Behavior of steel monopoles strengthened with high-modulus CFRP materials

B. Lanier a, D. Schnerch b, S. Rizkalla c,*

a American Tower, 400 Regency Forest Drive, Suite 300, Cary, NC 27518, USA
b Wiss, Janney, Elstner Associates, Inc., 245 First Street, Suite 1200, Cambridge, MA 02142, USA
c Constructed Facilities Laboratory, North Carolina State University, 2414 Campus Shore Drive, Campus Box 7533, Raleigh, NC 27695-7533, USA

ARTICLE INFO
Available online 23 December 2008
Keywords:
Elastic modulus
Carbon fiber reinforced polymers
Steel structures
Design recommendations
Monopole towers

ABSTRACT
This paper introduces a strengthening technique for steel monopole towers using high-modulus carbon fiber reinforced polymer (CFRP) materials. The technique is based on a theoretical and analytical investigation including testing large scale steel monopole towers strengthened with different CFRP materials and connection details. Based on the research findings, design aspects and installation procedures are introduced. The recommended installation procedure describes the surface preparation, application of the adhesives and the sequence of CFRP application. The design aspects are based on flexural elastic analysis and material properties of the CFRP and steel monopole shaft. This paper recommends specific connection details to ensure the development of the forces from the CFRP to the steel tower baseplate. The research findings conclude that CFRP materials provide a viable alternative for strengthening steel monopoles that can be easily designed and installed to increase their flexural strength and stiffness.

1. Introduction

During the past two decades, the telecommunications industry has experienced significant growth in the wireless sector. Introduction of wireless phones, email, and internet have increased the demand on existing cellular networks to support new consumer services. Monopole towers are typically used to support the necessary cellular equipment, coaxial cables and antennas. Community resistance to building new towers is common, so reuse and strengthening of existing towers is vital and often the only option to support the additional services. As the need to install additional cellular equipment grows, existing monopoles, shown in Fig. 1, are frequently structurally inadequate to support the cellular equipment expansion due to the increased lateral wind loads. Thus, there is a need to develop a cost effective, durable strengthening system that significantly increases the strength and stiffness of monopoles.

Research conducted at North Carolina State University indicates that high-modulus carbon fiber reinforced polymer (CFRP) materials can provide an excellent solution to enhance the flexural strength and stiffness of monopoles. The inherent strength and stiffness qualities of CFRP offer significant load carrying improvement while eliminating welding or bolting steel members to the existing structure. High-modulus CFRP also has excellent fatigue and corrosion resistance properties, which could significantly improve serviceability over the lifespan of the monopole.

The main objective of the research summarized in this paper is to determine the effectiveness of high-modulus CFRP in increasing the flexural strength and stiffness of steel monopole towers. This paper discusses design aspects for existing full-scale monopole towers based on tests to failure of scaled steel monopole towers strengthened with three different CFRP strengthening configurations. Measured experimental data provides detailed information on the behavior and effectiveness of the three CFRP configurations at increasing the scaled monopole flexural strength and stiffness, as well as the failure modes. The study also provides insight into the installation process, presenting the methodology of material handling and the proper connection to transfer the forces from the shaft to the baseplate of the tower.

1.1. Current design and strengthening practice

Monopoles are typically made of high-strength steel and vary between 7 and 75 m in height. Their cross-section consists of a round or polygonal shape with shaft thicknesses varying from 15 to 120 mm. The structures are either directly embedded into the concrete foundation or installed atop various concrete foundations through connections with anchor rods. Monopoles are designed and fabricated to resist various combinations of dead, wind, seismic, and ice loads, with most of the applied design load resulting from wind and seismic lateral forces. Typical wind loads comprise of 80–90% of the structure design criteria for these
The bars are u-bolted to clip angles which are blind bolted to the Systems International and range in diameter from 30 to 45 mm. The threaded bars are manufactured by Dywidag-with the monopole shaft to increase their flexural strength and stiffness. The bar strengths are developed at each end though use of extended clip angles with multi u-bolt and blind bolt connections. The bars are developed by grouting into the existing concrete foundation of the monopole.

AeroSolutions [3] has designed the AeroForce Monopole and Tower Upgrade System which utilizes both standard modulus CFRP and steel plates bonded parallel to the existing monopole shaft to increase both flexural strength and stiffness. CFRP is used when higher strength increases are required while steel plates are typically installed when strength demands are lower. This solution utilizes an epoxy adhesive for both the CFRP and steel bonds. Ultimately, the AeroSolutions solution demonstrates an adhesive bond can be reliably developed for either steel or CFRP materials to support the strengthening system.

Several solutions are currently available for strengthening of existing field installed steel monopoles. The primary design objective is to enhance the flexural strength and stiffness by bolting, welding or bonding longitudinal steel plates, bars, tubes, shells or fiber composites along the monopole shaft. [1]Morrison Hershfield Group (2004) designed the DualPole system, which increases monopole strength by increasing the lateral stiffness of the structure. Two sections of high-grade steel are fabricated in sheet form and impregnated with resin as they are bonded to the monopole to form a non-composite shell surrounding the existing monopole, which increases the flexural stiffness of the overall structure. Through increasing the flexural stiffness, the monopole flexural strength is proportionally enhanced.

[2]Westower Communications (2004) developed a strengthening system using high-strength, threaded bars installed parallel with the monopole shaft to increase their flexural strength and stiffness. The threaded bars are manufactured by Dywidag-Systems International and range in diameter from 30 to 45 mm. The bars are u-bolted to clip angles which are blind bolted to the monopole shaft, as shown in Fig. 2. Intermittent clip angles are spaced to limit the buckling length of the bars per the compressive strength demands and to adequately transfer the shear forces. The bar strengths are developed at each end though use of extended clip angles with multi u-bolt and blind bolt connections. The bars are developed by grouting into the existing concrete foundation of the monopole.

Fatigue performance of this structural system can be critical for a given variable such as multi-directional wind loading. While bolted connections are preferable to welding when considering the fatigue performance of a connection, bolted connections are often difficult to implement due to the complex geometry of the monopole tower. Adhesive connections can provide a reliable alternative to cyclical loading. Scaled steel bridges strengthened with high-modulus CFRP have been shown to have excellent fatigue performance without notable deterioration of strength [5].

2. Material properties

The proposed strengthening technique in this paper include high-modulus carbon fiber materials with a modulus of elasticity approximately three times that of steel. The fibers are typically fabricated into solid, rigid, pultruded laminate strips that are bonded to steel structures as an external reinforcement using an epoxy adhesive. Another application method is by wet-lay-up, whereby the dry fibers are fabricated in flexible sheet form and are impregnated with resin as they are bonded to the monopole to form a solid, rigid material.

Two types of high-modulus pitch-based carbon fibers were used in the experimental program. Pitch-based carbon fiber utilizes petroleum pitch fiber as its precursor, unlike the more common polyacrylonitrile (PAN) based carbon fiber. Material properties for the two types of carbon fiber are listed in Table 1. The first monopole was strengthened using high-modulus carbon fiber installed in sheet form and impregnated with resin to increase the flexural capacity of the monopole. The remaining two monopoles were strengthened using CFRP strips, pultruded from

\[
\begin{align*}
M_s & \quad \text{flexural nominal strength of tower shaft} \\
S_{c,min} & \quad \text{minimum transformed section modulus of tower shaft}
\end{align*}
\]

\[
\begin{align*}
F_y & \quad \text{yield strength of tower shaft} \\
R & \quad \text{ratio of CFRP rupture or crushing strain to tower steel shaft yield strain}
\end{align*}
\]
either the high- or intermediate-modulus carbon fiber. The properties for the two types of strips are listed in Table 2. Steel coupons were taken from the unloaded portion of the monopole near the tip and tested in accordance with ASTM A 370-02, using plate-type standard specimens. The average yield strength for the steel and elastic modulus were 455 MPa based on the 0.2% offset method and 194 GPa, respectively.

3. Experimental program

The experimental program consisted of three tests, referred to as Test HM-WL, HM-ST, IM-ST on three separate steel monopoles.

Table 1
Dry fiber material properties for high-modulus carbon fibers.

<table>
<thead>
<tr>
<th>Material property</th>
<th>High-modulus carbon fiber (HM-WL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>2600</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>640</td>
</tr>
<tr>
<td>Ultimate elongation (millistrain)</td>
<td>4.0</td>
</tr>
<tr>
<td>Effective sheet thickness (mm)</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 2
Material properties for pultruded high-modulus CFRP strips.

<table>
<thead>
<tr>
<th>Material property</th>
<th>Intermediate-modulus CFRP strip</th>
<th>High-modulus CFRP strip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber volume fraction (%)</td>
<td>55.4</td>
<td>55.2</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>1224</td>
<td>1186</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>229</td>
<td>338</td>
</tr>
<tr>
<td>Ultimate elongation (millistrain)</td>
<td>5.08</td>
<td>3.32</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>471</td>
<td>353</td>
</tr>
<tr>
<td>Compressive modulus (GPa)</td>
<td>177</td>
<td>317</td>
</tr>
<tr>
<td>Strip thickness (mm)</td>
<td>3.2</td>
<td>1.45</td>
</tr>
</tbody>
</table>

The first part of the designation indicates the modulus of the fibers used, either high modulus (HM) or intermediate modulus (IM), and the second part of the designation indicates the application method, either by wet lay-up of dry-fiber sheets (WL) or adhesive bonding of CFRP strips (ST). Each test included three loading and unloading cycles. During the initial loading cycle, the unstrengthened monopole was loaded elastically to 60% of its nominal flexural yield capacity and unloaded to serve as a comparison with the later tests. Prior to the second loading cycle, the monopole was strengthened with CFRP materials to achieve a calculated 20–40% increase in the flexural strength and allowed to cure. The strengthened monopole was then loaded until the deflection at the mid-span was equal to the deflection of the first cycle. After unloading, the final loading cycle was up to failure of the strengthened monopole. A single loading exceeding the yield flexural capacity of the steel monopole was chosen, since monopole shafts are typically designed to remain elastic while resisting lateral forces per pressures from a single 50 (TIA-222-F) to 500 (TIA-222-G) year wind event. Given the rarity of such an extreme loading event and design criteria, cyclical loading of the structure beyond its flexural yield capacity is not typical of loads encountered for monopole towers in service.

Design considerations of the tested specimens included fabrication of a scaled monopole to represent the behavior of full-scale monopole towers, utilizing a strengthening system that could be used for a full-scale monopole. Surface preparation and CFRP installation techniques were selected to simulate methods that would be used in a field application. The applied load was designed to simulate moment and shear forces equivalent to field wind loading conditions. The diameter to thickness ratio, face width to thickness ratio and shaft taper were similar to monopoles in service.

3.1. Fabrication of scaled monopoles

Tested monopoles were fabricated using A572 Grade 65, 5 mm thick, steel plate and cold-formed into two, equally sized, six-sided, cross-sections measuring 6096 mm in length. The bend radius between the flat sections measured 40 mm. The two halves of the final closed cross-section were welded together with a 5 mm, full length, partial penetration E80 weld, creating a closed...
twelve-sided polygonal shape, as shown in Fig. 3. The cross-section diameter across flats of the combined sections measured 457.2 mm across flats at the larger, base end and 330.0 mm across flats at the smaller, free end, resulting in a tapered shape factor of 21 mm/m. The monopole baseplate was cut from 38 mm thick, A572 Grade 50 steel and was 700 mm along each side. The baseplate was welded to the pole shaft using a 5 mm partial penetration E80 weld and topped with an additional 13 mm E80 fillet weld. Six A325, 32 mm diameter, anchor bolts were centered on a 305 mm by 610 mm bolt square, to allow attachment of the base plate to the reaction wall. Eight stiffeners were welded to the base of the HM-ST and IM-ST monopoles. These monopoles were loaded before and after installation of the stiffeners to isolate the strengthening effect of the CFRP from the effect of the stiffeners alone. The stiffener length along the shaft was 200 mm. The length along the baseplate was 100 mm and thickness of the stiffeners was 13 mm. A572 Grade 50 steel was used to fabricate the stiffeners and 7 mm E80 fillet welds were applied along at all connecting surfaces.

3.2. Surface preparation

Surface preparation of the steel was conducted to ensure complete chemical bonding between the steel and the adhesive. This typically involves the removal of mill scale, rust and any protective coatings. It was found that the most effective method to achieve a chemically active surface is the use of grit blasting [6]. Surface preparation prior to strengthening was completed by sandblasting the entire monopole and base plate until a rough, white steel surface was achieved. Strengthening was completed within 24 hours of sandblasting to minimize the oxidation to the surface. Dust was removed by blowing with compressed air. No surface preparation was required for the unidirectional sheets used for the strengthening. For the two monopoles strengthened with CFRP strips, the strips were lightly abraded with 120 grit sandpaper and cleaning by wiping with methanol until no additional sanding residue was present.

3.3. Strengthening configuration

Monopole HM-WL was strengthened by wet lay-up of 330 mm wide unidirectional, CFRP sheets in both the longitudinal and transverse directions using a saturating epoxy resin. This process allowed the composite material to conform to the surface configuration of the monopole. Strengthening was performed to match the demand placed on the monopole due to the cantilever loading condition. From the preliminary analysis, it was found that most of the strengthening is required at the base of the monopole and no strengthening was required from mid-span to the tip. As such, the thickness of the applied CFRP sheets was tapered from four plys of the sheets at the base to one ply terminating at mid-length of the monopole as shown in Fig. 4. The reinforcement ratio of the applied strengthening was 7.0%, accounting for the fiber volume fraction. Anchorage was provided for the sheets by continuing the fibers past the shaft of the monopole and bending the fibers up onto the base plate. More resin was applied to the surface of the fibers and several steel clip angles were used to mechanically anchor the fibers to the base plate. The clip angles were connected by bolting through the anchor bolts at the base plate, allowing the CFRP sheets to be clamped between the clip angles and the base plate. The heels of the clip angles were machined to have a larger radius, to minimize the stress concentration at the change in geometry. Six L6 × 4 × 3/8 clip angles were used in total.

Half-width sheets were used to wrap the longitudinal sheets transversely to prevent possible premature debonding of the strengthening applied to the compression side of the monopole. These sheets were wrapped around the cross-section in two halves such that they overlapped by 100 mm at mid-depth of the monopole. The transversely oriented sheets were applied continuously from the base to 1200 mm along the length also to delay the onset of local buckling of the steel on the compression side. From this point to the mid-span, the transversely oriented sheets were spaced apart from each other.

The two remaining monopoles were strengthened by externally bonding of CFRP strips. Monopole HM-ST used high-modulus CFRP strips and Monopole IM-ST used intermediate-modulus CFRP strips. For both monopoles, the same epoxy resin was used to bond the strips to the monopole. Six strips were applied to three flat sides on both the tension and compression sides of the monopole, using twelve strips in total. Strips were omitted from the flats at the neutral axis depth to make economical use of the material for testing, but it is expected that the strengthening would be applied concentrically about the major and minor axes since the direction of the wind loading varies for monopole towers in the field. Due to the requirement for greatest strength increase at the base, the amount of strengthening provided decreased with increasing distance from the base as shown in the exploded view of the strengthening system in Fig. 5.

For Monopole HM-ST, all twelve CFRP strips had a width of 75 mm. The applied strengthening for Monopole IM-ST used two different widths of strips. The four strips located on the center flats had a width of 75 mm, while the eight adjacent strips had a width of 50 mm. This resulted in the two specimens having approximately equal values of axial stiffness for the applied strengthening material. The reinforcement ratio based on the CFRP axial stiffness for Monopoles HM-ST and IM-ST was 10.0% and 17.3%, respectively.

The two monopoles also had stiffener plates welded from the shaft of the monopole to the base plate. This technique was used to increase the flexural stiffness of the monopole shaft at the base, allowing the forces at the ends of the strips to be transferred through the stiffeners into the base plate. Research by Lanier and Rizkalla [7] has indicated full development of the strips can be
achieved through use of stiffener plates. The monopole specimens were loaded to 60% of the yield stress initially before installation of the stiffeners or CFRP strengthening. The monopole specimens were then tested to the same load following installation of the stiffeners, but before application of the CFRP strengthening. This allowed the increased lateral stiffness due to the stiffeners alone to be determined. The stiffener plates increased the lateral stiffness of the monopole by approximately 6%.

3.4. Testing configuration and instrumentation

The loading applied for the experimental program was designed to simulate flexural wind design loads in field structures. It was impractical to apply a distributed wind loading, so each monopole was tested as a cantilever with a single applied load approximately 5750 mm from the pole base to generate equivalent moments and shear forces. The loading was applied with nylon straps or chains to allow free rotation of the pole shaft at the point of load application, as shown in Fig. 6.

Measurements were recorded of the deflection and extreme fiber strains at the quarter-points of the monopoles. Displacements were measured using wire potentiometers, while the strains were measured using strain-gauge type displacement transducers with a gauge length of either 200 or 300 mm. Additional electrical foil gauges, with a gauge length of 6 mm were applied to the surface of the CFRP. Deflection was also measured at the base plate to determine slip and rotation at the support. All instrumentation in addition to the applied load was recorded at a sample rate of 1.0 Hz.
4. Test results and discussion

Results from the three tests indicate significant additional flexural yield and ultimate strength and stiffness can be developed due to the use of CFRP strengthening while the pole steel remains within elastic limits. Stiffness increases, which parallel elastic flexural strength increases, varying between 13% and 64% were measured at various locations along the monopole shaft from the three tested specimens. This was determined by comparing the applied lateral loads from the first and second loading cycles, shown in Table 3, as the second loading was terminated once mid-span deflection equivalent to the first loading was achieved. Measured elastic longitudinal strains were also reduced by 20–50% along the monopole shaft from the three tested specimens. Table 4 lists the stiffness of the unstrengthened and unstrengthened monopoles at the tip and mid-span for each of the three tests. Fig. 7 illustrates the measured deflection results from the first and second load cycles of the Monopole HM-ST test. Similar results were obtained for the tests of Monopoles HM-WL and IM-ST. Fig. 8 shows the load deflection behavior to ultimate for the three tests.

Apart from some minor, localized debonding observed in the third load cycle, the installed high-modulus CFRP sheets used for Monopole HM-WL remained intact throughout the second and third load stages. This was the only test to be unloaded and reloaded past yield due to the large deflections obtained. Fig. 9 shows Monopole HM-WL just prior to the ultimate lateral load of 95 kN. Failure was due to local buckling, which resulted in the rupture of the transversely applied CFRP sheets. The rupture occurred, shown in Fig. 10, just outside the clip angles at a tip deflection of 353 mm or L/17. Inspection of the remainder of the monopole shaft after failure found the adhesive bond in excellent condition outside of the buckled region. No deterioration of the adhesive bond or high-modulus CFRP material was found under the clip angles. As evident from the tests with the adhesively bonded CFRP strips, the presence of the transversely applied sheets delayed the onset of local buckling.

Table 3
Summary of applied load (Equivalent to 60% of unstrengthened flexural yield capacity) resulting in equivalent mid-span deflections.

<table>
<thead>
<tr>
<th>Monopole test</th>
<th>Loading cycle</th>
<th>Applied load at L (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopole HM-WL</td>
<td>Unstrengthened</td>
<td>32.0</td>
</tr>
<tr>
<td></td>
<td>Strengthened</td>
<td>36.3</td>
</tr>
<tr>
<td>Monopole HM-ST</td>
<td>Stiffeners alone</td>
<td>32.6</td>
</tr>
<tr>
<td></td>
<td>Strengthened</td>
<td>42.8</td>
</tr>
<tr>
<td>Monopole IM-ST</td>
<td>Stiffeners alone</td>
<td>32.6</td>
</tr>
<tr>
<td></td>
<td>Strengthened</td>
<td>41.5</td>
</tr>
</tbody>
</table>

Table 4
Summary of elastic stiffness increase (Maximum loading equivalent to 60% of unstrengthened flexural capacity).

<table>
<thead>
<tr>
<th>Monopole test</th>
<th>Loading cycle</th>
<th>Stiffness at 0.5L (kN/mm)</th>
<th>Stiffness at L (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopole HM-WL</td>
<td>Unstrengthened</td>
<td>1.18</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Strengthened</td>
<td>1.48</td>
<td>0.44</td>
</tr>
<tr>
<td>Monopole HM-ST</td>
<td>Stiffeners alone</td>
<td>1.33</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Strengthened</td>
<td>1.91</td>
<td>0.57</td>
</tr>
<tr>
<td>Monopole IM-ST</td>
<td>Stiffeners alone</td>
<td>1.29</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>Strengthened</td>
<td>2.11</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Fig. 7. Comparison of load-deflection behavior of Monopole HM-ST before and after strengthening.
resistance, was measured at 79 kN. Local buckling of the monopole shaft occurred outside the ends of the stiffeners. Post failure inspection of the adhesive bond found significant voids between the strips to shaft and strip to strip interfaces, due to slip during installation. However, within the stiffener boundary, no deterioration or delaminating of the strip matrix or adhesive bond was found.

Similar behavior was observed for Test IM-ST, although the initial strength loss was due to debonding of the strips in tension. At loading of 55 kN, almost all strips in tension debonded and ruptured near the end of the stiffeners. The strips in compression remained bonded until loading exceeded 85 kN, which was the ultimate load capacity of the monopole, when all remaining strips simultaneously debonded or crushed just outside the stiffener ends. The compressive crushing strain was measured to be 0.25%. After loss of strength to 78 kN, the monopole was loaded until buckling occurred outside the ends of the stiffeners at 83 kN, as shown in Fig. 12. As with the test of Monopole HM-ST, the adhesive bond and strip matrix remained intact throughout the loading between the stiffeners.

Based on comparison of the ultimate load capacities from the HM-WL and HM-ST tests, a minimum ultimate load increase of 16 kN, or 20% flexural strength increase, was found from the HM-WL test. The IM-ST found an ultimate load increase of 6 kN, or 8% flexural strength increase. The HM-ST monopole buckled at the ultimate load with the high-modulus CFRP strips debonded and ruptured, thus the ultimate strength of this specimen may be considered as the ultimate strength of a control specimen.

5. Analytical model

An elastic stiffness model was designed to account for lateral flexural stiffness and strength of the monopoles both with and
without the sheets and strips. The model was limited to within the steel elastic range as the strip compressive strain would not allow development of the steel beyond its yield strain. This limits ultimate strength design as the model is limited to the crushing strain of the CFRP or the yield strain of the monopole steel. However, the intent was to model the elastic behavior of the monopole as steel monopole shafts are typically designed to elastic flexural limits. The model, therefore follows current design practice [8,9].

5.1. Elastic flexural stiffness model

The flexural stiffness model used to predict shaft deflection is based on the moment-area method and the transformed-section method [10]. The moment-area method is especially effective as it allows for non-prismatic pole sections to easily be modeled using a finite number of elements. The transformed-section method allows for easy conversion of materials with un-similar modulus to be modeled together. Since the model was limited to within the elastic range of both materials, no special accommodations were applied to the model, aside from the strip crushing strain. Strain was calculated based on transformed-section mechanical properties and moments derived from both methods.

Several assumptions were included in the model to predict the load deflection and strain behavior of the unstrengthened and strengthened monopoles. These assumptions are:

1. Strains are assumed to vary linearly across the depth of the cross-section.
2. Perfect composite action was considered. No bond slip or failure between the monopole shaft and the high-modulus CFRP was assumed to occur.
3. Clip angles were assumed to have no impact on the deflection or stress calculations, but the moment of inertia of the stiffeners was included in the analysis.
4. Both the steel and high-modulus CFRP are linear elastic materials.
5. Shear deformations are not included in the analysis.
6. The boundary condition at the base is rigid, with no rotation or slip.
7. The adhesive thickness is ignored.

5.2. Model results

Based on the predicted load deflection slope, the calculated elastic flexural stiffness values of the unstrengthened monopole model at mid-span and tip were 1.28 and 0.37 kN/mm, respectively. The flexural stiffness values predicted from the HM-WL model resulted in calculated stiffness of 1.76 and 0.46 kN/mm at mid-span and tip, respectively. Comparison of the calculated stiffness values at the respective locations reveals that the strengthened monopole stiffness increased 38% and 26%. These predicted stiffness increases are significantly higher as compared to measured stiffness values of 25% and 17%.

The predicted elastic flexural stiffness values calculated at the mid-span and tip before and strengthening of the HM-ST monopole was 1.40 and 0.39 kN/mm versus 2.08 and 0.53 kN/mm, respectively. Calculation of the stiffness values from the HM-ST model at mid-span and tip resulted in stiffness increases of 48% and 37%, respectively. Like the results from the HM-WL model, these results conform very well with respect to the measured stiffness increases of 43% and 41%. Measured versus calculated deflection from the first and second load cycles of monopole HM-ST are illustrated in Fig. 13.

Calculated elastic flexural stiffness values of the IM-ST unstrengthened monopole were identical from HM-ST as the monopoles had identical dimensions of shaft and stiffeners. Predicted stiffness values from the IM-ST monopole model were calculated to be 2.21 and 0.59 kN/mm at the mid-span and tip, respectively. The resulting monopole stiffness increase was calculated as 68% and 52%. Measurements taken from IM-ST test indicated stiffness increases of 64% and 44%. This indicates the model is largely accurate in predicting mid-span deflection, but is not particularly accurate in determining tip deflection.

Comparison of the calculated elastic longitudinal strain of the of the HM-WL monopole before and after strengthening shows the strains were reduced by an average of 31% from the base to mid-span due to the strengthening system. This resulted in overestimation of the expected strain reductions as compared to the measured strain reduction of 20%. Average elastic calculated strain reduction from the HM-WL test was 39% from the base to mid-span. This compares well to the measured 31% reduction. Fig. 14 illustrates the measured versus calculated longitudinal strains from the first and second load cases of the HM-ST test. Comparison of the elastic monopole strain before and after strengthening the IM-ST test revealed a calculated 55% decrease in strain from the base to the mid-span. Measured strain reduction was found to be 52%, thus the calculated results conform very well to the measured values. Strains calculated at the mid-span to the tip for all three models before and after the
monopole was strengthened were equivalent in magnitude and conformed very well to the measured results.

Comparison of the tested results versus the calculated results indicates the calculated values are not effective for the HM-WL model and fairly accurate for the ST models. The reason for the HM-WL model being somewhat higher than observed is likely due to lack of full initial development of the fiber modulus. The sheet modulus in tension and compression is likely slightly less than the coupon values due to out of straightness and any waviness of the fibers installed on the monopole. This behavior would reduce the expected strengthened increases. Reasons for the good conformity of the strip models are likely due to the exact compressive and tensile modulus provided by the manufacturer. Also, the stiffeners may have helped create a more rigid, moment resisting base, which more closely replicated the model assumption.

6. Design aspects

High-modulus strips are recommended for strengthening structurally deficient monopoles as opposed to high-modulus sheets due to their ease of installation and much better conformance of tested compared to the modeled results. Also, lesser amounts of material are necessary to generate equivalent strength and stiffness results when compared to the intermediate-modulus strips. Yield strength design of the monopole should consider the ultimate strain of the strips in compression, which may be more critical the rupture strength. Strengthening with high-modulus sheets, particularly in the transverse direction, may be beneficial in delaying the onset of local buckling, but additional study is necessary before further recommendations can be developed. The high-modulus sheets have also demonstrated that significant ultimate flexural strength capacity can be achieved through their use, but additional research is necessary to confirm the extent of this strength increase. The design procedure for utilizing high-modulus strips for strengthening monopoles should consider the following criteria; elastic flexural design of the high-modulus strips, strength of the adhesive bond and development of the high-modulus strips, specifically at the base of the structure. A load and resistance factor design approach is presented, although the allowable stress approach is still used in practice and remains a viable design approach with appropriate factors of safety.

6.1. High-modulus CFRP strip design

Use of any set of reasonable assumptions can be used for determining the flexural elastic stiffness of the monopole shaft strengthened with high-modulus strips. The simplest approach for modeling the combined cross-section of steel shaft and strip shapes is using the transformed area method. Use of this method will generate reliable results assuming the effective flexural stresses are limited to the ultimate compressive or rupture strain.
of the strips or yield strength of the steel shaft. The design should be considered fully composite, with the adhesive thickness being ignored when calculating the section modulus. The compressive modulus should be considered in addition to the tensile modulus when calculating the transformed section. The nominal moment capacity should be limited lesser of the crushing or rupture strain ($e_y$) of the strips or the steel yield strain ($e_y$), as follows:

$$M_n = S_{t,\text{min}}F_yR$$

where $S_{t,\text{min}}$ is the minimum transformed-section modulus, based on steel elastic modulus, $F_y$ is the effective steel yield strength, $R$ is the $e_y/d_{yR}$, not to exceed 1.0.

Flexural tower strength design is typically limited to the yield strength of the steel as standard tower design practice for polygonal shaped tubular poles [8,9] is to limit the nominal moment capacities to the steel yield strength. Local buckling criteria, which could potentially lead to inelastic behavior, can limit the effective flexural yield strength of the sections and are applicable.

Plastic design is allowed for round tubular poles as per TIA-222-G and is expected to be a design alternative for polygonal shaped tubular poles with future editions of the TIA-222 standard. Assuming that both the tensile rupture and compressive crushing strain of the strip material exceed a strain of 0.004, plastic design can be an alternative. However, scaled testing is recommended prior to utilizing plastic design. The 0.004 strain limit is based on identical limits placed on tension-controlled flexural strength of reinforced concrete sections (ACI, 2005). Also, full development of the steel shaft at the extreme fiber strain of 0.004 can be expected and 0.004 will provide ductility of approximately twice that of the steel yield.

Strengthening using high-modulus strips should be limited to the flexural nominal capacity of the structure to ensure that the monopole remains safe in case of possible loss of the strengthening system. The flexural nominal capacity of the strengthened monopole should be limited to the strength of the unstrengthened monopole as follows:

$$M_{U} \leq 1.6M_{Y}, \text{Unstrengthened}$$

The justification for allowing up to 60% increase in strength is design wind loads are factored by 1.6, thus even during an extreme design wind event, significant unused capacity of the steel shaft is available. The monopole will still meet the unfactored wind design loading.

Although the intended strengthened tower design of this paper considers a ductile steel cross-section resisting flexural loads, the potential failure of the strengthened system is very similar to reinforced concrete or steel shear connection design. Failure mechanisms include failure of the strip in compression or tension, or by ductile yielding of the steel shaft. The recommended flexural strength reduction factor ($\phi_y$) for strip design is based similar failure mechanisms for CFRP strengthened concrete or steel flexure design criteria, per ACI440R-07 [11] and AISC LRFD Steel [12] manuals. If the CFRP tensile rupture strain ($e_t$) controls the design, then a factor of 0.85 may be used for $\phi_y$, whereas if the yield strain ($e_y$) controls, a factor of 0.90 may be used due to the greater ductility of this failure mode. No existing guidelines indicate appropriate factors for the CFRP material in a compression controlled failure. It is anticipated that this factor would be lower numerically, providing a higher factor of safety against this undesirable failure mode. High-modulus CFRP strips should be installed though the deficient section of the monopole into shaft sections with sufficient nominal flexural capacity. The length of the high-modulus CFRP strips used will be dependent on the length of shaft that does not have the required flexural capacity and the adhesive bond design.

### 6.2. Adhesive bond design

Specific design of the adhesive bond is dependent upon many variables such as surface preparation, specific epoxy, strip thickness, and environmental conditions that make general recommendations for adhesive bond design very difficult. Bond design should be based on recommendation by the adhesive manufacturer as well as tested results shown through published research or data provided by the manufacturer. Detailing of the high-modulus CFRP strip ends can significantly enhance most adhesive connections by limiting localized stress concentrations and should be implemented when using high-modulus CFRP strips to strengthen monopoles. Tapering strip ends has proven to significantly relieve stress concentrations. Increasing adhesive thickness at the strip ends has also been shown by Wright et al. [14] to lower adhesive layer stiffness, which in turn reduces shear stress increase at the end of the strip. This ultimately has proven more effective than tapering the strip ends alone. Combining these two effects has provided the best results (price and moulds [15]) and should be implemented in strengthened monopole design.

Maximum bond stress should also be limited to 20–30% of the published ultimate strength of the adhesive as fatigue loading beyond the adhesive elastic strength can result in poor creep performance [6]. Effective small scale testing can be accomplished through single or double lap shear coupon tests, assuming identical materials, adhesive, surface preparation and application techniques are followed. Maximum normal and shear stresses can be calculated using established bond models [16], with maximum principle stress being derived from these values. Appropriate factors of safety can then be applied to complete the adhesive design [17].

### 6.3. Development of high-modulus CFRP strips at monopole base

Development of the high-modulus CFRP strips at the base of the monopole can be achieved through use of steel stiffeners. The intent of stiffener design is to limit the stress on the monopole shaft surface such that gradual transfer of the design forces can be imparted into high-modulus CFRP strips. Stiffener installation also reduces stresses in the base weld connecting the shaft to the base plate that cannot be accounted for using strips alone unless the strips can be effectively grouted through the base plate and into the existing concrete foundation. A stiffener should be installed on both sides of the strip, although strips installed on adjoining shaft flats can share stiffeners. Stiffener thickness, height away from monopole shaft and material grade should be designed to carry the full design moment at the base without assistance from the high-modulus CFRP material. The stiffener height should be tapered back to the monopole shaft thorough the required development length of the adhesive bond.

### 7. Conclusions

Initial testing has shown that high-modulus CFRP materials may be used to provide flexural stiffness and strength increases within the elastic range of the monopole. Strengthening with high-modulus CFRP sheets in the transverse direction, may also provide ultimate strength increases by delaying the onset of local buckling. Additional research is required to confirm this observation. Simple analytical tools can be used to determine the flexural behavior of the strengthened material and to design the
strengthening for given loading conditions. To prevent debonding of the high-modulus CFRP material, it is important to consider the actual state of stress near the end of the CFRP strip including shear and peeling stress components. Proper installation of the high-modulus CFRP material is critical to ensure that the strengthened member behaves as intended by the designer. High-modulus CFRP materials are an effective alternative to conventional strengthening techniques for steel monopole towers.

Acknowledgements

The authors acknowledge the National Science Foundation (NSF) Grant EEC-0225055, the NSF Industry/University Cooperative Research Center (I/UCRC) for the Repair of Buildings and Bridges with Composites (RB2C), Mitsubishi Chemical FP America, Mr. David Brinker of Radian Corporation, and Simon Weisman of Weisman Consultants for their contributions towards this research and paper.

References