer to the enclosed **PileMedic® Installer's Reference Guide** (*Figure 1*) **& Cheat Sheet** (*Figure 2*) to calculate the appropriate zip tie assembly, skirt and jacket length for your specific pile types and sizes.

Figure 1

Figure 2

Your PileMedic® Installation Box includes the following materials:

- Underwater Grout additive
- Foam
- Skirt
- Gloves
- QuakeBond® Epoxy Cartridges
- String
- Static Mixers for the Cartridges
- Putty Knives
- Starter Spacers
- Corner Spacers
- Skirt Pins
- Omega Spacers
- Marker
- Measuring Tape
- Zip Ties
- Duct Tape
- Shrink Wrap
- Roll of PileMedic® Jacket with a height of 4 feet

Your PileMedic® Tool Box includes the following:

- A pneumatic cartridge gun
- Electric drill
- Shears
- Vise Grips
- Mixing Paddle
- A manual cartridge gun

Installing Base, Top, and Bottom Zip Tie Assemblies

The appropriate type and number of spacers can be found in your PileMedic® Installers Cheat Sheet.

Note: Please ensure you are wearing appropriate safety gear during this installation.

1) Measure, Cut and Wrap skirt around the pile followed by the base zip tie assembly (*Figure 3*). The base zip tie assembly serves to pinch the skirt as tightly against the pile as possible. Shift the skirt pins around the pile to their appropriate positions, and let skirt hang down around the base spacers (*Figure 4*).

Figure 3

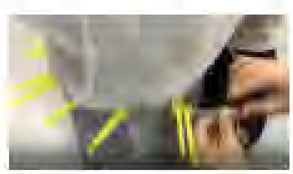


Figure 4

2) The top zip tie assembly begins with a starter spacer (*Figure 5*). This starter spacer is the anchor point for the jacket as you wrap the jacket around the pile. (Refer to Installer's Cheat Sheet for the number and type of spacers required).

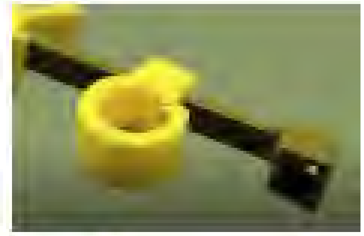


Figure 5

3) Assemble the bottom zip tie assembly (*Figures 6 and 7*). (Refer to Installer's Cheat Sheet for the number and type of spacers required).

Figure 6. Bottom zip tie assembly for round piles.

Figure 7. Bottom zip tie assembly for square columns.

Installation of the PileMedic® Jacket

Figure 8

1) Measure, Mark and Cut the Jacket (*Figure 8*) Please refer to the PileMedic® Installers Cheat Sheet to determine the length of jacket and what materials will be needed for your specific pile size.

Figure 9

2) Punch a small hole in the top corner of the jacket, and tie a loop through the hole (*Figure 9*). This loop will be used to anchor the top corner of the jacket to the pile.

3) Unscrew the cap of the QuakeBond® cartridge and screw the static mixer nozzle onto the cartridge. Load the cartridge into the manual or pneumatic dispenser. Dispense mixed epoxy on only HALF the jacket, and be sure it is on the jacket half that is **opposite** of the hole that was punched earlier. Spread mixed epoxy with a putty knife (*Figure 10*). The coat of epoxy should be about as thick as a credit card (or approximately 30 mils).

Figure 10

Attaching a pair of vise grips to the end of the jacket will allow the installer to get a tight grip on the jacket, as it is wrapped around the pile (*Figure 11*).


Figure 11

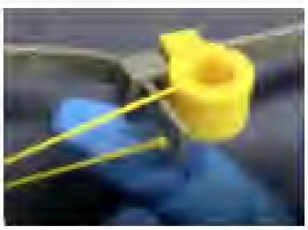


Figure 12

4) Secure the string into the starter spacer, then wrap the jacket around the pile allowing the epoxy to stick to the inside layer of the jacket (*Figure 12*).

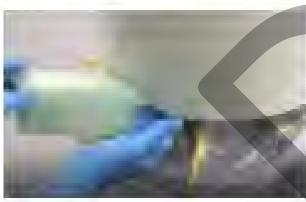


Figure 13

5) Wrap a few zip ties around the jacket to hold it in place during cure. Shove pieces of foam between the jacket and pile to fill the bottom of the annular space (*Figure 13*).


Figure 14

6) Lift the skirt up along the jacket and tightly secure with a zip tie (*Figure 14*).

Installing the Grout

Mix a Non-Shrink grout and pour it into the space between the pile and the PileMedic® jacket. Be sure to mix the grout according to manufacturer's recommendations. For applications below water level, you will need to use the **tremie grout placement method**.

For tremie grouting, place the end of the grout hose on the inside of the jacket, making sure it runs all the way to the bottom. Pump the grout until the inside level of grout is approximately six inches above the hose nozzle (*Figure 15*). Continue pumping while lifting the nozzle of the hose at the same rate, until the entire annular space between the pile and the jacket is filled. The water inside the jacket will turn grey during this process, so make sure you feel for sand when the grout level reaches the top of the annular space to make sure it is completely filled with grout.

Figure 15