Strengthening Steel Structures and Bridges with High Modulus Carbon Fiber Reinforced Polymers: Resin Selection and Scaled Monopole Behavior

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ABSTRACT
Cost-effective solutions for the rehabilitation and strengthening of steel structures, including bridges and monopole towers, are greatly needed. Rehabilitation is often required due to cross-section losses occurring due to corrosion and strengthening may also be required due to changes in the use of a structure. Current techniques for strengthening steel structures have several drawbacks including their fatigue performance and the need for ongoing maintenance due to continued corrosion attack. The current research program makes use of a high modulus carbon fiber for strengthening of steel structures. This program, currently in progress, includes phases for the resin and adhesive selection for wet lay-up of carbon fiber sheets and bonding of pre-cured laminate plates. Test results of the first scaled monopole tower showed a 25% increase in stiffness in the elastic range over the same monopole before strengthening.
INTRODUCTION

With the significant number of structurally deficient bridges in North America, innovative techniques to repair and rehabilitate these bridges are required. Fiber Reinforced Polymer (FRP) materials have been found to be successful for flexural strengthening, shear strengthening and ductility enhancement of concrete bridges. However, many steel bridges are also in need of rehabilitation due to fatigue or corrosion damage. Strengthening may also be required due to changes in use or due to increases in truck weights. In fact, of the 108,000 structurally deficient bridges in the United States, more than 58% are constructed of steel (1).

There is also a demand to increase the flexural capacity of steel monopole towers that are the predominant type of tower design for the cellular phone industry. The monopole was used initially because the height requirements for cellular frequencies favor the cost effectiveness of this type of structure. However, the demand for cellular phones has often required the placement of additional antennas on a monopole. These antennas increase the wind load applied to the monopole, requiring strengthening to match this demand. Existing techniques for strengthening monopoles by the use of steel collars or with an additional lattice structure, typically cost in the range of $80,000 to $100,000 (2). Appearance of the towers is also critical, since many of these towers are located near residential areas. These factors make the possibility of developing a low-cost FRP strengthening system, which results in minimal difference to the visual appearance of a monopole, desirable.

There are many advantages in favor of the use of FRP materials for repair and rehabilitation of bridges and structures. Cost savings may be realized through labor savings and reduced requirements for staging and lifting material. Due to its ease of application, disruption of service during construction may be reduced or eliminated. The dead weight added to a structure is minimal and there is typically little visual impact on the structure, such that good aesthetics can be maintained.

In particular for the strengthening and rehabilitation of steel structures, existing techniques often require welding or bolting to the structure. Welding is not desirable in many cases due to the poor fatigue performance of welded connections. In contrast, the fatigue performance of bonded composite repairs to cracked steel cross-girders has been shown to be effective up to 20 million cycles (3). It has also been estimated that bonded Carbon Fiber Reinforced Polymer (CFRP) patches have been used over 10,000 times for the repair of corrosion and fatigue damage of aircraft, illustrating the increasing acceptance of the technique in an application where safety and durability are critical (4).

The work presented in this paper makes use of a high modulus type of carbon fiber provided by Mitsubishi Chemical America. This type of fiber has approximately 2-3 times the stiffness of standard modulus carbon fiber or mild steel. The tensile modulus of this fiber is reported by the manufacturer to be 640 GPa (93,000 ksi), with a tensile rupture strength of 2400 MPa (355 ksi) and a maximum elongation of 0.4% at failure. This fiber is also used to manufacture a unidirectional tow sheet that has a width of 330 mm (13 in) and is suitable for applications requiring a wet lay-up process to conform to the surface configuration of the structure.

Where a greater degree of strengthening is required and flat uniform surfaces are available for bonding the CFRP, it is often advantageous to adhesively bond pre-cured laminate strips to the structure. As such, the same fiber used to manufacture the tow sheets has also been pultruded into pre-cured laminate strips by Diversified Composites using Resolution Performance Products Epon 9310 epoxy resin with Ancamine 9360 curing agent. These strips have a width of 74.93 mm (2.95 in) and a thickness of 1.45 mm (0.057 in). The fiber volume content for the strips used was determined to be 55%.

Previous work has illustrated the importance of surface preparation, adhesive working time, curing methods and the prevention of the formation of galvanic couples in selecting an adhesive system (5).
Different types of adhesives have been used to bond FRP to steel, but generally room-temperature cured epoxies have been chosen due to their performance and ease of use. Adhesion promoters, such as silanes, have been shown to increase the durability of steel-epoxy bonds without affecting the bond strength (6). For this reason, silanes were not used in the testing program, though their use would be recommended for any field application or durability study. For preparation of the steel surface, abrasive treatment (such as sandblasting) followed by removal of the abrasive dust results in the highest bond strengths due to the creation of a chemically active surface on the steel that promotes the formation of strong chemical bonds to the adhesive (7).

**EXPERIMENTAL PROGRAM**

The experimental program currently in progress consists of three phases. The first phase testing was conducted to determine a suitable resin for the wet lay-up of unidirectional carbon fiber sheets bonded to steel and the adhesive selection for bonding pre-cured laminate strips to steel. Resin selection for the wet lay-up process was determined through testing of double lap shear coupons using ten different resins. Additional variables included different cure temperatures, use of a wetting agent and resin hybridization, resulting in a total of twenty-two different trials. For determination of the adhesive to be used for the bonding of pre-cured laminate strips, a different type of specimen was used. A Super-Light Beam (SLB) was used with an additional steel plate welded along the length of the compression flange. The addition of the steel plate simulates the presence of a concrete slab by decreasing the neutral axis depth such that the strain profile of the cross-section would be similar to a bridge girder acting compositely with a concrete deck.

The second phase of the experimental program, to be completed using the SLB-section specimens, will determine the development length of the strengthening technique using two of the resins selected from the first phase of testing for wet lay-up and two of the adhesives for laminate bonding. The third phase consists of testing large-scale members to determine the overall performance of the strengthening system and the evaluation of different strengthening details. This paper also discusses the testing and experimental results of a steel monopole strengthened by wet lay-up of carbon fiber sheets.

**RESIN SELECTION FOR THE WET LAY-UP PROCESS**

**Test Specimens**

Double lap shear coupons were used to determine the resins with the best performance for wet lay-up of dry fiber sheets. Test specimens consisted of two plates fabricated from grade A36 steel with dimensions as shown in Figure 1. These plates were joined together with unidirectional carbon fiber sheets by wet lay-up. Surface preparation for the steel consisted of sanding with 80 grit sandpaper to achieve a uniform surface that was free from surface contamination and mill scale. Immediately prior to application of the resin, the surface was cleaned with acetone. The steel plates were then clamped in a fixture to maintain their alignment during the strengthening process.

For the wet lay-up process, a uniform coating of resin was applied to one side of the steel plates in the bonded region. Five tows of the unidirectional carbon fiber sheets were applied across the steel plates, with a 25.4 mm (1.0 in) overlap on each of the steel plates. The sheets were pressed into the resin on the steel plates, and additional resin was placed as an overcoat on the sheets. A 1.9 mm (0.075 in) gap was left between the steel plates to minimize the effect of end-to-end bonding. Once the resin had achieved sufficient working strength, the same strengthening procedure was completed on the reverse side. The coupon specimens were then marked 31.8 mm (1.25 in) from their ends to indicate the area to be clamped within the hydraulic grips of the test machine. Coupons were cured at least seven days prior to testing.
Test Matrix

The test matrix for evaluation of the wet lay-up resins included several different parameters as indicated in Table 1. Ten resins were cured at room temperature. Two of these tests were repeated with an elevated temperature (ET) cure, where the specimens were placed in an oven at 50°C (122°F) for sixteen hours as recommended by the manufacturers, then removed from the oven and allowed to cure for the remaining time at room temperature. Three resins were also evaluated with a wetting agent to improve the saturation of the fibers. Two different doses of the wetting agent were used: the low dose (LD) that was 0.5% of the total resin weight and the high dose (HD) that was 1.0% of the total resin weight.

Test Procedure and Instrumentation

Testing was completed using an MTS closed-loop universal testing machine with hydraulic grips. The specimens were instrumented with strain gauge type displacement transducers to monitor the overall longitudinal strain across the bonded region. These displacement transducers had a gauge length of 100 mm (3.94 in) and two were positioned one on each side of the specimen. A data acquisition system was used to record the data from the instrumentation as well as the machine load and displacement at a sample rate of 5 Hz. Load was applied under displacement control at a rate of 0.12 mm/min (0.005 in/min).

Results and Observations

Wet Lay-Up Resins Cured at Room Temperature (RT)

Ten resins were evaluated for use as a saturant. Of these, seven were amine-epoxy resins, DP810-RT was an acrylic resin, EP1246-RT was an acrylic-epoxy blended resin and ATP2-RT was a urethane resin. The ultimate shear strength and the strain at peak stress across the bonded region are shown in Figure 2 with the number of tests for each resin given in parenthesis beside its label. The smaller bars show plus and minus one standard deviation from the mean for each series of data. For brevity, only the results of the three resins with the highest shear strengths will be discussed in detail. The complete stress-strain behavior of these coupons is shown in Figure 3.

MBSAT-RT  All of the coupons using this resin failed due to rupture between the two plates, with no apparent debonding between the resin and the steel surface. Observation of the rupture surface typically showed air voids within the composite. The average shear strength for these coupons was 12.3 MPa (1790 psi).

S330-RT  The predominant failure mode was by rupture of the fibers, although some pullout was also observed indicating incomplete fiber wetting. This may be due to the relatively high viscosity of this resin. The average shear strength for these coupons was 12.1 MPa (1750 psi).

DP810-RT  The coupons fabricated using this resin failed by pullout of the fiber tows as a group. Examination after testing showed that the individual fibers within the tow were not fully saturated with resin. The stress-strain behavior for these specimens showed significantly more elongation before failure due to this failure mode. The average shear strength was found to be 10.8 MPa (1560 psi).

Wet Lay-Up Resins Cured at Elevated Temperature (ET)

For the resins cured at elevated temperature, the shear strength tended to be lower than for the same resin cured at room temperature, as shown in Figure 4. The same trend could be observed for the strain, with lower ultimate strains occurring for the elevated temperature coupons. This trend was statistically significant for the S330.RT and S330.ET tests using a two-sample t-test assuming unequal variances. A possible explanation for this finding was the possibility of residual stresses induced during the heated curing. After returning to room temperature, the resin would be subjected to a residual shear stress due to the opposite coefficients of thermal expansion between the steel and the carbon fiber.
Wet Lay-Up Resins Using Various Amounts of Wetting Agent (LD and HD)

Due to incomplete fiber wetting, and the presence of visible air voids in some of the coupons, a wetting agent was used to improve the properties of the resin. However, no clear improvement in performance could be determined through the use of the wetting agent, as shown in Figure 5. For two types of resin, the strength difference was within one standard deviation, while for the DP-810 resin, the shear strength clearly decreased due to the presence of the wetting agent. Statistical hypothesis testing using ANOVA indicated a significant decrease in shear strength for the DP810 tests while the other tests showed no difference.

ADHESIVE SELECTION AND DEVELOPMENT LENGTH STUDY FOR BONDED LAMINATE STRIPS

Test Specimens

The test specimens used for the adhesive selection and development length tests simulated a wide-flange steel beam that acts compositely with a concrete deck, such that the neutral axis is towards the compression flange. Super Light Beams, SLB 100x5.4 (SLB 4 x 3.63) were used, as shown in Figure 6. An additional 6.4 mm (0.25 in) thick, grade A36 steel plate was welded to the compression flange to simulate the strain profile of a bridge girder that acts compositely with a concrete deck. The beams were then strengthened on the tension flange with a laminate strip fabricated with a 55 percent fiber volume fraction using the fibers described previously. The width of the laminate strip was 36 mm (1.4 in) and the thickness was 1.4 mm (0.056 in). Different strip lengths were used to determine the development length for the adhesive bonding process.

Test Procedure and Instrumentation

The development length of six adhesives was evaluated to determine the adhesive with the most suitable properties for bonding to steel. The adhesives evaluated for this study were: Fyfe Tyfo MB2, Jeffco 121, Sika Sikadur 30, SP Spabond 345, Vantico Araldite 2015, and Weld-On SS620. The steel surface was prepared for strengthening by sandblasting, followed by wiping with acetone. The surface of the laminate strips was prepared by roughening the surface with 120-grit sandpaper and wiping it clean with methanol. The strengthening process immediately followed the surface preparation to ensure that the steel surface was minimally oxidized. Testing of the strengthened beams occurred after the adhesive cured at room temperature for at least seven days.

The beams were simply supported and loaded under four-point loading using a spherically seated bearing block, as shown in Figure 7. The lateral bracing was provided by supporting the top flange of the beam over the supports with two angles that were fixed to each support. Load was applied at a constant displacement rate of 0.75 mm/min (0.03 in/min).

Strain and displacement were measured at the mid-span of the beam. Strain was measured using foil strain gauges bonded on the welded plate on the compression flange, inside of the tension flange, and outside of the tension flange for the unstrengthened specimen and outside on the CFRP strip for the strengthened beams. Displacement was measured using two linear voltage displacement transducers.

Results and observations

The results of the tests are shown in Table 2, which lists the ultimate strain of the laminate strip at the time of failure either by rupture or debonding of the strip. The specimens fabricated using the Weld-On SS620 and the SP Spabond 345 adhesive had the shortest development lengths; they were able to develop the ultimate strain in the strip at approximately 76-102 mm (3-4 in). Figure 8 shows the peak
strain in the strip for all of the adhesives tested with varying development lengths. An example of a typical fiber rupture failure is also shown in Figure 8.

**SCALED MONOPOLE**

**Test Specimens**

The scaled steel monopole was fabricated from A572 grade 60 steel with similar proportions to monopoles used as cellular phone towers. The length of the pole was 6090 mm (240 in) and had a dodecagonal, or twelve-sided, cross-section. This cross-section was tapered uniformly along the length, starting at 457 mm (18 in) at the base and ending at 330 mm (13 in) at the tip. The thickness of the steel used to fabricate the pole was 4.69 mm (0.185 in). Cold forming was used to fabricate the pole from two equal halves and was welded together along its length near the mid-depth of the pole. The monopole was welded to a base plate that was 38 mm (1.5 in) in thickness to allow mounting to the structural wall at the Constructed Facilities Laboratory.

The first monopole represents one of the three different strengthening configurations planned to be examined in this series of testing. The strengthening technique used for this monopole was wet lay-up of unidirectional dry fiber sheets for strengthening in the longitudinal direction. Strengthening was completed to match the demand placed on the monopole due to the cantilever loading condition. From a preliminary analysis, it was found that most of the strengthening was required at the base of the pole and no strengthening was required from mid-span to the tip. As such, thickness of the applied strengthening was tapered from four plys of full-width sheets on the tension and compression sides to one ply terminating at mid-span.

Surface preparation was completed by sandblasting of the entire monopole and base plate, until a rough, bare steel surface was reached. An outside contractor completed the sandblasting and delivered the pole so that the strengthening could be completed within 24 hours of the sandblasting. Once the pole was delivered to the lab, dust was removed by thoroughly blowing the pole with compressed air. Cleaning with acetone completed the surface preparation.

The resin used for the wet lay-up process was Sika Sikadur 330, which was based on the results of the first phase of testing and the availability of the product. The strengthening was completed by first applying a layer of resin to the pole then adding the first ply of fiber, and continuing by adding additional layers of resin and fiber sheets until the entire strengthening was completed. Anchorage was provided for the sheets by continuing the fibers past the base of the pole and bending the fibers up onto the base plate. More resin was applied to the surface of the fibers and then a steel angle was used to clamp the fibers to the base plate before the pot life of the epoxy had been reached.

Half-width sheets were also used to wrap the longitudinal sheets transversely to prevent possible premature buckling failure of the strengthening applied to the compression side of the pole. These sheets were wrapped around the cross-section in two halves such that they overlapped by 100 mm (4 in) at the mid-depth of the pole. The transversely oriented sheets were applied continuously from the base to 1200 mm (48 in) along the length to also 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.

**Test Procedure and Instrumentation**

Each of the three monopoles was loaded to 60% of the specified yield stress and unloaded to determine the initial stiffness properties. The poles were tested as cantilevers using the test set-up shown in Figure 9. A detail of the mechanical anchorage with steel angles is also shown in Figure 9. The pole was mounted horizontally to the structural wall by bolting to a steel fixture. Load was applied with nylon
straps near the tip of the pole. This type of loading was used to most closely represent the conditions of loading of a field monopole, whereby most of the loading is concentrated at the location of the antennas and no stiffening is provided to the end of the pole from a loading fixture.

After strengthening, the first monopole was loaded to the same load as the corresponding unstrengthened monopole. The monopole was then reloaded to the same mid-pole displacement and unloaded. Finally, the monopole was loaded to failure.

Measurements were taken of the deflection and strain at various locations on the monopole in addition to the actuator load and displacement. Deflection was recorded at quarter points on the monopole. Deflection was also recorded at the base to determine the uplift as well as the rotation of the base plate. From the uplift and rotation of the base plate, the net deflection of the monopole could be determined. This net displacement was used for all the results presented here. In addition, strains were measured using strain gauge type displacement transducers with a gauge length of 100 mm, 200 mm or 300 mm (3.94 in, 7.87 in or 11.81 in).

**Results and Observations**

Testing performed after strengthening showed that the net deflection of the monopole was reduced by 25% at the middle of the monopole. The loading and unloading curves at each quarter point for the unstrengthened monopole, and the same monopole after strengthening is shown in Figure 10. The monopole was then reloaded to failure, which occurred due to rupture of the sheets on the tension side underneath the anchorage. Immediately following the rupture of the fibers, redistribution of the stresses in the pole resulted in local buckling of the monopole on the compression side 150 mm (6 in) from the base. This buckling ruptured the longitudinal and transverse fibers surrounding the buckled region. The ultimate moment capacity of the monopole was 548 kN-m (403 ft-kip) with a maximum net deflection at the tip of 129 mm (5.1 in). Figure 11 shows the deflection of the monopole at 95% of the ultimate load, and the ultimate rupture of the CFRP sheets on the tension side of the pole.

**CONCLUSIONS**

Of the ten resins studied for the wet lay-up of high modulus carbon fiber, several have showed promise for use in a system to strengthen steel structures. One of these resins was used in conjunction with the unidirectional carbon fiber sheets to achieve a 25% stiffness increase of a scaled steel monopole in the elastic range using a limited number of plys. The selection of the best adhesives for bonding CFRP laminate strips to steel was determined from the increase in strength and stiffness over the unstrengthened control specimen, ultimate CFRP strain, and mode of failure by rupturing of the strip. Factors that will be explored to help explain the failure behavior of the different adhesives are workability, viscosity, and shear strength of the adhesive.

**ACKNOWLEDGEMENTS**

The authors would like to acknowledge Mitsubishi Chemical for sponsoring this project and Mr. Bryan Lanier for his assistance in testing the monopole.
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TABLE 1 Resin Selection Test Matrix for Wet Lay-Up Process

<table>
<thead>
<tr>
<th>Resin</th>
<th>Room Temp. Cure</th>
<th>Elevated Temp. Cure</th>
<th>Low Dose Wetting Agent</th>
<th>High Dose Wetting Agent</th>
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<tr>
<td>3-M DP-460</td>
<td>DP460.RT</td>
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<td>DP460.LD</td>
<td>DP460.HD</td>
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<tr>
<td>3-M DP-810</td>
<td>DP810.RT</td>
<td>-</td>
<td>DP810.LD</td>
<td>DP810.HD</td>
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<tr>
<td>Degussa MBrace Saturant</td>
<td>MBSAT.RT</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jeffco 121</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reichhold Atprime2</td>
<td>ATP2.RT</td>
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<tr>
<td>Sika Sikadur 300</td>
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<tr>
<td>SP Ampreg 22 (Fast hardener)</td>
<td>AM22F.RT</td>
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<td>-</td>
<td>-</td>
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<td>SP Ampreg 22 (Slow hardener)</td>
<td>AM22S.RT</td>
<td>AM22S.ET</td>
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- No tests conducted
TABLE 2 CFRP laminate strip ultimate strain (millistrain) and failure mode for various development lengths ($L_d$)

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>$L_d = 203$ mm</th>
<th>$L_d = 152$ mm</th>
<th>$L_d = 102$ mm</th>
<th>$L_d = 76$ mm</th>
<th>$L_d = 51$ mm</th>
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<td>Weld-On SS620</td>
<td>3.08 m$\varepsilon$ rupture</td>
<td>2.96 m$\varepsilon$ rupture</td>
<td>3.22 m$\varepsilon$ rupture</td>
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<td>SP Spabond 345</td>
<td>2.88 m$\varepsilon$ rupture</td>
<td>2.93 m$\varepsilon$ rupture</td>
<td>3.29 m$\varepsilon$ rupture</td>
<td>2.43 m$\varepsilon$ rupture</td>
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<tr>
<td>Vantico Araldite 2015</td>
<td>3.09 m$\varepsilon$ rupture</td>
<td>2.98 m$\varepsilon$ rupture</td>
<td>2.88 m$\varepsilon$ rupture</td>
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<td>Jeffco 121</td>
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<td>Fyfe Tyfo MB2</td>
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<td>-</td>
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<tr>
<td>Sika Sikadur 30</td>
<td>2.81 m$\varepsilon$ debond</td>
<td>-</td>
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<td>-</td>
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</tr>
</tbody>
</table>

- No tests conducted
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