CHARACTERIZATION OF IMPACT DAMAGE AND FIBER REINFORCED POLYMER REPAIR SYSTEMS FOR METALLIC UTILITY POLES

by

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B.S.C.E., University of Central Florida, 2011

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil, Environmental and Construction Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Spring Term
2013

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ABSTRACT

Previous studies have demonstrated that the behavior of fiber reinforced polymers (FRPs) bonded to metallic utility poles are governed by the following failure modes; yielding of the metallic substrate, FRP tensile rupture, FRP compressive buckling, and debonding of FRP from the substrate. Therefore, an in situ method can be devised for the repair of utility poles, light poles, and mast arms that returns the poles to their original service strength.

This thesis investigates the effect of damage due to vehicular impact on metallic poles, and the effectiveness of externally-bonded FRP repair systems in restoring their capacity. Damage is simulated experimentally by rapid, localized load application to pole sections, creating dents ranging in depth from 5 to 45% of the outer diameter. Four FRP composite repair systems were selected for characterization and investigation due to their mechanical properties, ability to balance the system failure modes, and installation effectiveness. Bending tests are conducted on dented utility poles, both unrepaired and repaired.

Nonlinear finite element models of dented and repaired pole bending behavior are developed in MSC.Marc. These models show good agreement with experimental results, and can be used to predict behavior of full-scale repair system. A relationship between dent depth and reduced pole capacity is developed, and FRP repair system recommendations are presented.
This thesis is dedicated to my husband, my family, and to the glory of God.
ACKNOWLEDGMENTS

The author would like to thank the Florida Department of Transportation (FDOT) and Neptune Research Inc. for their sponsorship and contributions to this thesis project. Specifically, the following individuals contributed to the success of this research:

- David Wagner, FDOT Structures Research Center
- Debra Sjoberg, FDOT District 5
- Alberto Sardinas, FDOT District 4
- Erblina Vokshi, Neptune Research Inc.
- Chris Lazzara, Neptune Research Inc.
- David Wilburn, CarbonWrap Solutions LLC

Thanks are also extended to the advisor for this thesis, Dr. Kevin Mackie. Several other members of the research team at the UCF Structures Lab have made important contributions to this thesis. Dr. Jun Xia’s assistance with the finite element modeling is gratefully acknowledged, as well as the advice and input of Robert Slade, who worked on the earlier portions of this project. Also, the help received from Daniel Kellner, Kyle Paradis, Mathew Adamira, Elie El Zghayar, and James Duryea was hugely important to the accomplishment
of this work. Finally, thank you to all of the other students of the UCF Structures Lab for your encouragement, support, and general awesomeness:

- Haider Al-Jelawy
- Munaf Al-Ramahee
- Brice Latham
- Patricia AuBuchon, Stanford
- Nikola Najdovski
- Zachary Haber, UNR
# TABLE OF CONTENTS

LIST OF FIGURES ................................................................. xi

LIST OF TABLES ............................................................... xv

CHAPTER 1 INTRODUCTION .................................................. 1

1.1 Problem Statement ...................................................... 1

1.2 Research Objectives .................................................. 2

1.3 Thesis Outline ......................................................... 5

CHAPTER 2 LITERATURE REVIEW ........................................... 6

2.1 Externally-Bonded FRP Composites ................................. 6

2.1.1 Epoxy-Matrix Composites ....................................... 7

2.1.2 Polyurethane-Matrix Composites .............................. 8

2.2 Civil Infrastructure Applications of FRP ........................... 9
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 Damage Determination Tests</td>
<td>37</td>
</tr>
<tr>
<td>4.2.1 Specimen Preparation and Testing</td>
<td>37</td>
</tr>
<tr>
<td>4.2.2 Damage Determination Test Results</td>
<td>38</td>
</tr>
<tr>
<td>4.3 Single-Ply Tests</td>
<td>50</td>
</tr>
<tr>
<td>4.3.1 Single-Ply Test Results</td>
<td>52</td>
</tr>
<tr>
<td>4.4 Wrap Configuration Tests</td>
<td>68</td>
</tr>
<tr>
<td>4.4.1 Wrap Configuration Test Results</td>
<td>69</td>
</tr>
<tr>
<td>4.4.2 Summary of Wrap Configuration Results</td>
<td>81</td>
</tr>
<tr>
<td>CHAPTER 5 FINITE ELEMENT MODELING</td>
<td>83</td>
</tr>
<tr>
<td>5.1 Details of the Finite Element Model</td>
<td>83</td>
</tr>
<tr>
<td>5.1.1 Model Geometry</td>
<td>83</td>
</tr>
<tr>
<td>5.1.2 Material Properties</td>
<td>88</td>
</tr>
<tr>
<td>5.2 Finite Element Results</td>
<td>90</td>
</tr>
<tr>
<td>5.2.1 Scanned Model Results</td>
<td>90</td>
</tr>
</tbody>
</table>

ix
5.2.2 Dented Model Results ........................................ 91

5.2.3 Filled Model Results ........................................ 94

5.2.4 Wrapped Model Results .................................... 95

CHAPTER 6 CONCLUSIONS ........................................ 97

6.1 Conclusions .................................................... 97

6.2 Continuing Work ............................................... 100

LIST OF REFERENCES ........................................... 102
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Vehicle-impact damage of steel utility pole.</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>Laser scan of dented utility poles.</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>Reinforcement scheme for CFRP strengthening of steel monopoles.</td>
<td>12</td>
</tr>
<tr>
<td>2.2</td>
<td>Bond-slip relationship models between FRP and concrete [20].</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>Bond-slip relationship between FRP and steel.</td>
<td>17</td>
</tr>
<tr>
<td>3.1</td>
<td>NRI Syntho-Poxy HC.</td>
<td>23</td>
</tr>
<tr>
<td>3.2</td>
<td>Pilgrim EM 5-2 Gel low-sand fill.</td>
<td>24</td>
</tr>
<tr>
<td>3.3</td>
<td>Pilgrim EM 5-2 Gel high-sand fill.</td>
<td>25</td>
</tr>
<tr>
<td>3.4</td>
<td>Sikadur 31, Hi Mod Gel fill.</td>
<td>25</td>
</tr>
<tr>
<td>3.5</td>
<td>Application of QuakeBond repair system.</td>
<td>30</td>
</tr>
<tr>
<td>4.1</td>
<td>Pole substrate tensile data.</td>
<td>35</td>
</tr>
<tr>
<td>4.2</td>
<td>Cuts applied to aluminum component level test specimens.</td>
<td>35</td>
</tr>
<tr>
<td>4.3</td>
<td>Dent application to pole ALw-5.b.</td>
<td>36</td>
</tr>
<tr>
<td>4.4</td>
<td>ALw-5.b point cloud from 3D scan.</td>
<td>39</td>
</tr>
<tr>
<td>4.5</td>
<td>Damage Determination test configuration.</td>
<td>39</td>
</tr>
</tbody>
</table>
Figure 4.6  ALu-4.a test configuration during testing. ........................................ 40
Figure 4.7  Plastic hinging at load applicator. .................................................. 40
Figure 4.8  ALu-4.a test data. ........................................................................... 41
Figure 4.9  Alu-1.a laboratory-applied dent and test configuration. ................. 43
Figure 4.10  Alu-1.a plastic hinge failure at dent center. .................................... 43
Figure 4.11  ALu-1.a test data. ........................................................................... 44
Figure 4.12  ALu-1.b laboratory-applied dent. ................................................... 46
Figure 4.13  ALu-1.b plastic hinging failure. ...................................................... 46
Figure 4.14  ALu-1.b test data. ........................................................................... 47
Figure 4.15  ALu-2.b plastic hinging failure. ...................................................... 47
Figure 4.16  ALu-2.b test data. ........................................................................... 48
Figure 4.17  Damage Determination experimental stress factor vs. dent depth. .... 51
Figure 4.18  Single-Ply test configuration. ............................................................ 51
Figure 4.19  ALw-5.b filled dent. ........................................................................ 52
Figure 4.20  Alw-5.b failure. .............................................................................. 53
Figure 4.21  ALw-5.b test data. ........................................................................... 54
Figure 4.22  Alw-4.b initial loading. ................................................................. 55
Figure 4.23  Alw-4.b failure modes. ................................................................. 56
Figure 4.24  ALw-4.b test data. ........................................................................... 57

xii
Figure 4.25 ALw-4.b combined test data. .................................. 58
Figure 4.26 Progressive strain profiles at section BB’ for pole ALw-4.b test 2. .... 58
Figure 4.27 ALw-6.a Testing and failure. ............................................. 60
Figure 4.28 Alw-6.a test data. ............................................................ 61
Figure 4.29 Alw-7.a test data. ............................................................ 62
Figure 4.30 ALw-7.a Failure modes. .................................................... 63
Figure 4.31 Alw-8.a test data. ............................................................ 64
Figure 4.32 ALw-8.a wrap and failure mode. .......................................... 66
Figure 4.33 Single-Ply experimental stress factor vs. dent depth. ................. 70
Figure 4.34 Wrap Configuration test configuration. .................................. 70
Figure 4.35 Combined Wrap Configuration permutations. .......................... 72
Figure 4.36 Tension wrap before testing. ............................................. 73
Figure 4.37 ST-20.a test data. ............................................................ 74
Figure 4.38 ST-20.a failure modes. ..................................................... 75
Figure 4.39 Compression wrap before testing. ....................................... 76
Figure 4.40 ST-25 test data. ............................................................ 77
Figure 4.41 ST-25 failure modes. ..................................................... 78
Figure 4.42 ST-26.a wrapped section. ............................................... 79
Figure 4.43 ST-26.a test data. ............................................................ 80
Figure 4.44 ST-26.a failure. .................................................. 80

Figure 4.45 Normalized strain vs. normalized moment. .......................... 82

Figure 5.1 ALu-2.b 3D scan generated mesh. .................................. 85

Figure 5.2 Comparison of dent surface function to scanned dent surface. .... 87

Figure 5.3 Numerically dented pole mesh. ........................................ 87

Figure 5.4 Load application modeling. .......................................... 87

Figure 5.5 Supports modeling. .................................................. 88

Figure 5.6 Aluminum plasticity model. ......................................... 89

Figure 5.7 ALu-2.b comparison of experimental, scan model, and dent model results. 91

Figure 5.8 ALu-4.a comparison of experimental and analytical results. ....... 93

Figure 5.9 Dented Model Results. .............................................. 93

Figure 5.10 ALw-5.b comparison of experimental and dent model results. .... 95

Figure 5.11 ALw-7.a comparison of experimental and dent model results. ..... 96
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3.1</td>
<td>Filler Materials</td>
<td>23</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Selected Repair Systems</td>
<td>31</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Component Level Test Specimens</td>
<td>34</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Damage Determination Results Summary</td>
<td>49</td>
</tr>
<tr>
<td>Table 4.3</td>
<td>Single-Ply Results Summary</td>
<td>67</td>
</tr>
<tr>
<td>Table 4.4</td>
<td>Wrap Configuration Test Matrix</td>
<td>71</td>
</tr>
</tbody>
</table>
1.1 Problem Statement

In the years 1996-2000, The Alabama Department of Transportation recorded 3,364 utility pole related crashes in the state of Alabama. This number comprised about 1% of all vehicle crashes in Alabama during this period, and it is estimated that this percentage is the case in the rest of the United States [1]. As shown in Figures 1.1 and 1.2, and discussed by Slade [2], the damage caused by these vehicular impacts does not typically cause a global failure of the pole structure, but induces localized damage only. This damage, while it does not cause immediate collapse of the structure, under extreme service loadings may result in degradation or corrosion of the pole surface, or in a global structural failure. In order to avoid the high cost and traffic interruptions which result from replacement of damaged poles, an *in situ* repair method for these damaged structures is desirable.

The current available options for repairing these structures include the use of steel jackets attached around the exterior of the dented region, cutting and welding a repair plate to the damaged portion, or filling the interior of the pole with grout. The use of externally-bonded fiber reinforced polymer (FRP) composites has been proven a successful
repair system alternative for these structures. This repair technique allows for inexpensive, in-field, and efficient restoration without the need for large equipment, service interruption, or lane closures. Additionally, the flexibility of composite systems allows repairs to work with and around pole features such as access ports, which is not possible with steel jacket repairs. These features, as well as a limited environmental impact, make the composite systems an attractive option for repair [2].

The objective of this thesis is to investigate the effect of dents of various depths on the capacity of metallic utility poles, and the ability of various composite repair systems to improve the degraded capacity. This is accomplished through experimental testing as well as finite element modeling. Four composite systems are compared, each consisting of a fiber weave impregnated with a saturating resin, and paired with an adhesive and a dent filler material. A set of component-level laboratory tests are conducted using these systems. A finite element model was also created, which can be expanded to evaluate full composite repair systems.

1.2 Research Objectives

A Study was funded recently initiated by the Florida Department of Transportation (FDOT) to investigate the use of externally-bonded fiber reinforced polymer composites to repair vehicle impact-damaged metallic poles. This study investigated response relationships for repair components related to determined system failure modes, including substrate
strength properties, FRP tensile and compressive strengths, and bond behavior between FRP and metallic substrates. Compatibility of repair system materials was also considered, including galvanic corrosion interactions between the metal and the composite. Due to the required vertical application of composite repairs to utility poles, it was noted that use of a highly viscous adhesive should be implemented in avoid excessive sliding and sagging. It was found that commercially available externally-bonded FRP was capable of restoring the capacity of these damaged structures. However, additional study is necessary to investigate further characteristics of these repair systems, the understanding of which is required for the development of a standard design guideline [2].

This thesis will experimentally examine several externally-bonded composite repair systems for metallic utility poles. Material properties for the components will be determined and used in the development of a nonlinear finite element model that can be used to predict global system response. A preliminary investigation into variations of wrap geometry due to differences in pole and damage geometry, including the location of access ports, will be conducted. A reliable and repeatable method of applying damage to pole sections for experimental testing purposes which accurately represents observed vehicle impact damage will be developed. Recommendations for standard design properties will be presented which include guidelines for in situ damage quantification, repair system selection, and installation techniques.
Figure 1.1: Vehicle-impact damage of steel utility pole.

Figure 1.2: Laser scan of dented utility poles.
1.3 Thesis Outline

This thesis is presented in the following format:

1. Literature Review: The chapter provides a summary of the material systems and previous work relating to this study.

2. Composite Repair Systems: Here, a description of the selection process for the composite repair systems utilized in this study and their material properties is presented.

3. Experimental Testing: A series of tests were performed to evaluate the response of unrepaired and repaired damaged metallic poles. The different testing series are described and experimental results are presented.

4. Finite Element Modeling: A finite element model was created in order to quantitatively examine the structural responses of repaired pole structures. Computational results were compared to experimental results for verification.

5. Discussion and Conclusions: Conclusions are drawn relating to FRP repair system selection and design, as well as the applicability of the generated finite element model. Areas for ongoing future research are also presented.
The literature review conducted for this thesis is presented in the following chapter. The materials that make up FRP composites are discussed, and a brief survey of applications of externally-bonded fiber reinforced polymer (FRP) composites as related to civil infrastructure is presented. Current literature on finite element modeling of tubular metallic structures is also reviewed. Finally, the standard modeling approach for FRP, and the current set of FRP design guidelines are briefly summarized.

### 2.1 Externally-Bonded FRP Composites

Fiber reinforced polymer (FRP) composites consist of fibers impregnated, or saturated, with a polymer matrix. Primarily, the strength of the composite is provided by the fibers, while the matrix maintains the composite's shape and the orientation of the fibers and acts to transfer stress between the fibers. FRP can be used as an externally-bonded reinforcement. This structural technique involves adhering composites to the exterior surface of a structural member. Advantages of this method include quick installation and the repair’s low profile which conforms to the member geometry. Additionally, these composite retrofit
systems can be customized by selection of different fibers or matrix materials, creating an optimized repair for any specific application. Available reinforcing fibers include carbon, glass, basalt, aramid, and boron. Polymer resins include polyesters, epoxies, vinyl esters, phenolic resins, polyurethanes, and others. Of these, civil infrastructure applications most commonly utilize carbon and glass fibers with epoxy or, more recently, polyurethane resins.

2.1.1 Epoxy-Matrix Composites

Although epoxy resins are more expensive than other matrix materials, they possess several advantages over other options. These characteristics, including high strength, low viscosity, good fiber wetout, low volatility, low shrinkage, and ease of availability, have combined to make epoxies the most common matrix material used in externally-bonded FRP composites [3].

The most typically used application method for externally-bonded FRP applications involving epoxy resins is a wet layup. This involves impregnation of dry fibers by a saturating matrix material, consisting of an epoxy resin and a hardener which initiates a chemical curing reaction. The FRP composite can then be applied directly to the structural member, using the adhesive properties of the epoxy resin itself, or a separate adhesive layer can be applied.

Another option is the use of a pre-cured epoxy laminate sheet. With these composites, fibers are impregnated with an epoxy and allowed to cure before application to the structure. The laminate plates can be very stiff or somewhat flexible, depending the materials used.
This method is desirable in many cases where field preparation of the composite is difficult to control.

2.1.2 Polyurethane-Matrix Composites

The use of polyurethanes in structural composites is a relatively practice. The term polyurethane encompasses a group of resins that possess similar chemical and physical properties. Most polyurethanes share many of the advantageous properties of epoxy resins, such as good fiber wetout. Additionally, polyurethanes have a low cure times and are more cost effective than epoxies. However, it has been shown that they also have limited thermal and hydraulic stability and are sensitive to bulk moisture [4].

These composites are typically prepared as pre-impregnated laminates. This process differs from that of a wet layup in that the polyurethane resin is combined with the fibers off-site by the manufacturer, and the wet composite is then sealed until application. Upon opening the sealed packaging, water is sprayed onto the laminate surface and acts as a curing catalyst for the polyurethane. The composite can then be applied to the substrate, typically with a primer or adhesive material.
2.2 Civil Infrastructure Applications of FRP

Since the 1980s, research has been performed on the use of externally-bonded FRP to reinforce civil infrastructure. Applications have extended from concrete bridge girders and decks to column and pile reinforcement, retrofit of joint connections for seismic considerations, and even blast wall reinforcement [5]. This section discusses just a few of the applications of FRP reinforcement for the major civil substrate materials, concrete, steel, and aluminum.

2.2.1 Concrete Substrate

The popularity of FRP composites to reinforcement of structural concrete members has increased over the last few decades. Extensive research has been conducted to investigate the effectiveness of these repairs. As a result of this, the mechanical response of FRP repair systems is well understood, and it has been shown that they can be effectively used to improve the stiffness, static, cyclic, and fatigue load carrying capacity of structural members [6].

FRP debonding is an important design consideration for FRP-reinforced concrete members. Due to the sudden occurrence of this type of failure, a brittle system failure may result. This is undesirable from a design standpoint because it does not provide a warning period before failure [7]. Another important design consideration is shear failure.
It is possible for FRP tension reinforcement to cause the applied load to exceed the shear capacity of an RC member. This failure mechanism can be alleviated by U-jacketing or side bonding of FRP, but this in turn causes shear debonding and cover peel-off become critical failure modes [8].

2.2.2 Metallic Substrate

As opposed to concrete applications, steel and aluminum structural reinforcement with externally-bonded FRP has only recently been investigated. However, ease of application and favorable material characteristics of FRP make it a good candidate for many retrofit and repair scenarios.

The electro-chemical interaction associated with using FRP to reinforce metallic structures does require consideration. Corrosion is a major concern when dealing of carbon fiber composites due to the high degree of carbon’s galvanic potential. If these repair systems come in contact with a material that is low in the galvanic series, such as steel or aluminum, there is a significant potential for corrosion [9]. This potential demands that necessary precautions are taken when dealing with carbon fiber composite reinforcement of metallic structures.

Another concern, particularly in FRP reinforcement of steel structures, is the relative stiffness of the materials. Generally, a strengthening material has a higher stiffness than that of the material that it is strengthening. While this is the case for FRP reinforcements
of concrete substrates, or softer metals such as aluminum, steel has a much higher stiffness than most FRP composites. Although this fact makes the strengthening of structural steel members with composites less mechanically advantageous than other substrate systems, FRP repair of damaged steel members has been demonstrated to be economically and mechanically effective [6].

2.2.2.1 Steel Substrate

Several studies have shown steel bridge reinforcement using FRP composites to be a promising retrofit option [10]. These studies indicate that tension face reinforcement of a steel girder can improve the overall stiffness and strength of a structural member [11]. Recent studies examine the use of FRP wraps to reinforce damaged steel columns [12]. This technique was shown to improve the capacity of the damaged member.

FRP tubes have been studied as a reinforcement option to improve buckling resistance of steel members. Feng et al. [13] tested several L-shaped steel sections surrounded by an FRP tube which was filled with a lightweight grout material. It was demonstrated that the reinforcement significantly improved the capacity of the structural members by averting global buckling failure.

The use of CFRP composites in reinforcement of steel monopoles was investigated by Lanier et al. [14]. The surface of the monopoles was prepared for the composite bond by grit blasting. The composite was applied to the lower portion of the poles, with the number
of reinforcing layers increasing toward the base, as shown in Figure 2.1. Poles were tested in a cantilever configuration, and it was demonstrated that the flexural stiffness and strength of the system was improved by the CFRP reinforcement. An elastic flexural stiffness model of the experiment was also created, which was able to accurately characterize the elastic behavior of the reinforced monopoles.

Figure 2.1: Reinforcement scheme for CFRP strengthening of steel monopoles.

2.2.2.2 Aluminum Substrate

Few investigations have been completed on FRP reinforcement of aluminum sections. One such study, involving composites of carbon fibers with various adhesive materials, found that composite reinforcement systems were able to resist web buckling of rectangular aluminum hollow sections [15].
A series of studies was conducted in the 2000s investigating the use of composites in the repair of fatigue joints in aluminum highway sign structures. It had been determined that failure of these structures was caused by fatigue-induced cracking at welded joints. Several organizations, including the Delaware, Utah, and New York State departments of transportation, sponsored research on the effectiveness of composite repairs for these systems. These studies concluded that commercially available glass and carbon fiber composite systems could be used to restore damaged aluminum connections with good economic efficiency [16, 17, 18]. Few additional studies exist in the literature that investigate composite retrofit or repair of aluminum infrastructure.

2.3 Modeling of FRP Composites

Modeling of FRP materials, due to their composite nature, requires the combination of multiple component materials into a single material. These materials behave orthotropically, according to the alignment of the reinforcing fibers. The material properties of composites are determined by the rule of mixtures. The bond between the composite and the substrate is best modeled using nonlinear finite element analysis.
2.3.1 FRP Material Properties

Fiber-reinforced polymer composites consist of a woven fiber fabric saturated in a polymer matrix. The alignment of these layered fibers produces a dominant direction for stiffness and strength. Some of the fundamental equations describing characteristics of FRP composites are presented in this section. Full derivations for these and other formulations are given by Kaw [3].

2.3.1.1 Mechanical Properties of FRP Composites

Mechanical properties of a single layer of FRP are described by the rule of mixtures, which states that the composite properties are determined by proportional combination of its component properties. The volume of fibers in a composite divided by the total volume of the composite (fibers and matrix) is called the fiber volume fraction, and is typically abbreviated as \( V_f \). The remaining volume, that of the matrix material, as a fraction of the total volume is called the matrix volume fraction, typically denoted as \( V_m \). It is assumed that the void content of the composite is negligible, thus the sum of \( V_f \) and \( V_m \) necessarily equals unity.

Most FRP composites have a nearly linear stress vs. strain relationship. Therefore, Hooke’s Law, that is proportionality of stress and strain, can be accurately applied to these
materials. The modulus of elasticity of a composite in the direction of fiber alignment can be given by Equation 2.1.

\[
E_1 = (E_f V_f) + (E_m V_m)
\]  

(2.1)

2.3.2 FRP Bond Modeling

Within the bond between an composite laminate and substrate, a complex state of stress can exist. Typically, bond mechanics are described by the relationship between the shear stress in the adhesive layer and the relative displacement of the FRP to the substrate. This relative displacement is referred to as slip. If the bond is fully developed, the shear strain decreases to zero along the bond length. Therefore, integration of the strain along the bond length yields the total slip at the free end in the direction of load. The slip and shear stress at the free end of a lapped bond can be found by Equations 2.2 and 2.3, in which \( \epsilon_i \) is the axial strain at the location \( x_i \), \( t_f \) is the thickness of the FRP laminate, and \( E_f \) is the modulus of elasticity of the composite [19]. Bond-slip relationships for FRP adhered to concrete have a shape that has been described by several functions. Some common examples of these are shown in Figure 2.2, and include linear, bilinear, exponential, and linear-exponential relationships.
\[ \tau = \sum E_f \left( \frac{\tau_f}{x_{i+1} - x_i} \right) \left( \epsilon_{i+1} - \epsilon_i \right) \]  \hspace{1cm} (2.2) \\

\[ \text{slip} = \int_0^1 \epsilon_x \, dx = \sum \left( \frac{\epsilon_{i+1} - \epsilon_i}{x_{i+1} - x_i} \right) \left( x_i^2 \right) + (\epsilon_i \cdot x_i) \]  \hspace{1cm} (2.3) 

Figure 2.2: Bond-slip relationship models between FRP and concrete [20].

The behavior of composites bonded to metallic substrates has not been as thoroughly explored. Unlike concrete debonding failure, which typically occurs within the substrate, the plane of debonding failure for metallic substrate usually falls within the adhesive layer or at the interface between the adhesive and the substrate. Thus bonds to metallic structures are usually stronger than those to concrete substrates. However, this form of debonding action also tends to occur more quickly than with concrete [21, 17]. It has also been shown that accurate prediction of the bond-slip mechanics is achievable [22]. Some examples of bond-slip behavior between steel and FRP composites is shown in Figure 2.3 along with a simplified generalization of the bond-slip relationship [10].
2.4 Modeling of Metallic Pole Structures

Many studies have been performed in order to describe the behavior of damaged metallic tubular structures. The majority of these studies have been focused on applications to tubular members in offshore structures, and as such have focused on axial loading of the members [23, 24, 25, 26]. However, several researchers have also investigated the capacity of damaged or corroded members to resist lateral loadings [27, 28, 29, 30, 31].

In one such study, a finite element program was developed by Duan et al. [27] in order to calculate the capacity of damaged tubular members. This program utilized a moment-thrust-curvature method developed previously. The assumptions for the analysis included small deflections, negligible shear and torsional deformations, and no strain reversal. Boundary conditions employed by this program are either pinned or pinned with small end
restraints. This accuracy of this program was validated by comparison of predictions to test results and other analytical methods. This analysis demonstrated the versatility of the modeling method in application to numerous boundary conditions.

The most prevalent method in the literature for representing deformed shape of damaged tubular members is the application of beam-on-elastic-foundation principles. Durkin [28] presents an analytical method for predicting damage-induced strength reduction of tubular members subject to axial compression and end moments. An idealized dent shape was used, thus reducing the amount of detailed information on the dent geometry that is required for the analysis, which was based on beam-elastic-foundation relationships. As in the previous case, various end restraint conditions can be used with this method.

Fatt et al. [29] also used beam-on-elastic-foundation formulations to describe damage-deformed member shape for an investigation of response of a metallic tubular member to lateral dynamic loading. For this analysis, however, axial deformations were neglected, and the material of the member was assumed to be isotropic, time-independent, and rigid-plastic. The members were analyzed for a lateral impulsive load, and the results were compared to those of a computer program, DYNA 3D. The analytical deformations under-predicted those found by DYNA 3D by 25%. This difference was attributed to neglecting the bending mode of the shell.
CHAPTER 3
FRP REPAIR SYSTEMS

In this study, damaged metallic utility poles are repaired with several different externally-bonded FRP composite systems. These repair systems consist of reinforcing fibers, a resin matrix, a bonding adhesive, and a dent filler material. This section discusses the selection process for the various component materials that make up the multiple composite repair systems included in this thesis investigation. The discussion will begin with the selection of fiber materials and weaves, and then will move onto the matrix resins and adhesives. The assembled composite permutations will then be summarized. Finally, the selection process for the dent filler material will be described.

3.1 Fiber Selection

Several factors should be considered in the selection of reinforcing fibers for a given composite repair application. These include the micro-level mechanical properties of the fibers and the commercial availability of the material, as well as economic cost. In this case, as the substrate materials are metallic, galvanic corrosion interactions must be addressed.
Mechanical properties of a reinforcing fiber are dependent on the fiber material itself, and on the weave design of the fabric. Three fiber materials were considered for inclusion in this investigation: carbon, glass, and basalt. Likewise, two bi-directional weave patterns, high and low density, were evaluated for each material. These fibers are each widely commercially available, and have been used in civil infrastructure applications. Additionally, the mechanical properties of these fibers have been investigated and their behavior has been well characterized in the literature.

Based on the results of tensile tests performed according to ASTM D3039, it was determined that the low density weaves did not provide the stiffness and strength properties required for an effective repair system. Therefore, they were eliminated from consideration. Additionally, no carbon fiber composites were adopted for use in this project, due to their potential to cause corrosion problems for the metallic pole structures. Therefore, two fiber systems, high-density glass and high-density basalt, were chosen for inclusion in the experimental testing portion of this research. Both of these fibers are configured in a balanced, bi-directional weave, with a density of 24 oz/yd² [2].

3.2 Matrix and Adhesive Selection

Three commercially available composite matrix resins were evaluated for use in these utility pole repair systems. These include two epoxy systems and one polyurethane resin.
Each resin was paired with an adhesive provided by the same manufacturer. Important criteria for these systems include mechanical properties and ease of field application.

The first epoxy system, the QuakeBond (QB) system, is manufactured by QuakeWrap®. This system consists of a two part epoxy resin QuakeBond™ J300SR saturating resin, and a two part epoxy adhesive QuakeBond™ J201C tack coat. The QuakeBond composites are prepared as pre-cured sheets. The tack coat epoxy is drill mixed and possesses a high viscosity, which allows it to be applied to vertical poles without significant sagging.

A second epoxy system was also evaluated, referred to as the CarbonBond (CB) system. This system is manufactured by CarbonWrap™ Solutions LLC, and is similar to the QuakeBond system, except that the saturating resin, CarbonBond™ 200P, is used in a wet layup procedure, being applied to the fibers on site. This can potentially lead to quality control issues for the composites, and makes the field application process more cumbersome.

The final system investigated for use in this study is manufactured by Neptune Research, Inc. (NRI), and is a polyurethane saturating resin system, Syntho-Glass®XT, paired with an epoxy adhesive, Syntho-Subsea™LV. The polyurethane composites are prepared as pre-impregnated, or pre-preg laminates and are stored in hermetically sealed packages. These packages are then opened on the field and the resin curing process, catalyzed by contact with water, begins. This process, while slightly more demanding than the pre-cured sheet application, is significantly easier to perform than the wet layup procedure. The LV epoxy resin is drill mixed, as in the case of the QuakeBond and CarbonBond systems, and is also highly viscous.
Finally, considering the requirements of field application to vertical utility poles, the QuakeBond and NRI systems were chosen for continuing investigations.

3.3 Dent Filler Selection

A required element of a successful repair of a dented utility pole is that it restores the pole to a generally round shape. For the FRP repair systems developed in this thesis, this is to be accomplished by the use of a dent filler material. The important characteristics of this filler material are that it be sufficiently viscous to apply to vertical poles in large quantities without significant sagging, and that it provide a surface to which the composite wrap can form an effective bond. Three commercially produced epoxies were evaluated for use in as filler materials in this study, and are summarized in Table 3.1. The evaluation of these materials consisted in trial applications to dented steel and aluminum utility poles. The workability, ease of application to vertical poles, and resulting filler surface were observed and used to select the filler material to be used in the final repair systems.

The Syntho-Poxy HC was evaluated first. Approximately one quart of the material was mixed by hand, according to manufacturer instructions, and was applied to a dented pole with small trowels. Initially, the epoxy was applied easily, without significant slumping. However, within approximately 10 minutes from mixing, the epoxy seized and became un-workable, and quickly gained a plastic consistency. Therefore, filling of the dent was not completed, as can be seen in Figure 3.1.
### Table 3.1: Filler Materials

<table>
<thead>
<tr>
<th>Filler Material</th>
<th>Compressive Strength</th>
<th>Compressive Modulus</th>
<th>Pot Life at 75°F</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRI Syntho-Poxy HC</td>
<td>8,000 psi</td>
<td>-</td>
<td>4 to 6 min.</td>
<td>$688.29/gal</td>
</tr>
<tr>
<td>Pilgrim EM 5-2 Gel</td>
<td>11,400 psi</td>
<td>1,459 ksi</td>
<td>20-35 min.</td>
<td>$40/gal</td>
</tr>
<tr>
<td>Sikadur 31, Hi Mod Gel</td>
<td>16,000 psi</td>
<td>795 ksi</td>
<td>60 min.</td>
<td>$52.98/gal</td>
</tr>
</tbody>
</table>

(a) Mixing.  
(b) Siezed fill in dent.

**Figure 3.1: NRI Syntho-Poxy HC.**
Two dented poles were filled with the Pilgrim EM 5-2 Gel. The manufacturer specifies that up to 3 parts oven-dried aggregate to 1 part epoxy can be added. The first dent fill contained 1 part dry sand to 6 parts mixed epoxy, and the second 1 part dry sand to 3 parts mixed epoxy. The thixotropic gel was combined using a mixing drill. The first, lower sand content mix was applied to the dented pole easily, with minimal signs of slumping during application. However, when the fill was left to cure, the majority of the epoxy slid out of the dent, as shown in Figure 3.2. The second, higher sand content mix was applied to another dented pole, and was significantly stiffer than the first batch. In order to create a smooth, even surface on the fill, the pole was wrapped in wax paper during curing. The result, pictured in Figure 3.3, was an effective, even fill which blended well with the pole’s surface.

![Figure 3.2: Pilgrim EM 5-2 Gel low-sand fill.](image-url)
(a) Application of fill.  
(b) Wax paper wrap.  
(c) Cured fill.

Figure 3.3: Pilgrim EM 5-2 Gel high-sand fill.

(a) Application of fill.  
(b) Cured fill.  
(c) Cured fill.

Figure 3.4: Sikadur 31, Hi Mod Gel fill.
Two poles were also filled with the Sikadur 31, Hi Mod Gel. The large size of the dent in one of these poles increased the difficulty of applying a complete fill without epoxy slumping. The fill was mixed with a drill mixer, according to manufacturer specifications. The workability of the mix was good, and there was no problem with slumping of the fill material. When the fill material had cured, the surfaces were sanded smooth. The resulting fills can be seen in Figure 3.3.

The result of this filler evaluations was that the Pilgrim EM 5-2 Gel with a 1:3 sand additive and the Sikadur 31, Hi Mod Gel are acceptable options for inclusion in the FRP repair system. The difference in price, as well as the ability to manipulate the texture of the EM 5-2 Gel by varying the amount of aggregate additive, make this material a more favorable option than the Sikadur epoxy. Therefore, the Pilgrim EM 5-2 Gel was chosen for inclusion in the repair system.

### 3.4 Selected Composite Systems Summary

Four final composite systems have been selected for inclusion in this project. These consist of two resin/adhesive systems paired with two types of fiber reinforcement, and a dent fill. These systems, and their material properties, are listed in Table 3.2. The material properties were obtained experimentally at the University of Central Florida’s Structural Engineering Laboratory [2].
These systems, each combined with the Pilgrim EM 5-2 gel dent fill, were chosen based on their ability to be quickly applied, their corrosive resistance, and their material properties. The pre-impregnated NRI polyurethane system lends itself to field application in that it does not require on-site mixing of resin, and preparation of the composite itself requires only rolling out on a flat surface. The QuakeWrap system also is preferential for efficient field application since the composite itself can be applied as a pre-cured sheet. The limitation of this system is that the precured epoxy composite is often too stiff to apply tightly to narrow utility poles.

3.5 Wrap Application Procedure

The application process used for composite repairs of dented utility poles is outlined below. This procedure assumes that the extent of the damage and the level of repair necessary have already been determined.

1. Application of dent filler material.

2. Preparation of FRP composite.

3. Application of adhesive material.


The first step in the FRP repair application process is to restore the damaged pole to a generally round shape by filling the dent with an highly viscous epoxy material. For
this project, the dent filler material was Pilgrim’s EM 5-2 Gel epoxy with a sand additive, which has been discussed in Section 3.3. Large amounts of epoxy sometimes experience sagging following application and before curing. Therefore, for large dents it was sometimes necessary to fill the dent about 75% full, allow the gel to cure, and then layer additional epoxy on top in order to completely fill the dent. The epoxy filler has a gel time of about 30 minutes, after which time the surface was sanded as needed, and additional filler or an adhesive layer was applied to its surface.

Once the filler material was been applied, the FRP laminate wrap was be prepared. The two FRP systems investigated in this study are prepared for application by different methods. The first system, with the NRI polyurethane matrix material, is prepared wet in the field. The pre-impregnated composite was first removed from the hermetically sealed packaging, and then cut to the desired dimensions. The composite was then misted with water in order to catalyze the resin curing process. The laminate was then rolled out on a flat surface for several minutes in order to ensure that the even resin distribution through the fibers, and to limit bubbling of the matrix due to the release of carbon dioxide during curing.

The second FRP system, which utilizes the QuakeBond (QB) epoxy resin and adhesive, was applied to the pole as precured laminate sheets. Therefore, this composite was prepared and cured several days before the repairs were applied. Fibers were saturated with the QuakeBond resin and allowed to cure for approximately 24 hours. In the field, precured sheets were cut to the desired dimensions with a Dremel tool.
The application of the NRI system adhesive, Syntho-Subsea LV epoxy, was performed while the FRP laminate is prepared whenever possible. The two-part epoxy, once thoroughly mixed, was applied to the pole specimens with a thickness of approximately 30 mils. The working time of this epoxy, once mixed, is 20 minutes at 77\(^\circ\).

The two-part QB adhesive was mixed and applied, not to the pole surface, but to the underside of the precured laminate sheet, with a thickness of about 30 mils. The pot life of the QB epoxy at 77\(^\circ\) is significantly greater than that of the NRI epoxy at 90 minutes. Both epoxies have a thick consistency when mixed, which increases the ease of application to vertical pole structures.

As soon as the Subsea LV epoxy is applied to the pole, the NRI composite was placed over it. The composite generally clung well to the adhesive, but some sagging was seen. In order to prevent sagging or sliding of the laminate along the pole, the repairs were wrapped tightly with a thin plastic cling wrap. Small punctures were then made in the plastic, in order to allow carbon dioxide to continue to escape from the curing polyurethane, and the composite was rolled on the pole for several minutes. Full curing of this system occurs within 24 hours.

In the application of the QB repair system to pole specimens, the main concern was to ensure that a tight wrap is obtained that does not allow significant voids to develop between the composite and the pole. The precured laminate sheets are stiff, and can be difficult to manipulate, especially in repairing narrower poles. In order to secure these repairs, hose clamps were tightened around the repairs at several points using an impact driver, as shown
in Figure 3.5. Tie wires were placed around the repair at additional locations to prevent air pockets from forming in between the hose clamps. The QB repairs were fully cured in 48 hours.

Figure 3.5: Application of QuakeBond repair system.
Table 3.2: Selected Repair Systems

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Matrix Resin</th>
<th>Adhesive</th>
<th>Application</th>
<th>Tensile Strength ksi</th>
<th>Tensile Modulus ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>NRI XT</td>
<td>Syntho-Subsea LV</td>
<td>pre-preg</td>
<td>36.68</td>
<td>3372</td>
</tr>
<tr>
<td>Basalt</td>
<td>NRI XT</td>
<td>Syntho-Subsea LV</td>
<td>pre-preg</td>
<td>13.78</td>
<td>1208</td>
</tr>
<tr>
<td>Glass</td>
<td>QuakeBond</td>
<td>QuakeBond</td>
<td>pre-cured sheet</td>
<td>30.79</td>
<td>1497</td>
</tr>
<tr>
<td>Basalt</td>
<td>QuakeBond</td>
<td>QuakeBond</td>
<td>pre-cured sheet</td>
<td>30.01</td>
<td>3261</td>
</tr>
</tbody>
</table>
As a major portion of this research, a testing program was performed in order to investigate the performance of externally-bonded FRP repairs of damaged utility poles. This program consisted of a series of three sets of tests pole segments, obtained from retired utility poles, in a four-point bending configuration. The first set of tests in the experimental program is called the Damage Determination tests. The objective of these tests is to determine the effect of various levels of damage on the capacity of utility poles. The second set of tests investigates the effectiveness of a single layer of FRP in restoring the strength of poles dented to various depths. Three composite systems are evaluated by these Single-Ply tests. The final set of tests, named the Wrap Configuration tests, which evaluates the behavior of several configurations of FRP repairs. The goal of this testing set is to improve understanding of the mechanics of the FRP repairs. The results of these tests will inform the design of repairs implemented in the field. This chapter discusses the implementation of these tests and presents a summary of the results.
4.1 Component-Level Specimen Geometry and Denting

The component-level tests include the Damage Determination, Single-Ply, and Wrap Configuration tests. The specimens used in these tests, their geometry, level of damage, and materials are listed in Table 4.1. The aluminum alloy AA 6036-T6 pole sections were cut from one of two utility pole geometries. Poles ALu-1 through ALw-6 were cut from poles 27 feet in length, and poles ALw-7 and 8 were cut from 36 foot long poles. Steel sections were cut from poles with various geometries, and so the specimens discussed in this thesis are described by Table 4.1. Dog-bone coupons were cut from both the steel and aluminum utility poles and tested in tension. The results of these tests can be seen in Figure 4.1.

The first step in the testing process, cutting the pole specimens, was carried out using a band saw according to Figure 4.2. These resulting pole sections were damaged in the laboratory by rapid application of a point loading using an MTS. Loading and deformation data were taken during the denting process, which created round, localized dent. The rate of dent application was between 2 and 3 in/sec. An example of the denting data is shown in Figure 4.3.

However, it was often noted that, when applying larger dents, significant global bending of the pole occurred. The poles with more global damage were not tested, as the induced dent was not representative of the field impact-damage that commonly occurs, and was too severe to be repaired by an FRP wrap. Poles with bends this extreme would always be replaced in the field.
Once poles were dented in the laboratory, the damaged sections of several poles were scanned with a 3D laser scanner in order to create point clouds which can be used to generate a finite element model of the damaged surface. An example of a scanned point cloud is shown in Figure 4.4 for pole ALw-5.b.

Table 4.1: Component Level Test Specimens

<table>
<thead>
<tr>
<th>Pole ID</th>
<th>Diameter (in)</th>
<th>Denting Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North Support</td>
<td>Dent Location</td>
</tr>
<tr>
<td>ALu-1.a</td>
<td>4.56</td>
<td>5.00</td>
</tr>
<tr>
<td>ALu-1.b</td>
<td>5.34</td>
<td>5.86</td>
</tr>
<tr>
<td>ALu-2.b</td>
<td>5.34</td>
<td>5.86</td>
</tr>
<tr>
<td>ALu-4.a</td>
<td>4.56</td>
<td>5.00</td>
</tr>
<tr>
<td>ALw-4.b</td>
<td>5.34</td>
<td>5.86</td>
</tr>
<tr>
<td>ALw-5.b</td>
<td>5.34</td>
<td>5.86</td>
</tr>
<tr>
<td>ALw-6.a</td>
<td>4.56</td>
<td>5.00</td>
</tr>
<tr>
<td>ALw-7.a</td>
<td>4.56</td>
<td>5.00</td>
</tr>
<tr>
<td>ALw-8.a</td>
<td>4.56</td>
<td>5.00</td>
</tr>
<tr>
<td>ST-20.a</td>
<td>6.50</td>
<td>N/A</td>
</tr>
<tr>
<td>ST-25</td>
<td>6.75</td>
<td>N/A</td>
</tr>
<tr>
<td>ST-26.a</td>
<td>4.75</td>
<td>N/A</td>
</tr>
</tbody>
</table>
(a) Aluminum.  (b) Steel.

Figure 4.1: Pole substrate tensile data.

(a) Poles AL-1 through 6.  
(b) Poles AL-7 and 8.

Figure 4.2: Cuts applied to aluminum component level test specimens.
(a) Denting load vs. time.

(b) Denting displacement vs. time.

Figure 4.3: Dent application to pole ALw-5.b.
4.2 Damage Determination Tests

As mentioned above, the Damage Determination tests were performed in order to ascertain the effect of dents of various depths on the strength and stiffness of highway poles. Three (3) aluminum poles were tested with dent depths ranging from 5 to 26%. One undamaged aluminum pole was also tested as a control.

4.2.1 Specimen Preparation and Testing

The Damage Determination tests were performed at the Marcus H. Ansley Structural Research Center in Tallahassee, FL. The four-point bending test configuration is shown in Figure 4.5. This loading configuration was designed to emulate wind loading on a utility pole in the region of the dent. Wind loading is typically assumed to have a parabolic distribution along the length of the pole, thus creating a cubic shear force distribution, and a fourth degree bending moment distribution. Since this is difficult to replicate in a laboratory test, the loading configuration was chosen in order to create the ratio of bending moment and shear force at the dent location as is created by wind loading. The asymmetric loading creates constant shear and linear non-constant moment within the loading zone.

Curved supports and load applicators were fabricated for these tests, and were lined with neoprene or rubber pads. The locations of strain and displacement measurements are shown in Figure 4.5. 6 mm, 120 Ω strain gages and displacement transducers were used.
The displacement-controlled loading rate for these tests was approximately 0.1 in/min. The load, strain, and displacement data obtained from these tests were used to determine the effect of pole denting, as is discussed in the following section.

4.2.2 Damage Determination Test Results

4.2.2.1 ALu-4.a

Pole ALu-4.a was tested as a control, that is, without being dented. The pole section was cut from the narrowest (or $a$) end of a 27-foot aluminum pole. The pole section tapers from an outer diameter of approximately 5.75 in to 4.5 in on the support span. At the midpoint of the load application, which is the dent location for the dented poles, the outer diameter is approximately 5.0 in. The test setup is shown in Figure 4.6, which was prepared according to Figure 4.5. The displacement gages D1 and D7 are intended to measure the settlement at the supports as well as crushing of the cross section. However, significant rotation at the supports prevents these measurements from cleanly capturing the settlement behavior, and makes the determination of the displacement profile difficult.

Load was applied to the pole section, and the strains and displacements shown in Figure 4.8. The pole achieved a maximum load of approximately 8.43 kips before undergoing local buckling of the section at the outside edge of the south load applicator, as shown in Figure 4.7.
Figure 4.4: ALw-5.b point cloud from 3D scan.

Figure 4.5: Damage Determination test configuration.
Figure 4.6: ALu-4.a test configuration during testing.

Figure 4.7: Plastic hinging at load applicator.
It is likely that the load applicator initiated failure by creating a small dip in the pole surface. The maximum moment and stress at the location of the hinge were 12.3 kip·ft. The maximum strain and deflection on the bottom of the section at the center of loading were measured as $7539 \, \mu\epsilon$ and 4.17 in, respectively, both measured on the under side of the section at the center of loading. This tensile and compressive strain values when maximum load was achieved were $7395 \, \mu\epsilon$ and $-2627 \, \mu\epsilon$, respectively. If the local buckling had not occurred under the load applicator, it is likely that the section at the center of loading would have withstood its theoretical maximum capacity, which is calculated from the theoretical plastic moment. This theoretical capacity has a value of 10.12 kips, and is approximately 1.2 times the load actually held by the pole. Test results are summarized in Table 4.2.
4.2.2.2 ALu-1.a

The first dented poles to be tested were cut from pole ALu-1. The narrower end of this pole, ALu-1.a, received a dent with a depth of approximately 5% of the outer diameter at the dent location, or 0.25 in (see Figure 4.9). Poles ALu-1.a and ALu-4.a have the same dimensions, as both are cut from the narrow (or a) end of the utility poles. This pole was tested in the same configuration as pole ALu4.a, as shown in Figure 4.9.

When tested, pole ALu-1.a carried a maximum load of approximately 7.62 kips. Measured strain and displacement data are shown in Figure 4.11. Plastic hinging occurred at the center of the applied dent as can be seen in Figure 4.10. The maximum moment at the location of the hinge was calculated from the maximum load as 10.0 kip-ft. From the strain curves, it can be seen that gages S4 and S5, which are located on the top and bottom of the dented section, respectively, show fast-growing strains after the peak load has been achieved. This indicates that the section at the dent is deforming plastically. The tensile and compressive strains experienced at the dent center at the time of maximum loading were measured as 6080 $\mu\epsilon$ and -3972 $\mu\epsilon$, respectively.
Figure 4.9: Alu-1.a laboratory-applied dent and test configuration.

Figure 4.10: Alu-1.a plastic hinge failure at dent center.
4.2.2.3 ALu-1.b

The ALu-1.b pole section was taken from the middle section of pole ALu-1. This section, and all other aluminum b pole sections, have an outer diameter ranging from 6.6 in to 5.4 in across the support span. The outer diameter at the location of the applied dent is approximately 5.77 in, and the dent depth is 0.75 in, or about 13% of the outer diameter (Figure 4.12). The load, support, strain gage, and displacement gage configuration is the same as that of the previous tests.

The data collected from pole ALu-1.b is shown in Figure 4.14. The maximum load experienced by this pole was about 12.34 kips, at which point a plastic hinge formed at the dent location. This failure corresponds to a maximum moment of 16.2 k·ft at the location
of failure. The maximum load induced a tensile strain at the dent section of 5414 με, and a compressive strain of -9928 με at this location.

4.2.2.4 ALu-2.b

Section ALu-2.b has the same geometry as section ALu-1.b, but was dented to approximately twice the depth. The 1.5-in dent has a depth of about 26% of the pole’s undented diameter at that location. The maximum load carried by this pole was approximately 8.12 ksi, which created a moment of 10.7 kip-ft at the dent center. The corresponding strains at the dent section were 4222 με in tension, and -10458 με in compression. This large compressive strain indicates that the dented area deformed significantly during loading, and that the behavior of the section was greatly effected by the presence of the dent. This is confirmed by the moment capacity measured for this pole, which is significantly reduced from the control capacity, indicating that the strength of the section is largely reduced by denting. The data obtained during this test are shown in Figure 4.16.
Figure 4.12: ALu-1.b laboratory-applied dent.

Figure 4.13: ALu-1.b plastic hinging failure.
(a) Load vs. strain.  
(b) Load vs. displacement.

Figure 4.14: ALu-1.b test data.

Figure 4.15: ALu-2.b plastic hinging failure.
4.2.2.5 Summary of Damage Determination Results

Because of the different geometries of the pole sections tested for damage quantification, the test results can be synthesized through the non-dimensional quantity of the stress factor $F_\sigma$. This factor, as illustrated by Equation 4.1, is calculated from the peak moment experienced and the undamaged section modulus at the location of denting, or at the location pole failure if different from the dent location, and the yield stress of the pole material. This factor minimizes the effects of varying geometry between the different pole specimens.

$$F_\sigma = \left( \frac{M_u}{S} \right) \frac{1}{\sigma_y}$$  \hspace{1cm} (4.1)
This stress factor has been calculated for each of the Damage Determination specimens, and is shown plotted in Figure 4.17 against the dent depth as a percentage of the outer diameter. It is important to note, which considering this data, that the failure of pole ALu-4.a was likely accelerated by the effect of the steel load applicator creating a localized failure at the contact point with the pole. The theoretical maximum value of the stress factor for an undented pole section is also shown in the figure. This factor is equivalent to the plastic section modulus divided by the elastic section modulus, and has a value of approximately 1.32. Considering the behavior of the dented poles illustrated by Figure 4.17, there seems to be a gradual decrease in the normalized capacity as the dent depth increases. These trends will be investigated and discussed in more detail in Chapter 5.

Table 4.2: Damage Determination Results Summary

<table>
<thead>
<tr>
<th>Pole ID</th>
<th>Dent Depth (%)</th>
<th>Stress Factor</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALu-1.a</td>
<td>5.0</td>
<td>1.10</td>
<td>Localized Steel Buckling</td>
</tr>
<tr>
<td>ALu-1.b</td>
<td>13</td>
<td>1.32</td>
<td>Hinging</td>
</tr>
<tr>
<td>ALu-2.b</td>
<td>26</td>
<td>0.87</td>
<td>Hinging</td>
</tr>
<tr>
<td>ALu-4.a</td>
<td>N/A</td>
<td>1.23</td>
<td>Hinging</td>
</tr>
</tbody>
</table>
4.3 Single-Ply Tests

The Single-Ply wrap tests were carried out in a similar regimen to that of the Damage Determination tests, except that the dented poles were repaired with a one layer wrap of one of three FRP systems. These repair systems are: (1) high density bi-directional glass fibers pre-impregnated with NRI polyurethane resin, (2) high density bi-directional basalt fibers pre-impregnated NRI polyurethane resin, and (3) pre-cured sheets of high density bi-directional glass fibers in QuakeBond epoxy resin. The objective of this set of tests was to determine the effectiveness of a uniform single layer of FRP repair. The resulting information is then to be used in the design of repair wrap systems.

The Single-Ply specimens were prepared and tested at the Marcus H. Ansley Structural Research Center, and the test configuration, similar to that of the Damage Determination tests, is shown in Figure 4.18. Again, steel fabricated supports and load applicators were used, with neoprene or rubber linings. The locations of the displacement gages and the 6mm, 120 Ω strain gages are indicated in the figure. The FRP wrap extends between the loading points for these tests. Although field repairs of damaged poles would not extend over such a long section, extending the wrap allows elimination of possible bond development length concerns and concentration on other failure methods.
Figure 4.17: Damage Determination experimental stress factor vs. dent depth.

Figure 4.18: Single-Ply test configuration.
4.3.1 Single-Ply Test Results

4.3.1.1 ALw-5.b

The first of the Single-Ply tests to be performed, ALu-5.b, investigates the effect of the epoxy dent filler in restoring pole capacity, and therefore a composite wrap was not applied to this pole. The pole was tested with only the gel dent filler portion of the repair, as shown in Figure 4.19. The epoxy gel filler was wrapped in wax paper during curing in order to maintain a smooth, round fill surface. The depth of the dent for this pole was approximately 1.875 in, or 33% of the outer diameter.

![ALw-5.b filled dent.](image)

Figure 4.19: ALw-5.b filled dent.

This pole specimen, as well as all other Single-Ply pole sections, was tested with the same loading configuration, but with additional strain gages on the FRP composite, as shown in Figure 4.18. The strain and displacement data from this test are plotted below.
As can be seen from these plots in Figure 4.21, the maximum load sustained by this pole was approximately 11.6 kips. This load induces a moment of 15.23 kip-ft at the dent center. The point at which the fill material begins compressive failure can also be seen in Figure 4.21. After this point, the mode of pole failure is plastic hinging at the dent, as can be seen in Figure 4.20.

4.3.1.2 ALw-4.b

Pole ALw-4.b was dented to a depth of 25% of the outer diameter, or 1.25 in. This dent was filled with the viscous epoxy gel and was reinforced with a single layer of the glass fiber/polyurethane matrix composite according to the procedure outlined previously. The composite wrap extended to the edge of the load applicators.
The first attempt to test pole section ALw-4.b had to be aborted because the I-beam used to distribute the load from the MTS actuator to the two loading points experienced flange buckling under the applied load (see Figure 4.22). The pole was unloaded from a load of 15.1 kips, leaving a residual mid-span deflection of approximately 0.8 in. A new spreader beam was used to continue loading the pole to 17.7 kips (Figure 4.3.1.2). As is shown in Figure 4.3.1.2, the residual strain and displacement from test 1 were added to the displacements measured in test 2. The strain values are taken from the gages on the steel (S5) and composite (S12) surfaces on the bottom of the section at the midpoint of loading. This yields maximum mid-span deflection, strain in aluminum, and strain in composite values of 4.4 in, 7361 $\mu\varepsilon$, and 4756 $\mu\varepsilon$, respectively. Fiber buckling was seen to have occurred on the compressive face of the pole at 1 in and 3 in from the dent center toward the small diameter end (Figure 4.23).
Debonding of the fibers was noted on the tension side of the pole. The debonded area is shown in Figure 4.23. The strain profile plotted in Figure 4.26 for section BB’ during test 2, with gages S6, S7, S13, and S14, shows that debonding of the tension dace laminate occurs between 16 and 17 kips of applied load. It appears from this plot that the compressive wrap does not have a good bond from the beginning of the test, which is also the case from the beginning of test 1. However, the likely cause of the apparent lack of bond is the placement of gage S13 directly over gage S6, which would cause only a very localized bond weakness. The final failure of the pole occurred through plastic hinging at the dent location.
(a) FRP buckling failure.  (b) FRP buckling failure.

(c) FRP debonding from tension face.

Figure 4.23: Alw-4.b failure modes.
Figure 4.24: ALw-4.b test data.
Figure 4.25: ALw-4.b combined test data.

(a) Load vs. combined strain.  
(b) Load vs. combined displacement.

Figure 4.26: Progressive strain profiles at section BB’ for pole ALw-4.b test 2.
4.3.1.3 ALw-6.a

This pole was wrapped with two layers of the glass/epoxy composite. The 1.5-in (30%) dent on this pole, however, was only partially filled with the QuakeBond Tack Coat epoxy, rather than the Pilgrim gel. Several of the strain gages underneath the FRP wrap were inoperable during testing. The data from the remaining strain and displacement gages are plotted in Figure 4.3.1.3. The pole failed in a sudden rupture of the aluminum at the narrower end of the composite wrap. This location corresponds to the lowest bending moment within the loading region.

The maximum load sustained by the pole was 7.98 kips. This load created a bending moment at the dent location and at the rupture point of 10.5 and 9.64 k-ft, respectively. The reason for the failure at this location can be seen in Figure 4.26. In parts (d) and (e) of this figure, the ruptured cross section is shown, and it can be seen that two bolt holes have been drilled into this pole, just under the composite wrap. These holes weakened the pole section at this location, causing the premature substrate failure. The ruptured section, pictured in Figure 4.27, has an uneven wall thickness, which is thicker in many locations than the thickness of the pole that was measured before testing. This fact necessitates increasing the theoretical capacity of this pole. At a load of approximately 7.25 kips, a small drop in load was detected, presumably due to the failure of the QuakeBond fill. Because of the incompleteness of the fill, the effect is not as great as that seen when the Pilgrim fill is used.
However, we see that it does contribute slightly to the structural stiffness.

Although this test does not allow for quantification of the increase in pole capacity due to the FRP wrap, because the failure occurred outside of the wrapped region, this data can be used to obtain a lower limit for the capacity of the dented region.
4.3.1.4 ALw-7.a

Pole ALw-7.a was dented to a depth of 1.25 in, or 25% of the pole’s outer diameter at the dent location. The dent was then filled, and the pole wrapped with a layer of basalt fiber/PU composite. Several strain gages on this pole were not functional at the time of testing. The strain and displacement data that were gathered are shown in Figure 4.29. The fibers on the top of the pole buckled at several points, as is shown in Figure 4.30. Buckling was observed at the center of the dent, and 6-8 inches from the dent along the pole in both directions. Debonding of the fibers also occurred on the tension face.

The final pole failure was plastic hinging in the dented region. The capacity of the pole was measured as 8.48 kips. The maximum sustained moment was 11.13 k·ft. A drop in the load occurred just after yielding of the pole section, as can be seen in Figure 4.29. A
corresponding jump in the strain data at gage S12, placed on the laminate surface over the center of the dent. This drop likely corresponds to the failure of the epoxy filler material, indicating that the fill material itself does not improve the strength of a composite wrapped section, except in its contribution to out-of-plane buckling resistance in the compressive reinforcing fibers. The compressive failure of the FRP laminate was first detected by strain gage S11 at a strain value of approximately 9205 \( \mu \varepsilon \), which is near to the compressive failure strain of 9300 \( \mu \varepsilon \) determined for this composite from material testing, as discussed in Chapter 3. Debonding behavior is detected by strain gage S12, located at the dent center on the tension side of the pole.

![Graphs](image)

(a) Load vs. strain. (b) Load vs. displacement

Figure 4.29: Alw-7.a test data.
Figure 4.30: ALw-7.a Failure modes.
4.3.1.5 Alw-8.a

This final Single-Ply specimen was wrapped with one layer of Glass/EP composite after being dented to a depth of 1.3125 in, or 26% of the outer pole diameter. When the wrap was applied to this pole, the wrap extended beyond the load application points for the pole. Therefore, the composite was cut with a rotary tool, and removed from the area under the load applicators. However, when the laminate was cut, the rotary disk penetrated deeper than intended, and etched a groove in the aluminum pole material at the south end of the wrap. Additionally, examination of the failed revealed that a bolt hole had been drilled into the substrate at this same location. When the pole was loaded, the reduced cross section at this point caused the aluminum to rupture at a maximum load of 7.51 kips.
Strain and displacement data are shown in Figure 4.31. This failure load corresponds to a maximum moment at the dent location of 9.86 k·ft. However, as the failure mode was aluminum rupture outside of the composite wrap, this values provide a minimum capacity of the repaired dent area. The steel strain measurements at the dent location at the time of aluminum rupture are 4513 µε on the tension face and -1165 µε on the compression face. When compared with the strain data for the other poles tested, these values are much lower than of the expected failure strains. This implies that, had ALw-8.a experienced a plastic failure at the dent, the capacity would have been much greater. The wrap and failure of pole ALw-8.a are shown in Figure 4.32.

4.3.1.6 Summary of Single-Ply Results

The results of the Single-Ply tests are summarized in Table 4.3 and Figure 4.33. It is important to note the failure modes of each specimen when considering the numerical results. For example, poles ALw-6.a and 8.a failed through rupture of the aluminum substrate outside of the wrapped region. Therefore, these results provide with lower-limit capacity of the repaired sections, rather than giving the increase in strength provided by the wraps. The additional failure modes listed, debonding and compressive buckling of the FRP, both occur more suddenly than hinging failure in the substrate. This should be considered in the design of full-scale repair systems. Analysis of pole ALw-4.b produced a stress factor approaching 2.5, as shown in Figure 4.33.
However, it was discovered that the thickness of this pole was greater near the dent location than had been originally measured, and the stress factor was reduced to account for the larger cross-section.
Table 4.3: Single-Ply Results Summary

<table>
<thead>
<tr>
<th>Pole ID</th>
<th>Wrap Type</th>
<th>Fill Type</th>
<th>Dent Depth (%)</th>
<th>Stress Factor</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALw-4.b</td>
<td>Glass/PU</td>
<td>Pilgrim</td>
<td>21</td>
<td>1.39</td>
<td>Debonding/Hinging</td>
</tr>
<tr>
<td>ALw-5.b</td>
<td>-</td>
<td>Pilgrim</td>
<td>33</td>
<td>1.27</td>
<td>Hinging</td>
</tr>
<tr>
<td>ALw-6.a</td>
<td>Glass/EP (2 layers)</td>
<td>QB (Partial)</td>
<td>30</td>
<td>1.15</td>
<td>Aluminum Rupture</td>
</tr>
<tr>
<td>ALw-7.a</td>
<td>Basalt/PU</td>
<td>Pilgrim</td>
<td>25</td>
<td>1.22</td>
<td>Fiber Buckling/Hinging</td>
</tr>
<tr>
<td>ALw-8.a</td>
<td>Glass/EP</td>
<td>Pilgrim</td>
<td>26</td>
<td>1.08</td>
<td>Aluminum Rupture</td>
</tr>
</tbody>
</table>
It appears from this data that each of the composite wraps tested is effective in improving the capacity of damaged poles, with the reinforced stress factors approaching, or in the case of ALw-4.b slightly surpassing, the theoretical maximum for an undented, unrepaired pole. These results will be investigated and discussed in more detail in Chapter 5.

4.4 Wrap Configuration Tests

The final set of component-level tests of this project is the Wrap Configuration tests. This set of test involves testing 18 tapered steel utility pole sections in a four-point loading configuration. Seven different wrap configurations are included in the test matrix, shown in Table 4.4. The objective of these tests is to make a more detailed investigation into the mechanics of FRP repairs of metallic pole structures. Each of the wrap configurations listed in Table 4.4 is designed to isolate, as much as possible, one element of a composite repair in order to investigate its contribution to the overall repair effectiveness. The purpose is not to obtain an increased pole capacity, but rather to monitor and understand the FRP load transfer and failure. An understanding of these mechanics will allow the development of more efficient, cost-effective composite repairs.

The wrapping of these poles uses the same procedure as the Single-Ply tests as described previously. Schematics of the different wrap configurations, along with the loading configuration and gage locations, are shown in Figures 4.34 and 4.35.
The loading configuration was chosen to simulate, between the load application points, the state of stress of a pole under a linear wind loading. The ratio between the extreme fiber moment and shear stresses at the center of loading caused by the offset four-point bending is the same as the ratio of extreme fiber stresses in the section 2.5 ft above the base of a utility pole under wind loading. The compression and tension face wraps are designed to investigate the load-carrying action of a composite wrap on these portions of the section without the effects of confinement. The transverse, or circumferential wrap was chosen to determine the shear load action of a repair. Finally, the neutral axis wrap is intended to provide information on the shear resistance provided by the composites.

4.4.1 Wrap Configuration Test Results

The results from three Wrap Configuration tests are included in this thesis. The remaining tests are ongoing, and results will be made available to the public through the FDOT at the conclusion of this project. Each of the poles tested and discussed here were reinforced with a basalt fiber/PU composite. One of each of the Tension Face, Compression Face, and Transverse Strips configurations have been tested. This section contains a brief discussion of the results of each of these tests, and a preliminary discussion of conclusions from these tests.
Figure 4.33: Single-Ply experimental stress factor vs. dent depth.

Figure 4.34: Wrap Configuration test configuration.
Table 4.4: Wrap Configuration Test Matrix

<table>
<thead>
<tr>
<th>Pole ID</th>
<th>Fiber Type</th>
<th>Resin Type</th>
<th>Wrap Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-13</td>
<td>Glass</td>
<td>NRi PU</td>
<td>Transverse Strips</td>
</tr>
<tr>
<td>ST-17.a</td>
<td>Glass</td>
<td>NRi PU</td>
<td>Neutral Axis</td>
</tr>
<tr>
<td>ST-17.b &amp; ST-25</td>
<td>Basalt</td>
<td>NRi PU</td>
<td>Tension Face</td>
</tr>
<tr>
<td>ST-19.a &amp; b</td>
<td>Basalt</td>
<td>NRi PU</td>
<td>Tension/Transverse</td>
</tr>
<tr>
<td>ST-20.a &amp; b</td>
<td>Basalt</td>
<td>NRi PU</td>
<td>Compression Face</td>
</tr>
<tr>
<td>ST-21.a &amp; b</td>
<td>Basalt</td>
<td>NRi PU</td>
<td>Compression/Transverse</td>
</tr>
<tr>
<td>ST-23.a &amp; b</td>
<td>Basalt</td>
<td>NRi PU</td>
<td>Neutral Axis/Transverse</td>
</tr>
<tr>
<td>ST-24</td>
<td>Basalt</td>
<td>NRi PU</td>
<td>Neutral Axis</td>
</tr>
<tr>
<td>ST-26.b</td>
<td>Glass</td>
<td>QB EP</td>
<td>Transverse Strips</td>
</tr>
<tr>
<td>ST-27.a</td>
<td>Glass</td>
<td>QB EP</td>
<td>Neutral Axis</td>
</tr>
<tr>
<td>ST-27.b</td>
<td>Basalt</td>
<td>QB EP</td>
<td>Transverse Strips</td>
</tr>
<tr>
<td>ST-27.c</td>
<td>Basalt</td>
<td>QB EP</td>
<td>Neutral Axis</td>
</tr>
</tbody>
</table>
(a) Compression face wrap.

(b) Tension face wrap.

(c) Neutral axis wrap.

(d) Transverse strips wrap.

(e) Compression and transverse strips wrap.

(f) Tension and transverse strips wrap.

(g) Neutral axis and transverse strips wrap.

Figure 4.35: Combined Wrap Configuration permutations.
4.4.1.1 Tension Face Wrap: ST-20.a

The tension side of this pole was wrapped, as is shown in Figure 4.35, and pictured in Figure 4.36. Five 5-mm strain gages were used, spaced at three inches on center over the 18-in laminate. The composite system used in this test is the NRI basalt fiber/polyurethane matrix system, paired with the NRI epoxy adhesive. The pole was loaded as described above, and the displacement controlled test rate was 0.2 in/min.

![Tension wrap before testing.](image)

Figure 4.36: Tension wrap before testing.

As can be seen in Figure 4.37, the capacity of pole ST-20.a was measured as 33 kips of total load. As loading continued beyond the peak, the steel pole formed a plastic hinge failure underneath the southernmost load point. This is the location of the greatest moment carried by the pole. The maximum moment carried at the center of loading was
approximately 86% of the theoretical yield moment for the section, and about 66% of the theoretical ultimate moment. The reasons for the large difference between the experimental and theoretical capacity include crushing of the cross section, and large local deformations, especially under the southern load point. As can be seen in Figure 4.38, the hinging occurred before any failure of the FRP wrap was detected.

The test was continued, and debonding of the wrap began, initiating at the southern end, and progressing northward. It can be seen in Figure 4.37 that debonding of the composite occurred under each of the southern gages. The strain values at debonding are 4398 and 2535 $\mu \epsilon$ for gages South 2 and South 1, respectively. The remaining gages remain at a constant strain level after steel failure. As the debonding occurs after yielding of the steel, it is probable that the debonding action was due more to interfacial shear between the laminate and the steel.

(a) Load vs. strain.  
(b) Load vs. displacement

Figure 4.37: ST-20.a test data.
Figure 4.38: ST-20.a failure modes.
4.4.1.2 Compression Face Wrap: ST-25

Pole ST-25 was arranged in the same way as pole ST-20.a, except that the wrap and gages were aligned on the Compression side of bending. This configuration is shown in Figures 4.35 and 4.39. As stated in Table 4.4, the same basalt/polyurethane composite system was used for this wrap as for the Tension Face wrap.

Figure 4.39: Compression wrap before testing.

This pole held a maximum load of 35.4 kips, at which point the section yielded under the south load point. This load is 87 and 66% of the theoretical yield and plastic moments for the section, respectively. As can be seen from the plots of Figure 4.40, the compressive strain measurements increased steadily up to a load of approximately 26 kips, and then began to decrease in magnitude as the deformation increased, eventually becoming tensile.
strains. This occurred because the large deformations experienced by the pole essentially caused the pole to act as a catenary. The wrap began to debond at its southern end, and it can be seen that the South 2 gage debonded at a load of about 33 kips, after steel failure, having achieved a compressive strain of \(-1132 \, \mu\epsilon\) and a tensile strain of \(1887 \, \mu\epsilon\). Debonding also reached gage South 1, which initially reached a compressive strain of \(-891 \, \mu\epsilon\) and then a tensile strain of \(1620 \, \mu\epsilon\). These strain values at debond are significantly lower than those seen in the tensile wrap test. This indicates that weakening of the bond occurred during compressive loading, and thus was not able to sustain higher tensile stress values. However, for this test the debonding mechanism was likely combined with a peeling effect, because of the large deformations under the load points.

![Load vs. strain](image1)

![Load vs. displacement](image2)

Figure 4.40: ST-25 test data.
4.4.1.3 Transverse Strips Wrap: ST-26.a

A third wrap configuration test was performed on a pole wrapped with three 3-in transversely-oriented strips. This wrap configuration, as well as the gage nomenclature, is indicated in Figure 4.35. This test was performed in accordance with the previous procedure, and a maximum load of approximately 26.5 kips, which is approximately 96% of the theoretical ultimate moment at the center of loading. This result is much closer to the theoretical capacity because of its smaller diameter, which experienced less crushing of the cross section. A selection from the test data is shown in Figure 4.43. The main failure mechanism of the system was failure of the steel section underneath the south load point. As the test continued, the top of wrap section A was separated from the substrate, as can be seen from
the strain data in Figure 4.43. This was likely caused by a peeling effect due to the load deformations at the near load point, rather than pure debonding.

The general behavior of sections B and C follows the same trends as section A, except that debonding does not occur. From this data, it is seen that the longitudinal strains at the top and bottom of the pole section are roughly equal in magnitude and opposite in sign before yielding of the steel. This is expected from a balanced section. It can also be seen that the longitudinal strain at the neutral axis is near to zero for the majority of the test, which is also expected for a balanced pole section. The transverse strain values at the neutral axis of the section are smaller in value than the longitudinal strains toward the extremities of the section.

Figure 4.42: ST-26.a wrapped section.
(a) Load vs. strain.  
(b) Load vs. displacement

Figure 4.43: ST-26.a test data.

(a) Residual displacement.  
(b) Yielded section.

Figure 4.44: ST-26.a failure.
4.4.2 Summary of Wrap Configuration Results

From these three tests, some conclusions can be formed as to the effectiveness of different wrap configurations. Examining the strain levels during elastic loading and comparing to the theoretical strain values in the steel substrate, the load-carrying effect of each wrap configuration can be evaluated. Figure 4.45 shows the strain measurements at the center of loading normalized by the theoretical yield strain and plotted against the applied moment as a fraction of the theoretical yield moment. Part (a) of this figure shows a comparison of the extreme fiber longitudinal tension and compression strains to the theoretical strain progression. Here, the values of strain in the tension and transverse wrap are shown to be significantly greater than the theoretical substrate strain values, whereas the compression strain values are slightly lower than the theoretical. This indicates that the tension and transverse wraps are effectively engaged in load transfer during elastic loading. The compression wrap is positioned below the theoretical strain curve, but this is due to the settling effects at the beginning of experimental loading. The slope of the compressive strains are approximately the same as that of the theoretical strain. However, the compressive wrap does not increase the slope of the strain curve, indicating that a compressive wrap, without transverse confinement, does not provide effective reinforcement. In part (b) of Figure 4.45, a comparison of normalized circumferential strain taken from the center of loading of the transverse wrap specimen compared to theoretical circumferential strain values is shown. It can be seen that the experimental composite strains are approximately 2.5 times greater
than the theoretical substrate strains. This indicates that the transverse wrap is playing a significant part in circumferential load resistance at this section. From these plots, it appears that while a tension face composite repair is able to improve load transfer, transverse confinement greatly increases engagement of the repair.

The Wrap Configuration investigation is ongoing, and several additional tests are planned. These tests include transverse wraps combined with compression and tension wraps. The results of these tests will provide more conclusive information on the effectiveness of these and other wrap designs.

(a) Bending strains.  
(b) Shear strains.

Figure 4.45: Normalized strain vs. normalized moment.
A finite element model (FEM) was created in MSC.Marc to model the Damage Determination and Single-Ply tests. The goal of this model is to fill in the gaps in the experimental data for both the Damage Determination and Single-Ply tests, and to improve the understanding of the behavior of dented and wrapped poles. Also, this model can be modified to investigate the response of full-scale damaged pole structures with various repair systems. This will allow repair designs to be evaluated numerically before they are implemented in the laboratory. This chapter describes the features of the finite element model, and discusses the results of the analysis as they relate to the component-level investigation.

5.1 Details of the Finite Element Model

5.1.1 Model Geometry

The geometric configuration of the finite element model, the element definition, and the various methods of mesh generation are discussed in this section. The process of gen-
Generating different model geometries was automated through the use of a Python program, WebFE, the functionality of which will also be briefly discussed.

5.1.1.1 Basic Geometry and Mesh Generation

The basic elements of the FE geometry are the same as the Damage Determination and Single-Ply test configurations, as shown in Figure 4.18. The origin of the model coordinate system is located at the center of the pole at the location of the deepest point of the dent. The right and left loading points are centered at +21 and -21 in, respectively, and the supports are located at +62 and -46 in. The thickness of the shell elements that make up the metallic pole section have a thickness of $\frac{3}{8}$ in.

Two methods of mesh generation for the utility pole models were used. The first was used for models generated from 3D scans of the dented component level test specimens. These scans were assembled into point clouds stored in ACIS, or *.sat, files. These files were imported into AutoCAD, where any required modifications were made, such as patching missing portions of the geometry. The refined scans were then exported as new ACIS files, which were in turn imported into Marc as a point cloud. These objects, once in Marc, can be exported again as *.dat files, which are readable by the WebFE script. One of the functions of WebFE is the adjustment and expansion of these point clouds into complete node/element pole structures. The scanned object is oriented so that the center of the pole at the location of the deepest dent point is at the origin, and the dent faces upwards. Additionally, the
ends of the pole object can be extended by this program to a user-specified distance from
the origin at each side, with a specified nodal spacing. For this project, the node spacing
used was approximately 0.41 in. The extended portion of these pole models are not tapered,
but extend straight from the end of the scanned portion. An example of these extended
pole meshes can be seen in Figure 5.1. This procedure also applies the appropriate element
and material definitions and boundary conditions to the pole models, and generates a Marc
model file.

![Figure 5.1: ALu-2.b 3D scan generated mesh.](image)

Another method of mesh generation was employed for the poles with numerically
generated dents. These numerical dent shapes are based upon a curve-fit of the scanned
dents, and is shown in Figure 5.2 and Equation 5.1. This determines the damaged pole
surface coordinates at a given distance along the pole \( x \) based on the angle of rotation \( \theta \)
and the deepest dent depth. As an example, a comparison between the scanned dent surface
points and the numerical dent surface is shown in Figure 5.2.

\[
z(\theta) = \begin{cases} 
\cos(1.065\pi \theta) & \text{for } 0 \leq \theta \leq 0.2 \\
0.225 + 0.562 \cos(\pi \theta) + 0.525 \cos(2\pi \theta) + 0.1875 \cos(3\pi \theta) & \text{for } 0.2 < \theta \leq 1
\end{cases}
\]

(5.1)
For such numerically generated dents, the entire pole mesh geometry is generated through WebFE. An example of the tapered, dented pole geometries, with a 20% dent depth, is shown in Figure 5.3. The nodal spacing is set to 0.41 in for these models, and the boundary conditions are applied to the mesh in Marc, as is discussed in the following section.

5.1.1.2 Boundary Conditions

The boundary conditions of the pole models were selected in order to emulate the conditions of the component level tests (see Figure 5.4). For the models utilizing the dent shape function, the loads are applied directly to nodes on the pole’s surface in Marc. The load is applied through a linearly-increasing point load applied to several nodes on the upper half of the pipe section for a distance of 2 in along its length, centered at 21 in from the origin. The application of the load to the scanned models is accomplished through two plates which are located 8 in above the pole section and connected to each pole node underneath them by a spring. The load is then applied to these plates, which are limited to vertical translation, thus transmitting the load evenly to pole’s nodes.

The pole is modeled as a simply supported structure. The vertical restraints are applied to several nodes on the lower half of the pipe section at each end. Additionally, horizontal restraints are applied to one node at the right (narrower) end of the pole section. These restraints are illustrated in Figure 5.5.
Figure 5.2: Comparison of dent surface function to scanned dent surface.

Figure 5.3: Numerically dented pole mesh.

(a) Experimental.  (b) Scanned model.  (c) Generated dent model.

Figure 5.4: Load application modeling.
5.1.2 Material Properties

The materials included in the FE model include that of the metallic pole, the dent fill, and the composite wrap. The properties of these materials are defined based on material tests that were performed in the course of this project or, in the case of the fill material, on manufacturer specifications.

5.1.2.1 Aluminum

The aluminum structural material is defined by an elastic modulus, Poisson’s ratio, yield strength, and plasticity behavior. The elastic modulus and yield strength were determined by tensile tests performed on dog-bone coupons cut from utility poles, and have values of 8,380 ksi and 29.5 ksi, respectively, and Poisson’s ratio was defined as 0.3. The plasticity
behavior was defined based on the stress-strain behavior of the aluminum dog-bone coupons, as shown in Figure 5.6.

![Figure 5.6: Aluminum plasticity model.](image)

5.1.2.2 Filler Material

The dent filler epoxy material is modeled as solid elements, and is added to the dented region, extending to the pole’s original surface. The fill was defined as an isotropic, elastic material, with elastic modulus of 79.2 ksi, and Poisson’s ratio of 0.3. A yield strength of 685 psi is also defined. These properties are specified by the material manufacturer for the unreinforced epoxy. Because the fill used in the physical repairs is reinforced with a dry sand aggregate, the model material behavior may be different from that seen in experiments.
Additionally, the material definition does not include the plasticity behavior of the fill. Material tests are required to determine this behavior, which, once implemented into the finite element model, will allow the fill material to be accurately characterized.

5.1.2.3 FRP Composite

The FRP composite materials are modeled as shell elements, and are placed above, and attached to, the pole or fill surface, as applicable. The material properties are defined for each composite material based on the results of the tensile tests performed in this research and discussed in Chapter 3. For the wrapped pole section discussed in this section, ALw-7.a, the Basalt/PU composite has elastic modulus, Poisson’s ratio, and yield stress of 183 ksi, 0.3, and 2.00 ksi, respectively.

5.2 Finite Element Results

5.2.1 Scanned Model Results

The first type of model to be investigated is that using the scanned pole surfaces. These models have the advantage of an accurate representation of the damaged surface, allowing them to be directly compared to experiments. The main criterion for evaluating the behavior of FE models in comparison is the relationship of the load to the displacement
at the midpoint of the load application. A plot of this relationship can be seen in Figure 5.7 for both the scanned dent model and the experimental results for pole ALu-2.b. It can be seen here that the stiffness of the finite element pole and the physical pole are in agreement, and the model is able to accurately characterize pole behavior.

Figure 5.7: ALu-2.b comparison of experimental, scan model, and dent model results.

5.2.2 Dented Model Results

The next step compares the results of models using generated dent surfaces to those of the scanned models and experimental tests. Again, results are presented for pole ALu-2.b in Figure 5.7. The object of this comparison is not to create an excellent match between the generated dent surface model and the scanned surface model or experimental results. Rather, the goal is to capture the overall system behavior, since the damage to the model

91
is different than that of the physical pole. Figure 5.7 shows that this has been achieved, as the shape of the load-displacement curve is similar to those of the experimental Damage Determination test results.

A model of an undented pole section was also created, and results were compared to those of pole ALu-4.a, the undented control specimen. The comparison of the midpoint deflection behavior is shown in Figure 5.8. The behavior matches that of the physical test well, and confirms that the material and boundary conditions of the experiment have been well characterized by the model.

Dented pole models were generated using the empirical dent surface formulation for dents of various depths. A summary of the results of these models can be seen in Figure 5.9. Aside from the load-displacement plots, a plot of the stress factors of these models against dent depth is also presented. The experimental stress factors from the Damage Determination specimens are also included in Figure 5.9, and show a good correlation to the numerical results.

The data represented in Figure 5.9 allow for characterization of the relationship between dent depth percentage and decrease in capacity for a utility pole. It can be seen from the data points that at a certain point (approximately 30%) an increase in dent depth produces an increase in capacity rather than a decrease. This is due to the change in the section modulus that occurs during denting. The section modulus initially decreases with dent depth, as the moment of inertia of the section decreases. However, as dent depth increases, the neutral axis of the section moves downward, and the distance from the neutral axis to
Figure 5.8: ALu-4.a comparison of experimental and analytical results.

(a) Dented model load vs. displacement results.  (b) Dented model stress factor vs. dent depth.

Figure 5.9: Dented Model Results.
the extreme fiber of the section, $y$, decreases also. Since the section modulus is inversely proportional to $y$, this effect begins to outweigh the effect of the decreased moment of inertia.

Utility poles damaged to a depth of more than 40% of its outer diameter are usually not considered for repair. This is due to the difficulty of restoring a circular shape, and to global bending deformations which generally occur with dents of this size. Therefore, it is not necessary or desirable to consider the reduction of decreases in pole capacity with larger dent depths for design purposes. Considering this, a stress factor for design is recommended according to Figure 5.9 (b). This recommendation consists of a linear decrease in capacity from an initial value of 1.2 with no dent to 0.9 at a 30% dent depth. Beyond this point, it is recommended that a stress factor of 0.9 be maintained for all larger dents.

5.2.3 Filled Model Results

Behavior of poles with filled dents was also modeled by finite element models. The characteristics of the fill model are described in Section 5.1. A model was created with a numerically generated dent surface in order to replicate the behavior of pole ALw-5.b, which was tested as a dented and filled pole without a composite wrap. The results of this model analysis, and that of the experimental test, are shown in Figure 5.10. It can be seen that the initial loading behavior correlates well with the experimental behavior up until the failure point of the fill material. This behavior is not captured by the FE model. Therefore, the
plasticity behavior of the fill material should be refined in order to produce an accurate model.

Figure 5.10: ALw-5.b comparison of experimental and dent model results.

An equivalent, unfilled FE model was also analyzed for this pole section. This result is also plotted in Figure 5.10. This comparison clearly illustrates the significant effect of the fill material in increasing section capacity. In this instance, the increase in total load is approximately 48%.

5.2.4 Wrapped Model Results

The final type of model included in the investigations of this thesis is that of a pole wrapped with a single layer of composite repair. This type of model is created to emulate
the Single-Ply component level experiments. An example of pole ALw-7.a is presented here, and results are illustrated in Figure 5.11. This model also has good agreement with the physical system. However, additional refinement of the composite material behavior model, such as failure criteria and plasticity behavior, is necessary before this model can be applied to additional repair systems.

Figure 5.11: ALw-7.a comparison of experimental and dent model results.
CHAPTER 6
CONCLUSIONS

The experimental and analytical investigations presented in this thesis were performed in the pursuit of a quantification of damage caused by impact-induced dents and effectiveness of FRP repairs on metallic utility poles. Three types of component-level tests were performed; Damage Determination, Single-Ply, and Wrap Configuration. The results of these tests were refined and expanded through finite element analysis. The conclusions that can be drawn from this research are discussed in this chapter. The effect of dent damage and FRP repairs are discussed, and recommendations for effective full-scale repair systems are made. Also, planned continuing investigations are outlined, and additional research is suggested.

6.1 Conclusions

Effect of Impact Damage: Bending tests were performed on four aluminum pole sections with varying levels of damage. The results of these tests indicate that pole capacity decreases with increasing dent depth for dents up to 26% of the pole’s outer diameter. Finite element models of the dented poles were generated using scanned pole surface data. These models were able to accurately characterize the bending behavior of
damaged utility poles. Results generated by these models indicate that the reduction in capacity of dented poles is a result of the geometric section reduction, rather than residual strains in the dented region. Additionally, an shape function for the dent shape was developed from the scanned pole surfaces. This relationship was used to generate ten additional dented pole models, which were used to determine the relationship between dent depth as a percentage of pole diameter, and load capacity reduction. Finally, design values for capacity of impact-damaged utility poles were proposed.

Effect of Single-Ply Repairs: Three FRP composite systems were tested as single-layer repair systems for damaged aluminum utility poles. These include two glass fiber systems, one with an epoxy resin and the other with a polyurethane matrix, and a basalt/polyurethane system. These systems were paired with an applicable adhesive material, and used in conjunction with a dent filler gel. Failure modes observed include FRP debonding, compressive buckling of FRP, and substrate yielding. Each of the repair systems investigated was able to improve the load carrying capacity of damaged pole sections. This confirms results of previous tests, which indicate that FRP wraps are an effective repair option for metallic utility poles. However, the stiffness of the pre-cured epoxy composite sheet makes this system difficult to apply to poles with smaller diameters. It is expected that additional tests performed on steel poles will experience each of the failure modes involving the composite (compressive buckling, tension rupture, debonding) with a lower occurrence of substrate initial failure. For
full scale utility pole repairs, it is necessary to consider interlaminar debonding failure in the FRP, in addition the the previously mentioned failure modes.

Wrap Configuration Investigations: Preliminary results of Wrap Configuration experiments indicate that tension face and transverse wraps are effective in improving load transfer in poles. Compression face wraps appear to be ineffective as load transfer mechanisms. Further testing is required in order to evaluate the effectiveness of combined wraps.

Repair System Recommendations: An effective externally-bonded FRP repair for metallic utility poles consists of three components: the FRP laminate, an adhesive acting between the composite wrap and the pole, and a high-viscosity epoxy dent fill. The primary consideration for selection of the fill material, is its ability to be used in vertical layup without excessive sagging or sliding. Based on the investigations discussed in this thesis, the following system recommendations are made. Pre-cured basalt or glass fiber-impregnated QuakeBond epoxy resin are highly effective repair systems, and are recommended for repair of damaged utility poles with diameters larger than twelve inches. These wraps should be paired with QuakeBond’s J201C TackCoat adhesive and Pilgrim’s EM 5-2 Gel dent filler. For pole less than twelve inches in diameter, basalt or glass fibers pre-impregnated with polyurethane resin are recommended. It is recommended that the PU composite be paired with NRI’s Syntho-Subsea LV adhesive and Pilgrim’s EM 5-2 Gel. Additional experiments and analysis is required to determine effective and efficient wrap designs for full scale utility pole repairs.
6.2 Continuing Work

Several additional investigations are required in order to achieve a complete set of repair system recommendations for poles with all levels of damage. This section discusses a few of these investigations which are planned for completion by this research group and FDOT within the coming year.

Composite Ambient Conditioning: Ambient outdoor conditioning of laminate plates for the composite systems included in the recommended design systems are in progress. The conditioning specimens include uncoated, plain laminates, and laminates coated with Sherwin Williams’ Diamond-Clad Clear Coat urethane. After six months of conditioning, tensile tests will be performed on these laminates in order to determine the degradation caused by ambient exposure, and the effectiveness of the urethane coating. In addition to mechanical evaluation, coated specimens will be evaluated for improved aesthetics as compared to uncoated laminates.

Finite Element Model Expansion: The finite element model used in this research can easily be expanded to model full-scale utility poles. When this is done, scanned or simulated dent surfaces can be analyzed with various repair systems in order to determine optimal repair systems. This will allow reduction of the full-scale testing program, and will greatly aid the repair selection process.
Wrap Configuration Tests: Testing of the remaining Wrap Configuration pole sections shall continue. Additional strain gages will be added to the test configuration in order to obtain data on composite strains as they relate to strains in the substrate. The results of these tests will be used to refine the composite behavior model in the finite element analysis, and to optimize repair systems.

Full-Scale Repair Tests: A set of full-scale verification tests shall be performed on field-dented metallic utility poles. Repair systems for these dented poles shall be designed based on the results of this research. Poles will be loaded in one of two ways. The first is a cantilever configuration, with a static point load applied 11 feet from the base, which will be anchored to a concrete buttress. Additionally, cyclic loading will be applied to specimens, in order to determine the fatigue behavior of the FRP repairs. Specimens for these tests have been selected, and testing will be performed at the FDOT Structural Research Center.

Repair Guideline Development: Once these tasks have been completed, generalized repair design guidelines should be developed. The elements effecting the choice of repair systems will include the size of the damaged pole and the extent of the damage.
LIST OF REFERENCES


