ABSTRACT

ABDELWAHAB, KARIM ASHRAF. Repair of Severely Damaged Timber Piles Using GFRP Shells Reinforced with Longitudinal GFRP Rebar and Transverse CF Strips. (Under the direction of Dr. Rudolf Seracino and Dr. Gregory Lucier).

Timber piles are used extensively in construction due to their durability and relatively low cost. However, timber is prone to decay due to environmental conditions, wave action causing abrasion by sand particles, in addition to repetitive cycles of moisture and dryness leading to rot of the transition region. Furthermore, timber is susceptible to insect attack, which uses the timber as shelter or a source of food. Typically, damaged piles are repaired either by splicing the damaged section with a new timber segment, or reinforcing the pile with a reinforced concrete jacket. While the use of FRP to strengthen concrete elements is a well-established repair method, the use of FRP to repair timber piles is relatively new. This project studied a commercially available system used to retrofit timber piles, comprised of a GFRP shell reinforced with CF strips for increased confinement and an epoxy-based grouted annular ring. The research included material testing, large-scale compression tests, and full-scale flexural tests. The experimental program successfully demonstrated the effectiveness of the retrofit system.
DEDICATION

To my parents, Azza and Ashraf, thank you for making me who I am. And, my brother, Omar, thank you for leading the way.
BIOGRAPHY

Karim Abdelwahab was born in Cairo, Egypt. He graduated from high school earning his International General Certificate of Secondary Education (IGCSE) in 2011 to study civil engineering at Cairo University. He received his Bachelor of Science in Civil Engineering after five years of undergraduate study. After working as an independent design engineer, he decided to pursue a Master of Science in Structural Engineering at North Carolina State University.
ACKNOWLEDGMENTS

This project was funded by Warstone Innovations through the NSF/IUCRC Center for the Integration of Composites into Infrastructure. I would like to start by thanking Warstone Innovations for their nonstop guidance. Especially Mr. Stewart Kriegstein for his ongoing support, keen involvement, and valuable input since the start of the project. I have learned tremendously from the dedication and perseverance of Mr. Kriegstein.

I am extremely grateful and will forever be in debt to my professors Dr. Rudolf Seracino, Dr. Gregory Lucier, and Dr. Sami Rizkalla for guiding me over the span of two years. Dr. Seracino, thank you for your trust and for giving me this opportunity. Your mentorship and guidance taught me far more than I could write. Thank you for teaching me the qualities and principals that build a high value professional. Dr. Lucier, thank you for your patience and kind guidance, I grew exponentially from our discussions which directed me into becoming a better researcher. Dr. Rizkalla, thank you for sharing your expertise and for always having your door open. I highly appreciate your support during tough times and for pushing me to be my best.

This experimental program would not have been possible without the help of Mr. Jerry Atkinson and Mr. Jonathan McEntire, thank you for you helping me implement the experimental program, I truly appreciate your help. To all my CFL colleagues and especially my close friend, Mike Lin, thank you for lending a hand when I needed it the most. I am forever grateful for your help.
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CHAPTER 1: INTRODUCTION

1.1 Use of timber piles in infrastructure

Dating back to the 14th century, timber was an extensively used material in deep foundations. In early Venetian construction, timber piles were driven below the water line protecting them from decay. The demand on round timber piles in the United States of America grew during the 18th century where they were used in the transportation sector serving as the foundation of timber bridges, ports, and dams. Furthermore, residential construction relied on timber piles as an inexpensive and widely available option that was easily driven into the soil due to the circular shape of timber. Currently, timber piles are still a viable option in modern day construction for applications due to the abundance of timber and relatively low cost.

1.2 The need to strengthen timber piles

Timber is an organic material that is prone to deterioration from environmental conditions. Insects and marine borers are the main causes of pile deterioration which leads to the loss of the effective timber cross section. Timber piles that are completely submerged in water are immune from decay due to the absence of oxygen. However, piles that extend above the ground water level are exposed to atmospheric oxygen, which in the presence of water, provides a suitable environment for fungi and rot to develop. Wave action displacing sand particles often causes abrasion of the timber pile as shown in Figure 1-1 that shows a severely deteriorated timber pile located in an ocean front house in California, suffering from rot and an abraded cross section where the pile intersects the ground level. Furthermore, insects carving out significant portions of the timber for shelter or food leads to a substantial loss in the structural integrity of the pile, which is often not visually apparent and occurs internally of the timber cross section. While preservatives like creosote that are applied initially on the timber pile during construction
can protect the timber, it does not restore the capacity of the original pile. Therefore, the need to
develop structural repair systems to strengthen deteriorated timber piles emerged. Currently the
available repair solutions are either removing the deteriorated segment of the pile and replacing it
with new timber, which is referred to as splicing, or adding new material to the existing pile in
the form of a confining jacket or wrap. Traditionally, the jackets used are reinforced concrete.
Recently, fiber reinforced polymers have been used in the form of carbon fiber wraps applied in
a wet layup technique or prefabricated glass fiber jackets.

Figure 1-1: Deteriorated Timber Pile.
1.3 Proposed repair system

The program uses the Structural Column Strengthening (SCS) system, a commercially available strengthening system developed by Warstone Innovations and used in timber pile repair. The system is based on the FX-70 Structural Pilling and Repair System manufactured by Simpson StrongTie sharing the same outer shell and epoxy grout. The outermost component of the SCS system is a glass fiber (GFRP) jacket which is circular in cross section and contains a tongue and groove joint allowing it to encapsulate the timber pile. The second component is the carbon fiber (CF) straps that are laminated internally on the jacket along the hoop direction and connected with a continuity connection placed at the tongue and groove joint. The purpose of the continuity connection is to guarantee the continuity of the carbon fiber strap. It consists of two prefabricated GFRP pockets located on either side of the splice and are positioned directly above the CF straps. A CF laminate spans over the splice and is secured inside the pockets where epoxy bonds the laminate to the CF strap. The third component is the longitudinal glass fiber bars which are secured on the GFRP jacket using custom made positioners. The GFRP jacket along with the installed straps and bars encapsulate the timber pile, leaving an annuls gap where an epoxy-based grout is poured filling the gap between the pile and the jacket. These components are presented in Figure 1-2. Incorporating continuous carbon fiber straps and longitudinal reinforcement in the SCS system are the two main differences from the existing FX-70 system. These two additions were introduced to enhance the capacity of the system towards axial and flexural loads, which are the two possible failure modes for timber piles used in on shore buildings or in timber bridges. The CF straps aim to increase confinement in applications where the axial compressive capacity controls, while the rebar is added to resist flexure related failure modes, which mainly govern in slender piles found in on shore buildings.
Figure 1-2: SCS System.

1.4 Research goals and scope

A rigorous experimental program was carefully designed and implemented to assess the ability of the repair in restoring the ultimate capacity of severely damaged timber piles, while analyzing the effectiveness of each individual component in the system. The research program was aimed towards:

1- Providing experimental data to aid in the development of design recommendations.

2- Identifying the optimum strap spacing, which was investigated during both the compression and flexure testing chapters.

3- Studying the contribution of CF straps and longitudinal GFRP rebar towards the behavior of the SCS repair system when subjected to axial compression and flexural loading.

4- Fine tuning the continuity connection and identifying the governing failure modes.
1.5 Thesis Layout

The thesis stars with a brief literature review highlighting the research conducted on the use of FRP in the repair of timber piles (Chapter 2). The experimental program is then described in the following order.

- Chapter 3: presents the studies and experimentation conducted on the materials used in the experimental program. The small-scale ICE tests are presented in this chapter. This chapter provides the material properties of the material used in the repair.

- Chapter 4: presents the compression tests, where the chapter first introduces the specimens and specimen preparation before presenting and discussing the results. A conclusion is provided after this chapter summarizing the findings of the experimental program.

- Chapter 5: is divided into three sections. The first section describes the full-scale flexural tests, the second section presents the results of the flexural program, while the third section shows the analysis conducted using the experimental results.

Chapter 6 then summarizes the conclusions derived from the experimental program.
CHAPTER 2: LITERATURE REVIEW

This chapter presents an overview of the literature related to the strengthening of timber piles. The focus is on the repair techniques that use Fiber Reinforced Polymers (FRP) systems, categorized by FRP Wraps and FRP Jackets.

2.1 FRP Wraps

The use of FRP wraps in retrofitting timber has been experimented with for a few decades. Plevris and Triantafullou (1993) conducted an analytical and experimental investigation of applying CF sheets in the tension regions of wood beams subjected to 3-point flexure and eccentric compression. The experimental results showed that the CF sheets displaced the failure location to outside the strengthened region leading to a compressive failure mode in the timber section. Johns and Lacroix (2000) assessed the use of glass and carbon fibers in strengthening sawn timber sections to resist bending and shear. The strengthened beams showed an increase in the capacity of the wood inside the timber section and an overall increase in strength. Emerson (2004) experimentally assessed the use of glass fiber wraps and epoxy grout to repair deteriorated timber piles. The repair was successful in restoring the full compressive strength of the retrofitted timber piles. Recent publications have also been done on the use of FRP wraps to strengthen wooden beams. Andor et al. (2015) Conducted an experimental study on sawn Norway spruce beams strengthened with CF wraps which yielded an increase in load-bearing capacity and ductility of the retrofit. A slight increase in stiffness was also observed. Yeou-Fong et al. (2014) reinforced hollow section wood beams using glass fiber rods and CF wraps that were tested in 4-point bending. The experimental results show an increase in the flexural strength of the strengthened beams. Almitairi et al. (2020) studied the repair of softwood utility poles using glass fibre reinforced polymers by applying multiple layers of the GFRP fabric using a wet
layup technique. The prepared specimens were tested in three-point bending. The experimental results showed a significant enhancement in flexural capacity and stiffness.

2.2 FRP Jackets

FRP jackets are more convenient than FRP wraps as the jacket installation is less labor intensive and therefore less time consuming leading to a less complicated repair process. Lopez-Anido et al. (2003) developed a GFRP jacket to strengthen timber piles. Experimentation with done with the timber-jacket load transfer. Both a cementitious grout and steel shear connectors were assessed. The strengthened piles were tested in 3-point bending. Using the cementitious grout with the GFRP jacket the strengthened piles exceeded the ultimate bending capacity of the control specimens while the piles strengthened with the GFRP jacket and steel connectors were not able to restore the ultimate capacity of the damaged pile. Lopez-Anido et al. (2005) proposed using an FRP composite encasement filled with a grout material and shear connectors between the timber pile and the FRP encasement. Serving as both a strengthening and protection from marine borers and environmental conditions. Menkulasi et al. (2017) conducted an extensive experimental program evaluating the capacity of deteriorated timber piles strengthened with various commercially available FRP repair systems. 42 piles were concentrically and eccentrically loaded in axial compression. The strengthening systems were able to restore the original undamaged capacity of the timber piles, where the ultimate capacity of the pile was governed by the unstrengthened timber section. The effect of the grout ring was analyzed for systems that did use a GFRP jacket and a grouted annuls. The experimental results reached an inversely proportional relationship between the thickness of the grout ring and the strain experienced by the outer GFRP jacket.
2.3 Conclusion

FRP systems are gaining popularity as a means of retrofitting timber piles due to their success in restoring the original performance of an undamaged timber pile. Furthermore, the rapid installation process makes FRP a suitable solution for timber piles. Both wraps and jacketing are effective strengthening techniques. However, with the development of the composites industry the use of FRP jackets increased as they became available. According to the available literature, the topic of this research program which is incorporating GFRP rebars and confining CF straps in a FRP jacket strengthening system has not been conducted, as the Warstone SCS system introduced the continuity connection which allows for a continuous CF Strap bridging over the tongue and groove joint located in the GFRP shell. The benefit and effectiveness of the SCS System is rigorously assessed in the following chapters.
CHAPTER 3: MATERIAL TESTING

3.1 Introduction

This chapter presents the materials used in the experimental program along with the tests conducted each material. The small-scale Investigation of Circumferential-strain Experimental tests (ICE) tests conducted on segments of the repair are presented later in this chapter.

3.2 Materials Used

Most of the system’s materials remained unchanged during the experimental program. Therefore. However, the epoxy grout and timber did change between the two phases of testing, Table 3-1 provides the commercial product name of each material used in the experimental program. Table 3-2 provides the material properties obtained from the published data sheets from each respective manufacture. While data regarding the timber species is obtained from the National Design Specification for Wood Construction (NDS).

Table 3-1: Materials Used in Each Test.

<table>
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<tr>
<th>Test</th>
<th>Compression Tests</th>
<th>Full-Scale Flexure Tests</th>
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<tr>
<td>Timber</td>
<td>Douglas Fir</td>
<td>Yellow Southern Pine</td>
</tr>
<tr>
<td>GFRP Shell</td>
<td>Simpson StrongTie FX-70 Jacket</td>
<td>Simpson StrongTie FX-70 Jacket</td>
</tr>
<tr>
<td>Grout</td>
<td>Simpson StrongTie FX-70-6MP</td>
<td>Denso SeaShield 550</td>
</tr>
<tr>
<td>GFRP Rebar</td>
<td>-</td>
<td>Aslan 100 GFRP Rebars</td>
</tr>
<tr>
<td>CF Strap Fabric</td>
<td>Structure Wrap V2 190 UC</td>
<td>Structure Wrap V2 190 UC</td>
</tr>
<tr>
<td>CF Strap Saturant</td>
<td>BASF MasterBrace SAT 4500</td>
<td>BASF MasterBrace SAT 4500</td>
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</table>
Table 3.2: Material Properties

<table>
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<tr>
<th>Component</th>
<th>Material</th>
<th>Elastic Modulus, ksi</th>
<th>Tensile Strength, psi</th>
<th>Compressive Strength, psi</th>
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</thead>
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<tr>
<td>Timber</td>
<td>Douglas Fir</td>
<td>1,700</td>
<td>2,050*</td>
<td>1,300</td>
</tr>
<tr>
<td></td>
<td>Yellow Southern Pine</td>
<td>1,500</td>
<td>1,950*</td>
<td>1,250</td>
</tr>
<tr>
<td>Epoxy Grout</td>
<td>FX-70-6MP</td>
<td>310</td>
<td>2,200</td>
<td>9,950</td>
</tr>
<tr>
<td></td>
<td>SeaShield 550</td>
<td>310</td>
<td>2,200</td>
<td>9,950</td>
</tr>
<tr>
<td>GFRP Shell</td>
<td>FX-70 Jacket</td>
<td>701</td>
<td>14,939</td>
<td>-</td>
</tr>
<tr>
<td>CF Strap Fabric</td>
<td>V2 190 UC</td>
<td>16,849</td>
<td>205,140</td>
<td>72,000</td>
</tr>
<tr>
<td>CF Strap Saturant</td>
<td>MasterBrace SAT 4500</td>
<td>440</td>
<td>8,000</td>
<td>-</td>
</tr>
<tr>
<td>GFRP Rebar</td>
<td>Aslan 100</td>
<td>6,700</td>
<td>105,000</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes: *Unfactored Bending Design Value Table 6A – NDS Supplement.

3.3 Material Testing

3.3.1 Epoxy Grout

The epoxy-based grout transfers the stress between the timber pile and the GFRP jacket in addition to replacing the eroded timber section. For applications where the repair is partially or fully submerged in water, pouring the grout expels the water between the pile and the jacket during on site installation. Axial compression and splitting tensile tests were conducted on the two products used in the experimental program, in addition to testing an aggregate-grout mix as a lower cost alternative. The axial compression tests were conducted according to ASTM C39 and the splitting tension were according to ASTM C496. All cylinders measured 4 in. in diameter and 8 in. in height. The FX-70-6MP was tested on the 7th, 14th, 28th day. While the SeaSheild 550 specimens were tested on the 58th and 72nd day in compression and in tension, respectively.
Specimens were prepared using the directions provided by the respective manufacturer and let to cure at room temperature and under atmospheric pressure. The plastic molds were removed on test day. Table 3-3 shows the experimental results for the Simpson StrongTie FX-70-6MP grout material, while Table 3-4 presents the values for the Denso SeaShield 550 grout. These values are from plain grout cylinders.

Table 3-3: Simpson StrongTie FX-70-6MP Test Results

<table>
<thead>
<tr>
<th>Age (Days)</th>
<th>7</th>
<th>14</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Compression</td>
<td>Tension</td>
<td>Compression</td>
</tr>
<tr>
<td>Number of Cylinders</td>
<td>8</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Average Failure Load (kip)</td>
<td>99.5</td>
<td>64.5</td>
<td>111</td>
</tr>
<tr>
<td>Average Failure Stress (SD) (ksi)</td>
<td>7.92 (0.82)</td>
<td>1.29 (0.55)</td>
<td>8.83 (1.08)</td>
</tr>
<tr>
<td>Published Ultimate Strength (ksi)</td>
<td>7.90</td>
<td>1.70</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3-4: Denso SeaSheild 550 Test Results.

<table>
<thead>
<tr>
<th>Age (Days)</th>
<th>58</th>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Compression</td>
<td>Tension</td>
</tr>
<tr>
<td>Number of Cylinders</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Average Failure Load (kip)</td>
<td>139</td>
<td>-</td>
</tr>
<tr>
<td>Average Failure Stress (ksi)</td>
<td>11.1</td>
<td>-</td>
</tr>
<tr>
<td>Published Ultimate Strength (ksi)</td>
<td>9.95</td>
<td>-</td>
</tr>
</tbody>
</table>

The FX-70-6MP grout was mixed with pea gravel in attempt to reduce the cost. Two batches were prepared the first having a 1:1 ratio of grout to aggregate, while the second had a 3:1 ratio of grout to aggregate, which effectively reduces the grout bulk volume in the first batch by 50% and 25% in the second. Figure 3-1 presents a cylinder from each mixture after a splitting tension test showing the aggregate distribution, while the mixture ratios are provided in Table 3-5. The ratio of grout to aggregate was based on bulk volume and was achieved by marking the cylindrical molds at mid height for the 1:1 batch and at three quarters of the height for the 3:1 batch. That line represented the maximum amount of grout that would be poured into the cylindrical mold and the rest would be filled with aggregate to the top of the cylinder. After pouring the grout, the aggregate was dropped into the cylinders and mixed with a steel rod and left to cure at room temperature and under atmospheric pressure. The results of the grout-aggregate mixture testing is provided in Table 3-5.
Figure 3-1: Grout-Aggregate Mixture Cylinders After Testing: (a) 3 Grout: 1 Aggregate Batch. (b) 1 Grout: 1 Aggregate Batch.

Table 3-5: Grout-Aggregate Mixture Summary.

<table>
<thead>
<tr>
<th>Age (Days)</th>
<th>12</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grout to Aggregate Ratio</td>
<td>3G:1A</td>
<td>1G:1A</td>
</tr>
<tr>
<td>Height of Grout in 8-inch Cylinder (in)</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Reduction in Grout Volume (%)</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Number of Cylinders</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Average Failure Load (kip)</td>
<td>98.6</td>
<td>96.4</td>
</tr>
<tr>
<td>Average Failure Stress (SD) (ksi)</td>
<td>7.85(0.91)</td>
<td>7.67(1.51)</td>
</tr>
<tr>
<td>Reduction from Plain Grout at 7 Days (%)</td>
<td>-0.63</td>
<td>-2.91</td>
</tr>
</tbody>
</table>
3.3.2 CF Straps

Full-scale axial tensile tests were conducted on the CF straps and compared to the results of ASTM D3039 complying tension coupons, having the dimensions shown in Figure 3-2. In total, 20 full-scale CF straps were loaded in axial tension until failure. The 20 straps are divided into four sample groups all of which having the same V2 CF fabric mentioned earlier in this chapter. Table 3-6 shows detailed properties of the fabric. However, the saturating resin was different for each sample group. Table 3-7 provides the resin properties. In total, 12 tension coupons were prepared according to ASTM D3039 and were also divided to the same four sample groups as the full-scale straps.

![Figure 3-2: Specimen Dimensions: (a) Full-Scale Straps. (b) ASTM Coupons](image-url)
Table 3-6: Published CF Strap Fabric Properties.

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Tensile Strength (ksi)</th>
<th>Tensile Modulus (ksi)</th>
<th>Rupture Strain (%)</th>
<th>Tensile Strength per inch width (kips/in)</th>
<th>Laminate Thickness (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>StructureWrap V2 190 UC</td>
<td>205</td>
<td>16849</td>
<td>1.22</td>
<td>7.2</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Table 3-7: Published Resin Properties.

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Rupture Strain (%)</th>
<th>Tensile Modulus (ksi)</th>
<th>Ultimate Tensile Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MapeiWrap 31</td>
<td>1.60</td>
<td>377</td>
<td>5.80</td>
</tr>
<tr>
<td>MasterBrace SAT 4500</td>
<td>3.50</td>
<td>440</td>
<td>8.00</td>
</tr>
<tr>
<td>StructureWrap V2 200</td>
<td>2.25</td>
<td>470</td>
<td>10.5</td>
</tr>
<tr>
<td>CSS-ES</td>
<td>1.73</td>
<td>322</td>
<td>5.23</td>
</tr>
</tbody>
</table>
The average failure stress for the tested specimens is provided in Table 3-8 which is calculated by averaging 5 test specimens for the full-scale group and 3 test specimens for the ASTM coupon group. Typical failure modes are shown in Figure 3-3.

**Table 3-8: Tension Test Results.**

<table>
<thead>
<tr>
<th>Group</th>
<th>Average Failure Stress (SD) (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Scale</td>
</tr>
<tr>
<td>Mapei</td>
<td>149 (18.1)</td>
</tr>
<tr>
<td>BASF</td>
<td>146 (7.68)</td>
</tr>
<tr>
<td>V2 Composites</td>
<td>146 (13.0)</td>
</tr>
<tr>
<td>Simpson</td>
<td>121 (18.1)</td>
</tr>
</tbody>
</table>

**Figure 3-3: Typical Failure Modes: (a) Full-Scale Specimen Warped Rupture. (b) Full-Scale Specimen Eccentric Rupture. (c) ASTM Coupon.**
3.4 Small-Scale ICE Testing

The Investigation of Circumferential-strain Experimental (ICE) test was designed by Basalo et al. (2011) to measure circumferential strain of FRP laminates and was later used at NC State to test cylindrical FRP cylinders. The ICE test utilizes the expansion of water as it freezes to apply a uniform internal pressure on a cylindrical FRP laminate which is beneficial in determining the circumferential strain values and corresponding failure modes when an internal pressure is applied to the FRP cylinder. This technique was used in the experimental program to simulate the internal forces exerted on the repair system while confining a deteriorated timber pile. Figure 3-4 presents a typical ICE test specimen which is further discussed in the next section.

Figure 3-4: Typical ICE Test Specimen.
3.4.1 Test Setup

Segments of the repair were tested using the ICE test to determine the failure modes and corresponding ultimate strain values when the Warstone SCS repair system is subjected to a uniform internal pressure. The test setup consisted of two steel plates confining a segment of the Warstone SCS repair containing the GFRP jacket, a single CF strap and a single continuity connection, the steel plates were tied using three threaded rods. The top and bottom of the segment was sealed with silicone to provide a leak proof connection with the steel plates, a water valve was added to the top plate allowing the specimen to be filled with water. Specimens were placed in a thermal chamber set to -10°F and left to freeze. The specimens were taken out of the chamber once visual signs of failure were observed. For most specimens this occurred between 24 to 36 hours in the chamber. Three strain gauges were added to each specimen measuring hoop strain; two on the CF strap and one on the continuity connection as shown in Figure 3-5. This strain gauge setup remained unchanged for the entire length of the experimental program and is used in Chapter 4 and Chapter 5. In total 14 specimens were tested and are divided into two groups, the first having 5 specimens referred to as the tall segments group and were 11-inches in height. The second group had 9 specimens referred to as the short segments group and were 7-inches in height, both groups are shown in Figure 3-6. The tall segments group were used to obtain the failure strain of the GFRP shell as the 11-inch height allowed for failure to occur outside the CF strap and in the GFRP shell, while the short segments group were used to obtain the failure strain of the CF strap as the 7-inch height along with the fixation provided by the top and bottom steel plates allowed to directly test the CF strap. Testing a segment of the repair narrowed down the possible failure modes into two options: the rupture of the GFRP shell or CF strap while the continuity connection remained intact. While the second possible failure mode
was the rupture of the continuity connection. The first failure mode was more desirable as this would guarantee the development of the rupture strength of the CF strap before failure of the cross section. While the second failure mode is not desirable as it prevents the strength of the CF strap to develop and thus limiting the capacity of the cross section to the capacity of the tongue and groove joint in the GFRP shell. An experimental program was designed to obtain the optimum continuity connection design in terms of dimensions, epoxy gel and fabrication process that would guarantee the first failure mode where the CF strap would reach its rupture strength while the continuity connection would not rupture.

Figure 3-5: Typical Cross Section.
Figure 3-6: (a) Typical Tall Specimen. (b) Typical Short Specimen.
3.4.2 Specimens

The 14 specimens are divided into two groups based on the segment height. The five 11-inch tall specimens were all identical except for T-1 which had an internal 2-inch grout ring simulating a complete repair. Specimen T-1 was the first segment to be tested using the ICE test. The 7-inch short specimens consisted of nine specimens. Specimens S-1 and S-2 were the first two to be tested in this group each having a different epoxy gel in the continuity connection. The remaining specimens were identical to S-2 with slight modifications in the continuity connection made by Warstone Innovations. Figure 3-7 shows the specimens.

![Figure 3-7: (a) Specimen T-1 with Grout Ring. (b) Typical Tall Specimen. (c) Shown is Specimen S-2 Presenting a Typical Short Specimen.](image)
3.4.3 Test Results

This section presents the results of the experimental program. Focusing on the different failure modes and the corresponding failure strains. The results are focused on three specimens T-5, S-2 and S-8 that are representative for all specimens in terms of failure mode and failure strains. Specimen T-5 presents a specimen that failed in the GFRP shell while the CF strap and continuity connection remained intact. Specimen S-2 presents a specimen that failed in the CF strap while the continuity connection remained intact. Specimen S-8 presents a specimen that failed in the continuity connection while the CF strap and GFRP shell remained intact. A summary for the test results is presented in Table 3-9 where the mean strap and connection strains are calculated for the specimens having the same failure mode. The three types of failure modes are presented in Figure 3-8 showing specimens T-5, S-2 and S-8.

Table 3-9: Test Results.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Number of Specimens</th>
<th>Mean CF Strap Strain at Failure (SD) (µɛ)</th>
<th>Mean Connection Strain at Failure (SD) (µɛ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP Rupture</td>
<td>2</td>
<td>3366 (1205)</td>
<td>3689 (892)</td>
</tr>
<tr>
<td>CF Rupture</td>
<td>3</td>
<td>8142 (627)</td>
<td>6341 (1598)</td>
</tr>
<tr>
<td>Connection Slip</td>
<td>9</td>
<td>5141 (1793)</td>
<td>5005 (2116)</td>
</tr>
</tbody>
</table>
Figure 3-8: Failure Modes: (a) Connection of Specimen T-5. (b) Failure Location for Specimen T-5. (c) Connection of Specimen S-2. (d) Inner View showing Failure Location for Specimen S-2. (e) Connection Slip of Specimen S-8. (d) Inner View of Specimen S-2 Showing Intact CF Strap.
3.5 Conclusion

The grout cylinder tests verified the technical data published by the manufacturer. The results of the Denso SeaShield 550 were more desirable than Simpson StrongTie’s FX-70-6MP. Therefore, the experimental program continued with the Denso SeaShiled 550 epoxy grout for the flexural testing. A grout-aggregate mixture may be used as a low-cost alternative in cases where the full capacity of the epoxy grout is unnecessary. Reducing the grout by 50% had minimal effect on the 12-day compressive strength however the 14-day tensile strength decreased significantly with the reduction of volume of grout. The ASTM coupons achieved a higher rupture stress and a lower standard deviation for all the sample groups. This is due to the size effect phenomenon as the full-scale straps are larger which increases the number of defects in the specimen. The defects are usually in the form of warps in the CF fabric. The results of the ICE Tests provided experimental data on the failure modes and the corresponding rupture strains of the repair system, allowing the fine tuning of the individual components of the repair and identifying the optimum continuity connection design that would guarantee a desired failure mode.
CHAPTER 4: COMPRESSION TESTING

This chapter presents the compressive tests conducted on the strengthening system. The retrofitted timber specimens were tested in axial compression using the testing machine in Figure 4-1 by applying an axially compressive load to failure. This chapter introduces the experimental program and the adopted repair philosophy. Then, the measured test results and observed behavior during testing by means of load displacement diagrams, load strain diagrams and the failure modes are discussed.

Figure 4-1: Axial Compressive Testing Machine.
4.1 Experimental program

The experimental program was implemented to provide measured test data on the overall behavior of the retrofit when subjected to an axially compressive load. This was achieved by retrofitting artificially damaged timber segments and applying an axially compressive load on the timber segment till failure. Figure 4-2 shows a typical test specimen fully repaired inside the testing machine. The program was geared towards identifying the effect of the spacing and location of CF straps on the failure mode and ultimate compressive capacity, in addition experimentally assessing the ability of the repair to strengthen a severely deteriorated timber pile. The Warstone SCS system was also compared directly to the commercially available FX-70 Structural Repair and Protection System, in terms of ultimate capacity and ductility. Due to the absence of tensile loads, GFRP rebar were not incorporated in the retrofit. The test matrix consisted of testing 7 damaged and 1 undamaged control timber specimens. The specimens were divided into three sample groups where each sample group represented a different approach towards strap placement, in terms of strap location relative to the minimum timber cross section and spacing between consecutive straps. Specimens inside the same sample group shared a common strap placement approach while having different number of straps along with different strap spacing. Figure 4-2 shows a fully instrumented specimen inside the testing machine, where a 1.5-inch gap between the repair and the testing machine at each end can be seen. Hence 3
inches of total clearance between the repair and the testing machine is to guarantee that only the timber section is directly loaded in compression.

Figure 4-2: Fully Instrumented Specimen inside Testing Machine
4.2 Test Matrix

The round timber segments were 44-inches in height and 11-inches in diameter of Douglas Fir timber all sourced from the same provider, shown in Figure 4-3. Figure 4-4 presents the undamaged control specimen, used to obtain the capacity and failure mode of an undamaged timber segment. The damage shown in Figure 4-5 was induced in all but the undamaged control specimen to simulate a deteriorated pile. The induced damage was a 2-foot-long hourglass reduction in cross-section centered at the midspan of the specimen, reducing the cross section from the initial 11 inches diameter to 5.5 inches at midspan. Figure 4-6 shows the dimensions of the damaged segments. The timber specimens were damaged using a circular saw and a grinding tool to smoothen the tapered surface ensuring a gradual reduction in cross section.

Figure 4-3: Timber Segments Sourced from the Same Provider.
Figure 4-4: U-C Specimen.

Figure 4-5: Typical Induced Damaged Timber Segment.

Figure 4-6: Geometry of Damaged Timber Segments.
Six of the original eight timber segments proceeded to be retrofitted, 5 included internal straps representing the Warstone SCS system while the S-C specimen did not include internal straps which represented the FX-70 repair system shown in Figure 4-7. Structure Wrap V2 190 UC fabric was used for the carbon fiber straps and saturated with StructureWrap V2 200 Epoxy Resin. The grout used for all specimens was Simpson StrongTie’s FX-70-6MP marine epoxy grout while the GFRP shells used were Simpson StrongTie’s FX-70 Fiberglass Jacket.

Figure 4-7: S-C Specimen (GFRP jacket only).
The control sample group shown in Figure 4-8 presented the benchmark specimens, consisted of three specimens. An undamaged timber specimen U-C was chosen carefully to fairly represent the average condition of all the timber segments. This specimen provided the capacity and behavior of an undamaged and unstrengthened timber segment. This specimen was the only undamaged timber segment in all 8 specimens. The second specimen in this sample group was a damaged timber segment alone without providing any repair D-C to obtain the strength of the damaged timber segment. The third specimen was S-C which was the strengthened control, consisting of damaged a damaged timber segment repaired with the FX-70 repair system.

![Figure 4-8: Control Sample Group showing all Three Specimens.](image)

The second sample group is shown in Figure 4-9 is referred to as the interior strap sample group and consisted of three specimens with a common repair philosophy of providing CF straps at the minimum timber cross section to provide additional confinement at the most critical timber cross section. The first specimen INT-1 in this group had a single CF strap located at mid-height of the repair which corresponds to the location of the critical timber section. The number of straps were increased to two for the second specimen INT-2, where the straps were spaced 12
inches on center and positioned equidistant above and below the minimum damaged section by 6 inches. The third specimen INT-3 had three CF straps located at mid-height and two straps spaced 8-inches on center from the ends of the repair.

![Diagram of INT-1, INT-2, INT-3]

Figure 4-9: Interior Strap Sample Group.

The edge strap sample group shown in Figure 4-10 was developed after testing the control and interior strap sample groups. This will be discussed later in the chapter. The group consisted of two specimens sharing a common repair philosophy of strengthening the outer edges of the repair regardless of the location of the damaged timber section. This technique aimed at increasing the confinement at the edges of the repair to allow full development of the deformation capacity of the repair. Only two CF straps were installed in the first specimen of this sample group EDG-2, located 3 inches on center from both the top and bottom ends of the specimen. While in the second specimen EDG-4 intermediate straps were introduced between the two edge straps. Table 4-1 shows the specimen ID and strap information for each specimen.
Table 4-1: Test matrix.

<table>
<thead>
<tr>
<th>Sample Group</th>
<th>Specimen ID</th>
<th>Description</th>
<th>Number of Straps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>U-C</td>
<td>Undamaged Control</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>D-C</td>
<td>Damaged Control</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>S-C</td>
<td>Strengthened Control</td>
<td>0</td>
</tr>
<tr>
<td>Interior Strap</td>
<td>INT-1</td>
<td>Single Strap</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>INT-2</td>
<td>Two Straps</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>INT-3</td>
<td>Three Straps</td>
<td>3</td>
</tr>
<tr>
<td>Edge Strap</td>
<td>EDG-2</td>
<td>Two End Straps</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>EDG-4</td>
<td>Two Interior &amp; Two End Straps</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4-10: Edge Strap Sample Group.
4.3 Specimen Preparation and Instrumentation

Installing the CF straps and continuity connection was conducted by Warstone Innovations in addition to deteriorating the timber segments. The completed jackets along with the timber segments were shipped to the Constructed Facilities Lab where they were instrumented internally and externally on both the GFRP jacket and CF straps. After which the specimens were installed in wooden formwork and epoxy grout was poured and let to cure. The installation process began with placing the timber specimens on wooden formwork and lowering the GFRP jackets, silicone was applied between on the bottom of both the timber specimen and the GFRP jacket and let to cure. A 2-inch-thick layer of grout was then poured and left to harden before pouring the entire volume of grout in each specimen. The grout was mixed in 20-gallon buckets using a variable speed drill, then manually poured into the annular gap. Specimens were left to cure 30 days before testing, 1.5 inch wide carbon fiber wraps were added to the 2 inches of exposed timber outside the repair on both the top and bottom ends of all specimens to avoid local crushing of the timber segment outside the repair while testing. The installation process is presented in Figure 4-11. Instrumentation consisted of three linear potentiometers spaced at 120° to measure axial shortening for all specimens. Interior and edge strap specimens were instrumented with internal strain gauges on the CF straps and the continuity connection, two strain gauges were applied at mid height of the CF strap in the hoop direction at predetermined locations shown in Figure 4-12 while one strain gauge was added at mid height on the continuity connection. Displacement sensors were installed on all strengthened specimens measuring relative slip between the timber pile and the GFRP jacket, in total six sensors were installed on each specimen three on each end shown in Figure 4-13.
Figure 4-11: (a) Specimens Inside Temporary Formwork. (b) GFRP Jacket Sealed in Formwork. (c) Pouring the Grout. (d) Fully Strengthened Specimen.
Figure 4-12: Showing Typical Specimen Instrumentation.

Figure 4-13: Schematic Showing the Location of The Position Sensors.
4.4 Test Results

This section presents the test results of the compression testing program. The results are in the form of Load-Displacement diagrams, Load-CF Strain Diagrams and the corresponding failure modes. Furthermore, Table 4-2 provides a summary of the main results for all specimens. The axial deformation for each of the two edge strap specimens was greater than the 3-inch clearance, which lead to the repair being in direct contact with the testing machine and under axial compression. Therefore, the results of this sample group will be presented into two stages, the first is below 3 inches of deformation referred to as Stage 1 of loading and denoted by C.1, while the second is for deformations exceeding 3 inches referred to as Stage 2 of loading and denoted by C.2.
Table 4-2: Summary of Main Test Results

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>U-C</th>
<th>D-C</th>
<th>S-C</th>
<th>INT-1</th>
<th>INT-2</th>
<th>INT-3</th>
<th>EDG-2</th>
<th>EDG-4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Load (kips)</td>
<td>487</td>
<td>129</td>
<td>595</td>
<td>539</td>
<td>612</td>
<td>559</td>
<td>569</td>
<td>724*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>594</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>941*</td>
</tr>
<tr>
<td>Percent increase from U-C (%)</td>
<td>-</td>
<td>-73.5</td>
<td>+22.2</td>
<td>+10.7</td>
<td>+26.7</td>
<td>+14.8</td>
<td>+16.8</td>
<td>-</td>
</tr>
<tr>
<td>Percent increase from D-C (%)</td>
<td>+278</td>
<td>-</td>
<td>+361</td>
<td>+318</td>
<td>+374</td>
<td>+333</td>
<td>+341</td>
<td>-</td>
</tr>
<tr>
<td>Percent increase from S-C (%)</td>
<td>-18.2</td>
<td>-78.3</td>
<td>-9.41</td>
<td>+2.86</td>
<td>-6.05</td>
<td>-4.37</td>
<td>-</td>
<td>-0.17</td>
</tr>
<tr>
<td>Axial deflection at Ultimate Load (in)</td>
<td>-0.270</td>
<td>-0.800</td>
<td>-0.290</td>
<td>-0.217</td>
<td>-0.254</td>
<td>-0.230</td>
<td>-3.00</td>
<td>-3.74</td>
</tr>
<tr>
<td>CF strap strain at Ultimate Load (µε)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>655</td>
<td>809</td>
<td>623</td>
<td>950</td>
<td>2934</td>
</tr>
<tr>
<td>Connection strain at Ultimate Load (µε)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>403</td>
<td>506</td>
<td>482</td>
<td>805</td>
<td>3261</td>
</tr>
<tr>
<td>Strap rupture</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>-</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Notes: (a) C.1 represents stage 1 of loading; (b) C.2 represents stage 2 of loading, with total shortening > 3 in.. * These values were obtained when the Warstone SCS system was loaded directly.
4.4.1 Load – Deflection diagrams

Figure 4-14 presents the load-deflection graphs of the control specimens and the interior strap specimens. The behavior of S-C & INT-2 is relatively similar with a stiffer initial response compared to U-C and D-C until peak load where specimens S-C & INT-2 begin to sustain the applied load with an increase in axial displacement until failure. Figure 4-15 presents the load – deflection graphs comparing the edge and control specimens. For the edge strap sample group, stage 2 of loading is shown in dotted lines representing the response of the specimens when the repair is directly loaded by the testing machine.

Figure 4-14: Load Deflection Diagram Comparing the Interior Strap and Control Specimens.
Figure 4-15: Load - Deflection Diagram Comparing the Edge Strap and Control Specimens.

4.4.2 CF Strap strain

Figure 4-16 presents the applied load - strain diagram for specimen INT-1 which is representative of the interior strap sample group having. Figure 4-17 shows the applied load - strain diagram for specimen EDG-2, these figures compare the strain measured on the CF strap to the strain measured at the continuity connection. The strap strain values are the average strain values of the two strain gauges instrumenting the CF strap, while the connection strain values are the recorded values of a single jumper strain gauge. For comparison, the mean strap and connection strains measured during the ICE tests are 8142µε and 6341µε respectively as presented previously in Table 3-9. As expected, the connection shows lower strain values due to its higher stiffness.
Figure 4-16: Applied Load - Strain Diagram for Specimen INT-1.

Figure 4-17: Applied Load - Strain Diagram for Specimen EDG-2.
4.4.3 Failure modes

Figure 4-18 through Figure 4-25 present the failure mode for all specimens. Figure 4-19 shows the failure mode of the damaged timber specimen without repair, which is best described as crushing failure under axial load at the midsection, this failure mode in the timber pile is resisted by the grout material at the midsection for strengthened specimens. The interior strap specimens shown in Figure 4-21 through Figure 4-23 present a similar failure mode where the GFRP jacket ruptures near the top end of the specimen without propagating inwards as shown in Figure 4-20. The red circles mark the failure location and rupture of the GFRP jacket while the light blue rectangles mark the intact CF Straps. Finally, Figure 4-24 and Figure 4-25 show both edge specimens with a failure mode similar to S-C with an initial GFRP failure near the top of the specimen that propagates inwards. The carbon fiber strap in both edge specimens ruptured marked with a red circle.

Figure 4-18: U-C  
Figure 4-19: D-C  
Figure 4-20: S-C
Figure 4-21: INT-1.
Figure 4-22: INT-2.
Figure 4-23: INT-3.
Figure 4-24: EN-2.
Figure 4-25: EN-4.
4.5 Governing Behavior and Recommendations

Overall, the repair managed to restore the compressive capacity of a deteriorated segment, exceeding the capacity of the undamaged timber segment. The addition of CF straps did not improve the ultimate capacity of the strengthened piles compared to the strengthened control S-C. Furthermore, modest strain values were measured on the CF straps which implies a humble contribution to the overall confinement of the repair. Specimens that were strengthened with the SCS system did show an increased deformation capacity as shown in the interior strap group. The location of the CF strap is a strategic element in the repair. Providing CF straps at the ends of the repair allows the propagation of the fracture inwards thus increasing the deformation capacity of the repair at failure, which is presented in the Edge strap specimens. In summary, the CF straps did not increase the ultimate compressive capacity nor provide significant confinement. Strategically placing the CF straps at the ends of the repair would increase the deformation capacity near failure and allow more propagation of the fracture towards the center of the repair. Reducing the relatively low modulus 2-inch thick epoxy grout ring would also likely increase the mobilization of the outer shell.
CHAPTER 5: FULL-SCALE FLEXURE TESTS

5.1 Introduction

This chapter presents the full-scale flexural testing conducted on retrofitted timber piles. The ability of the repair to restore the flexural strength of a damaged timber pile was assessed from the experimental results. The experimental program was aimed towards identifying the minimum required repair length using the Warstone SCS system, which is a key aspect in the design of the repair. The repair length consists of the summation of two dimensions; the first is the length of the damaged region and the second is the length of repair on either side of the damaged region. The second length is referred to as the development length, and is expressed as multiples of the pile diameter. Figure 5-1 provides an example, showing the development length that is twice the pile diameter (2D) on each side of the repair. The program also assessed the contribution of each individual CF strap towards confinement by means of measuring hoop strain on the CF straps and continuity connection. The measured strains from GFRP rebar included for some specimens was used to conduct a layered sectional analysis at the repaired section, which is discussed later in this chapter. This chapter is divided to three sections. First, the experimental program and specimen preparation is discussed. Then the test results are presented. Finally, a post processing section is presented which includes the analysis conducted on the experimental data.

![Diagram of Total Repair Length](image)

Figure 5-1: Total Repair Length.
5.2 Experimental Program

Ten 18 ft. long timber piles were tested in flexure. Eight piles had a 2-foot-long hourglass reduction at midsection resembling the reduction previously presented Chapter 4. The cross-section was gradually reduced from the full 11 in. diameter to a reduced 6 in. diameter at the midspan as shown in Figure 5-2. One specimen was not damaged and used as the undamaged control specimen and one pile was hollowed out over a length of 24 in. at the midsection producing a roughly four-inch-thick shell of remaining timber around the hollowed out middle. This pile is intended to simulate a common problem experienced in practice, which is the repair of a timber pile suffering from internal decay usually caused by wood-boring insects. The experimental program divided the tested piles into four sample groups. Four control specimens in the first group while the remaining three groups had two specimens each. Each sample group targeted one or more of the test parameters. The control group served as a benchmark, by means of measuring the capacity of an undamaged (U-C) and a damaged (D-C) timber pile without strengthening. Two strengthened piles were included in the control group measuring the capacity of the FX-70 repair with the repair length suggested by the manufacturer denoted by S-2D and with a reduced repair length denoted by S-0.5D. The second sample group focused on experimenting with the effect of development length on the ultimate capacity and failure mode of the retrofitted piles. Two piles repaired with the Warstone SCS system, W-0.5D and W-1D having 0.5D and 1D development length, respectively. The third group tested the two specimens repaired with a partial Warstone SCS repair neglecting one component of the Warstone SCS system in each pile to assess the contribution of the different components independently from the other. Only CF straps were provided in the repair for the first pile (STP-2D) while longitudinal GFRP bars were not incorporated. The second pile (RBR-2D) did not have CF straps in the
repair, but GFRP bars were installed. The fourth sample group was used to determine the ultimate flexural capacity of piles repaired with the complete Warstone SCS system. The first pile (W-2D) had the hourglass reduction in timber cross section while the second pile (HW-W-2D) had the hollowed-out timber pile. Table 5-1 summarizes the specimen details.

Figure 5-2: Hourglass Reduction in Cross Section.

Table 5-1: Specimen Details.

<table>
<thead>
<tr>
<th>Group</th>
<th>Specimen ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>U-C</td>
<td>Undamaged Control</td>
</tr>
<tr>
<td></td>
<td>D-C</td>
<td>Damaged Control</td>
</tr>
<tr>
<td></td>
<td>S-0.5D</td>
<td>Strengthened control with minimum repair length</td>
</tr>
<tr>
<td></td>
<td>S-2D</td>
<td>Strengthened control with recommended repair length</td>
</tr>
<tr>
<td>Minimum Repair Length</td>
<td>W-0.5D</td>
<td>Full SCS system with minimum repair length</td>
</tr>
<tr>
<td></td>
<td>W-1D</td>
<td>Full SCS system with 1D development length</td>
</tr>
<tr>
<td>Single Component</td>
<td>STP-2D</td>
<td>SCS system without rebar. Using recommended repair length</td>
</tr>
<tr>
<td></td>
<td>RBR-2D</td>
<td>SCS system without straps. Using recommended repair length</td>
</tr>
<tr>
<td>Ultimate Capacity</td>
<td>W-2D</td>
<td>Full SCS system</td>
</tr>
<tr>
<td></td>
<td>HW-W-2D</td>
<td>Full SCS system with a hollow pile</td>
</tr>
</tbody>
</table>
5.3 Test Matrix

Eight specimens were tested in 4-point bending with a load span of 7.5 ft Control and Minimum Repair Length groups. The load span was reduced for the Single Component group to 2.5 ft. The Ultimate Capacity Group was tested in 3-point bending with the load applied directly at the midspan of the specimen. Table 5-2 provides the test matrix. The change in load span and loading points was to achieve a higher applied moment at the strengthened cross section. Figure 5-3 and Figure 5-4 present a complete sketch for the test setup showing piles U-C and D-C, respectively. The support spacing of 15 ft was constant for all specimens. Figure 5-5 through Figure 5-12 provides sketches of the retrofitted specimens, focusing on the repair details and the load span for each individual specimen. Figure 5-5 and Figure 5-6 show S-0.5D and S-2D, respectively, which were strengthened using the FX-70 system. Specimen W-0.5D in Figure 5-7, and W-1D in Figure 5-8, both had a development length less than the 2D recommended by the manufacturer. W-0.5D reduced the development length from the recommended length of 22-in. to 5.5-in. while W-1D reduced the development length to 11 in. Both specimens had an identical repair and test setup. The remaining four specimens shown from Figure 5-9 to Figure 5-12 had the recommended development length of 2D. Figure 5-9 shows specimen STP-2D with three CF straps in total, while Figure 5-10 shows the RBR-2D specimen with only GFRP rebars and no CF straps. W-2D and HW-W-2D are presented in Figure 5-11 and Figure 5-12, respectively, are strengthened with the full Warstone SCS repair.
<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>U-C</th>
<th>D-C</th>
<th>S-0.5D</th>
<th>S-2D</th>
<th>W-1D</th>
<th>W-0.5D</th>
<th>STP-2D</th>
<th>RBR-2D</th>
<th>W-2D</th>
<th>W-HW-2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length of Repair</td>
<td>-</td>
<td>-</td>
<td>2'-11&quot;</td>
<td>5'-8&quot;</td>
<td>3'-10&quot;</td>
<td>2'-11&quot;</td>
<td>5'-8&quot;</td>
<td>5'-8&quot;</td>
<td>5'-8&quot;</td>
<td>5'-8&quot;</td>
</tr>
<tr>
<td>Total Number of CF Straps</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total Number of GFRP Bars</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>8</td>
<td>-</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Loading Points</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Load Span</td>
<td>7'-6&quot;</td>
<td>7'-6&quot;</td>
<td>7'-6&quot;</td>
<td>7'-6&quot;</td>
<td>7'-6&quot;</td>
<td>7'-6&quot;</td>
<td>2'-6&quot;</td>
<td>2'-6&quot;</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 5-3: U-C

Figure 5-4: D-C
Figure 5-5: S-0.5D

Figure 5-6: S-2D
Figure 5-7: W-0.5D

Figure 5-8: W-1D
Figure 5-9: STP-2D

Figure 5-10: RBR-2D
Figure 5-11: ULT-W-2D

Figure 5-12: ULT-HW-W-2D
5.4 Specimen Preparation

The repair process began with damaging the timber piles at the Constructed Facilities Laboratory, using a circular saw and a grinding tool. The finished piles were then braced in groups of three and lowered through an opening in the strong floor, resting on the basement floor as shown in Figure 5-13. Assembly of the repair system began with installing the CF straps. The CF fabric was saturated with the epoxy resin, then rolled internally on the GFRP shell. Pressure was applied using a rib roller to remove the excess resin and air gaps. Rebar positioners were glued internally on the GFRP jacket for the specimens equipped with GFRP rebar. The CF straps and rebar positioners were left to cure over night before installing the GFRP rebar in the positioners as shown in Figure 5-14. The epoxy gel used in installing the rebar and rebar positioners was FX-763CTG. The tongue and groove joint of the finished jackets were sealed with the same epoxy gel used in installing the rebar and lowered onto the timber piles using an overhead crane. The bottom end of the jackets rested on temporary wooden formwork where silicone was applied to prevent the grout from leaking. The total height of the jacket was poured with grout form the top and left to cure for at least two weeks before testing, as shown in Figure 5-15.
Figure 5-13: (a) Timber Piles Braced Together. (b) Piles Resting on Basement Floor. (c) Top Half of the Piles
Figure 5-14: (a) Saturating the CF Fabric. (b) Applying the CF Fabric on the GFRP Shell. (c) Applying Pressure using a Rib Roller. (d) GFRP Rebar Positioners Installed in GFRP Shell. (e) Continuity Connection Installed on the CF Strap. (f) GFRP Rebar Installed in Positioners
Figure 5-15: (a) Lowering the Completed Jackets on the Timber Piles. (b) Pouring the Grout Through the Annular Gap. (c) Repaired Piles After Curing
5.5 Instrumentation and Test Setup

Specimens were instrumented internally and externally using strain gauges and cable actuated position sensors. All CF straps were instrumented using strain gauges at three locations measuring strain in the hoop direction. Two on the strap itself and a third strain gauge on the continuity connection, in the same configuration presented in the Chapter 4. For all specimens containing rebar, two bars on the extreme tension, and two bars on the extreme compression, sides of the specimens were instrumented at midsection using a single strain gauge measuring longitudinal strain. All eight bars in specimen W-0.5D were instrumented with strain gauges at midspan. Two strain gauges were applied externally on the GFRP jacket on the tension side for all the strengthened specimens, located at midsection measuring longitudinal and hoop shell strain. Figure 5-16 shows the instrumentation applied on the rebar. Specimens were pulled upwards with the splice connection on the compression side, using double acting hydraulic jacks mounted to a steel testing frame. The specimens were tied down using two nylon straps connected to a steel support secured to the strong floor. Specimens were preloaded to ensure that jacks and supports were seated. Loading then began and continued until failure. Figure 5-17 shows the test setup with specimen STP-2D before testing.

![Figure 5-16: Cross Section at Midspan Showing the Instrumented Bars. (CF Strap not shown)](image-url)
5.6 Results

The results of the experimental program are presented in the form of Moment-Deflection diagrams, Moment-Rebar Strain diagrams and Moment-Strap Strain diagrams where the measured data is plotted against the applied moment at midspan. In addition to the corresponding failure mode figures, Table 5-3 provides a summary of the test results.
Table 5-3: Summary of Test Results.

<table>
<thead>
<tr>
<th>Number of Load Points</th>
<th>4-Pt. 7’– 5” Load Span</th>
<th>4-Pt. 2’- 6” Load Span</th>
<th>3-Pt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen ID</td>
<td>U-C D-C S-2D S-0.5D W-1D W-0.5D STP-2D RBR-2D W-2D HW-W-2D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Applied Load (kips)</td>
<td>32.6 6.50 36.2 24.5 33.3 33.7 24.5 34.3 47.0 47.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Applied Moment (kip.ft)</td>
<td>61.1 12.2 67.9 46.0 62.4 63.2 76.6 107.2 176.3 176.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase in Moment Capacity from U-C (%)</td>
<td>- -80.0 +11.1 -24.7 +2.13 +3.44 +25.4 +75.5 +189 +189</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Moment Outside the Repaired Region (kip.ft)</td>
<td>61.1 12.2 67.9 46.0 62.4 63.2 56.8 80.0 110 110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Rebar Tension Strain με</td>
<td>- - - - 1048 987 - 1985 16750 8490</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure Mode*</td>
<td>ITF ITF ITF ITF ITF ITF ITF VTR VTR VTR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: *ITF represents Inclined Timber Fracture, VTR represents Vertical Timber Rupture.
5.6.1 Moment-Deflection Diagrams

Figure 5-18 shows the Applied Moment – Mid-Span Deflection diagrams. The minimum repair length piles are plotted in diagram (a), where specimen S-2D presented the largest deflection compared to the remaining specimens which had a sudden failure. STP-2D and RBR-2D are shown in diagram (b). All strengthened specimens shown in Figure 5-18 restored the capacity of a damaged pile D-C exceeding the ultimate capacity of the undamaged pile U-C except for specimen S-0.5D. Furthermore, W-0.5D and W-1D provided a stiffer response than the undamaged control while achieving approximately the same ultimate capacity. RBR-2D reached a higher ultimate capacity than STP-2D.

Figure 5-18: Applied Moment – Mid-Span Deflection Diagrams: (a) Minimum Repair Length Specimens., (b) Rebar only and Strap only Specimens with the Unstrengthend Controls.
Figure 5-19 shows the Applied Moment – Mid-Span Deflection diagrams where specimen, W-0.5D and W-1D are plotted with the unstrengthened controls and W-2D in diagram (a). There is a substantial increase in ultimate capacity and stiffness for W-2D compared to the reduced repair length specimens. Specimens HW-W-2D and W-2D have a similar behavior both specimens exceeded the ultimate capacity and stiffness of S-2D. Most specimens had a similar increase in stiffness compared with U-C.

![Image](a)

**Figure 5-19: Applied Moment – Mid-Span Deflection diagrams:** (a) The Minimum Repair Length Specimens along with the Recommended Repair Length Specimen. (b) Ultimate Capacity specimens along with S-2D and the unstrengthened controls.
5.6.2 CF Strap Strain Diagrams

Figure 5-20 presents the Applied Moment – CF Strap Strain Diagrams on each strap for the specimens that incorporated CF straps in the repair moving from the left to the middle to the right strap in diagrams (a), (b) and (c), respectively. The hoop strains measures were relatively modest in all specimens below a quarter of the strain values measured in the ICE tests.

Figure 5-20: Applied Moment - Strap Strain Diagrams for All Specimens with Instrumented CF Straps; (a) Left Strap., (b) Middle Strap., (c) Right Strap.
5.6.3 Rebar Strain Diagrams

Figure 5-21 shows the Applied Moment – Longitudinal Rebar Strain for (W-0.5D) in diagram (a). All eight bars were instrumented at midspan for this specimen. Each line on the graph represents the average strain of two bars at the same height. The graph is relatively symmetric where the extreme top and bottom bars are undergoing approximately the same strain, due to symmetry diagram (b) only shows the tension strain values. The rebar rupture strain is 16000 µε.

Figure 5-21: Applied Moment – Longitudinal GFRP Rebar Strain Diagram Specimens (a) (W-0.5D). (b) All Specimens containing GFRP Rebar
5.6.4 Failure Modes

Figure 5-22 presents the failure mode of the unstrengthened control specimens. U-C failed in the constant moment region between the loading straps with an inclined fracture spanning between two knots in the timber pile. Specimen D-C failed at midspan at the reduced cross section. All strengthened specimens failed outside the repaired section and fractured the timber cross section. The fracture plane varied from a shallow inclined fracture referred to as inclined timber fracture (ITF), to a vertical rupture of the timber through the cross section at the end of the repair referred to as vertical timber rupture (VTR). All specimens except for W-2D and HW-W-2D failed in ITF. The inclination of the fracture plane became steeper with the increase of the ultimate failure moment of the specimen. Specimens that failed in ITF remained intact after failure, while W-2D and HW-W-2D that failed in VTR had a sudden failure through the timber cross section. Figure 5-23 shows the strengthened specimens after failure.

![Figure 5-22: Failure Modes](image)

Figure 5-22: (a) U-D Failure Mode. (b) D-C Failure Mode.
Figure 5-23: Failure Modes: (a) S-0.5D. (b) S-2D. (c) W-0.5D. (d) W-1D. (e) STP-2D. (f) RBR-2D. (g) W-2D. (h) HW-W-2D.
5.7 Result Discussion and Conclusion

All specimens restored the capacity of the damaged pile, except for S-0.5D. Overall, the strain values measured on the CF straps were low which suggests that the CF straps were not engaged during testing. None of the specimens failed in the strengthened region, only two specimens had a vertical timber fracture through the timber section, while the rest of the specimens had an inclined timber rupture with the degree of inclination varying with the ultimate capacity. This section provides a discussion of the previously stated test objectives thereby concluding the results section of this chapter. Discussion of the GFRP rebar strains is presented in the analysis section of this chapter.

5.7.1 Development Length

W-0.5D and W-1D were successful at restoring the ultimate capacity of a damaged timber pile, reaching the strength of U-C. This shows that a reduced repair length using the Warstone SCS system could be effectively used to reduce the repair cost while restoring the ultimate capacity. The reduced repair length specimens achieved an ultimate moment capacity relatively comparable to S-2D, while S-0.5D was not successful in restoring the capacity to the U-C specimen.

5.7.2 Rebar and CF Straps

RBR-2D reached a significantly higher ultimate moment capacity providing a 75% increase in moment capacity compared to 25% for the STP-2D specimen, which is due to the addition of longitudinal GFRP rebars.

5.7.3 Ultimate Capacity

W-2D and HW-W-2D achieved the highest increase in moment capacity with an equal increase of 189% each, while the FX-70 control S-2D increased the moment capacity by 11%.
Due to the different load span for W-2D and S-2D direct comparison would not be fair, however W-2D was able to undergo a maximum applied moment of 176 kip.ft at midspan and failing in the timber cross section outside the repaired region at a moment of 110 kip.ft, when directly loaded from midspan.
5.8 Post Processing and Analysis

This section includes the analysis performed on the experimental results. Using the measured strain gauge data, a sectional analysis was conducted on the strengthened specimens, which calculated the ultimate moment capacity of the retrofitted timber section for a given strain profile. Post processing began with calculating the ultimate flexural capacity of the unstrengthened timber piles using the National Design Specification for wood construction guidelines and calculating the ultimate strain corresponding to that failure moment, which would be later used as a strain limit. Due to the varying load spans, the layered sectional analysis focused on two strengthened specimens, W-0.5D and W-1D, as those specimens shared many similarities with the unstrengthened controls, having the same load span, failure location and similar failure moment. However, this analysis could be also applied to any strengthened or unstrengthened cross section.

5.8.1. Moment Capacity of Unstrengthened Specimens using NDS

Table 5-4 presents the capacity of the unstrengthened piles U-C and D-C calculated using the NDS guidelines and the following procedure:

1. Obtaining the allowable bending stress \( f_b \) according to Table 6A – NDS Supplement.
2. Identifying the appropriate adjustment factors.
3. Multiplying \( f_b \) by the adjustment factors to give \( f_b' \).
4. Calculating the moment of inertia at the midspan, \( I_{xx} = \frac{\pi D^4}{64} \), where \( D \) is the diameter of the section.
5. Following the mechanics based equation, \( f_b' = \frac{M_{NDS} + R}{I_{xx}} \), where \( M_{NDS} \) is the allowable bending moment at the analyzed section, \( R \) is the radius of the cross section, and \( I_{xx} \)
is calculated from the previous step, we are able to predict $M_{NDS}$ which is the ultimate flexural capacity of the analyzed section based on the NDS guidelines.

Table 5-4: NDS based capacity.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>U-C</th>
<th>D-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable bending stress $f_b$ (ksi)</td>
<td>1.95</td>
<td>1.95</td>
</tr>
<tr>
<td>Duration factor $C_d$ (10-minute loading)</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Factored Allowable stress $f'_b$ (ksi)</td>
<td>3.12</td>
<td>3.12</td>
</tr>
<tr>
<td>Radius (in)</td>
<td>5.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Moment of Inertia $I_{xx}$ (in$^4$)</td>
<td>719</td>
<td>63.6</td>
</tr>
<tr>
<td>Ultimate Flexural Capacity $M_{NDS}$ (kip. ft)</td>
<td>34.0</td>
<td>5.51</td>
</tr>
</tbody>
</table>

5.8.2. Experimental Failure Strain of the Unstrengthened Specimens

Table 5-5 presents the experimental failure strain of the unstrengthened piles, U-C and D-C, which was calculated using the following procedure:

1. Identifying the experimental moment at failure, $M_{exp}$.

2. Calculating the moment of inertia at the midspan, $I_{xx} = \frac{\pi D^4}{64}$.

3. Using the equation $\varepsilon_{exp} = \frac{M_{exp} * R}{I_{xx} * E}$ where $\varepsilon_{exp}$ is the bending strain at the analyzed section corresponding to the failure moment $M_{exp}$, $R$ is the radius of the cross section, $E$ is the elastic modulus of the timber and $I_{xx}$ is calculated from the previous step, we are able to calculate $\varepsilon_{exp}$. 
Table 5-5: Failure Strain Calculations:

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>U-C</th>
<th>D-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental moment $M_{exp}$ (kip. ft)</td>
<td>61.1</td>
<td>12.2</td>
</tr>
<tr>
<td>Radius $R$ (in)</td>
<td>5.5</td>
<td>3</td>
</tr>
<tr>
<td>Elastic modulus $E$ (ksi)</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Moment of inertia $I_{xx}$ (in$^4$)</td>
<td>719</td>
<td>63.6</td>
</tr>
<tr>
<td>Failure strain $\varepsilon_{exp}$ (µε)</td>
<td>±3739</td>
<td>±4604</td>
</tr>
</tbody>
</table>

Due to symmetry we can assume a neutral axis at the center of the cross section, resulting in equal compressive and tensile strain values at the extreme fibers. The failure strain $\varepsilon_{exp}$ was used in the layered sectional analysis spreadsheet to calculate the corresponding moment capacity of the cross section $M_{LSA}$ is discussed in the next section. Table 5-6 provides an analysis summary for specimens U-C and D-C.

Table 5-6: Summary for Unstrengthened Specimens

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>U-C</th>
<th>D-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental moment capacity $M_{exp}$ (kip. ft)</td>
<td>61.1</td>
<td>12.2</td>
</tr>
<tr>
<td>Predicted flexural capacity $M_{NDS}$ (kip. ft)</td>
<td>34.0</td>
<td>5.51</td>
</tr>
<tr>
<td>Calculated moment capacity $M_{LSA}$ (kip. ft)</td>
<td>58.8</td>
<td>12.1</td>
</tr>
<tr>
<td>% increase in $M_{exp}$ from $M_{NDS}$</td>
<td>+79.7</td>
<td>+121</td>
</tr>
<tr>
<td>% increase in $M_{exp}$ from $M_{LSA}$</td>
<td>+3.95</td>
<td>+0.82</td>
</tr>
</tbody>
</table>
5.8.3. Sectional Analysis

Figure 5-24 shows the assumed continuous and linear strain distribution at failure for specimen W-1D, measured at midspan. The measured strain in the GFRP rebars was used to define the strain profile at midspan, and a sectional analysis spreadsheet was implemented using the following process:

1. Plotting the strain profile at the cross section using the rebar strain values.
2. Calculating the slope of the strain profile using the equation:
   \[ C = \frac{y_t - y_b}{\varepsilon_t - \varepsilon_b} \]
3. Dividing the cross section into 0.125” thick layers.
4. Calculating the area of the GF shell, grout, timber and rebar in each layer.
5. Obtaining the average strain value at each layer based on the strain profile.
6. Calculate the force in each material by multiplying the material area with its corresponding elastic modulus and corresponding average strain value at that layer. Repeat for all layers.
7. Obtain the moment arm, measured from the center of a layer to the neutral axis.
8. Calculate the moment capacity for each segment by multiplying the force obtained in step #6 with the moment arm in step #7.
9. Sum the moments about the neutral axis to obtain the total moment corresponding to the given strain profile from step #1.
The sectional analysis was implemented on four strengthened specimens all containing rebar. Table 5-7 summarizes the calculated results.

**Table 5-7: Sectional Analysis Summary**

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>W-1D</th>
<th>W-0.5D</th>
<th>RBR-2D</th>
<th>W-2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated moment capacity $M_{LSA}$ (kip. ft)</td>
<td>22.0</td>
<td>24.1</td>
<td>36.0</td>
<td>45.0</td>
</tr>
<tr>
<td>Experimental moment capacity $M_{exp}$ (kip. ft)</td>
<td>62.0</td>
<td>63.0</td>
<td>107.0</td>
<td>176.0</td>
</tr>
<tr>
<td>% error in $M_{LSA}$ from $M_{exp}$</td>
<td>-64.5</td>
<td>-66.5</td>
<td>-66.4</td>
<td>-74.4</td>
</tr>
</tbody>
</table>
5.9 Analysis Discussion and Conclusion

The calculated ultimate strain $\varepsilon_{\text{exp}}$ for U-C on the timber cross section was 3739 $\mu\varepsilon$ which is used as the benchmark for the failure strain of the full timber cross section. Specimens U-C, W-0.5D and W-1D all failed in the full timber cross section inside the area of maximum moment and at approximately the same ultimate applied moment, which should result to the same failure strain on the full timber cross section on all three specimens. However, the strains measured on the rebar were significantly lower at failure, 987$\mu\varepsilon$ and 1048$\mu\varepsilon$ for specimens W-0.5D and W-1D, respectively. Hence, the corresponding strain on the full timber cross section should be 829$\mu\varepsilon$ and 880 $\mu\varepsilon$ based on the assumed linear stain profile. This is significantly lower than the expected strain of approximately 3739 $\mu\varepsilon$. This suggests the absence of full interaction along the height of the cross section which would cause a nonlinear strain profile through the depth of the cross section, explaining the inaccurate calculations of the layered structural analysis. The strain distribution is likely not continuous as shown in Figure 5-25 and full interaction behaviour is not occurring in the strengthened region. This is likely due to the 4.5 in. thickness of epoxy grout between the timber pile and the outer GFRP jacket. Due to the relatively low stiffness of the grout, the deformations occurring in the timber section are not fully transferred through the grout to the GFRP rebars and outer jacket.

![Likely Non-Continuous Strain Distribution](image_url)

Figure 5-25: Likely Non-Continuous Strain Distribution.
CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

This chapter summarizes the findings of the experimental program and provides recommendations for the Warstone SCS system.

6.1 Material Testing

1- A 1:1 grout to aggregate mixture by volume may be used as a low-cost alternative when a 3% reduction in compressive capacity and a 43% reduction in tensile capacity from the plain epoxy grout is structurally acceptable.

2- The relatively low modulus of the epoxy grout (310 ksi), coupled with the thick annular gap, likely results in shear deformations such that the GFRP jacket system is not engaged to its full potential.

3- The ultimate tensile capacity of the flat full-scale CF straps is on average 14% lower than the that of the ASTM standard coupon due to the size effect.

4- From the ICE Tests, the continuity connection was optimized to prevent a premature failure. For the system tested, the rupture strain limits for the GFRP jacket and CF straps are 3,023µε and 8,142µε respectively. The controlling strain limit is likely related to the CF strap spacing.

6.2 Compression Testing

1- No improvement in ultimate compressive capacity or deformation capacity was observed for specimen INT-1 when compared to the strengthened control S-C. This information coupled with the CF strap strain data for INT-1 suggests minimum contribution of the CF Strap towards confining the repair and improving behavior, when placed remotely from the GFRP failure location at the ends of the repair.
2- CF straps located at the ends of the repair were more effective at increasing the deformation capacity of the repair, as shown in EDG-2 and EDG-4, compared to CF straps located at the damaged timber section as in the interior strap specimens. This may be a desirable characteristic for applications in seismic regions.

6.3 Flexural Behavior

1- The Warstone SCS system was able to restore the flexural capacity of a damaged timber pile to that of the undamaged pile when using the reduced development length of 0.5D when provided with CF Straps at the ends of the repair.

2- The layered sectional analysis approach was inaccurate when used to predict the moment at midspan using a full interaction assumption of a continuous linear strain distribution. This is likely due to the presence of shear deformation through the annulus gap and relative slip occurring.

3- The strain distribution is likely not continuous due to shear deformation through the epoxy grout in the annulus gap. This would need to be considered in a sectional analysis.
REFERENCES


