USE OF HIGH MODULUS CARBON FIBER REINFORCED POLYMERS (CFRP) FOR STRENGTHENING STEEL STRUCTURES

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ABSTRACT

Cost-effective solutions for the rehabilitation and strengthening of steel structures, such as steel bridges and steel monopole towers used for cellular phone antennas, are greatly needed by government transportation departments and industry. Rehabilitation is often required due to loss of cross-section due to corrosion and/or changes of the demand or use of a structure. Current techniques for strengthening steel structures have several drawbacks including requiring heavy equipment for installation, their fatigue performance in addition to the need for ongoing maintenance due to continued corrosion attack. The current research program proposed the use of a new high modulus carbon fiber reinforced polymer (CFRP) for strengthening of steel structures. This program, currently in progress, includes extensive research to select the resin for wet lay-up of carbon fiber sheets and the adhesives for bonding of pre-cured laminate strips. Test results of the first scaled monopole tower, tested at the Constructed Facilities Laboratory at North Carolina State University, showed a 25% increase in stiffness in the elastic range over the same monopole before strengthening. This paper summarizes also the remaining program, including the strengthening of other monopoles and a steel-concrete composite girder to be strengthened using different techniques. Experimental results for these tests will be reported at the workshop presentation.

INTRODUCTION

Fiber Reinforced Polymer (FRP) materials have been found to be successful for flexural strengthening, shear strengthening and ductility enhancement of concrete structures. Steel structures also require strengthening due to changes in use, demand for increases in load carrying capacity, corrosion of the existing structure, or to improve the fatigue performance by reducing the stress level for a given loading condition. These serious infrastructure problems have created the urgent need for innovative techniques for strengthening steel structures that are cost-effective and have good resistance to environmental degradation. This paper deals with rehabilitation and/or strengthening steel structures using new high modulus carbon fiber reinforced polymer (CFRP) material. This technique has the potential to correct difficulties associated with existing techniques while being cost-effective and causing minimal disruption to the users of the structure.

Currently, strengthening and rehabilitation of steel structures and bridges often requires welding or bolting steel plates or other members to the structure. Welding is not desirable in many cases due to the poor fatigue performance of welded connections under fatigue loading conditions. Bolted connections are often used to improve the fatigue performance, however the cross-section loss resulting from drilling holes requires additional strengthening material be used in addition to the cost of labor for drilling. Furthermore, the corrosion performance of these techniques may also be affected by the material difference between the weld and parent metals used for welded connections and due to the accumulation of moisture and debris surrounding bolted connections.

Another type of steel structure that often requires strengthening are steel monopole towers that are the predominant type of tower design for the cellular phone industry. 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 [1]. 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, that also results in minimal difference to the visual appearance of a monopole, desirable.

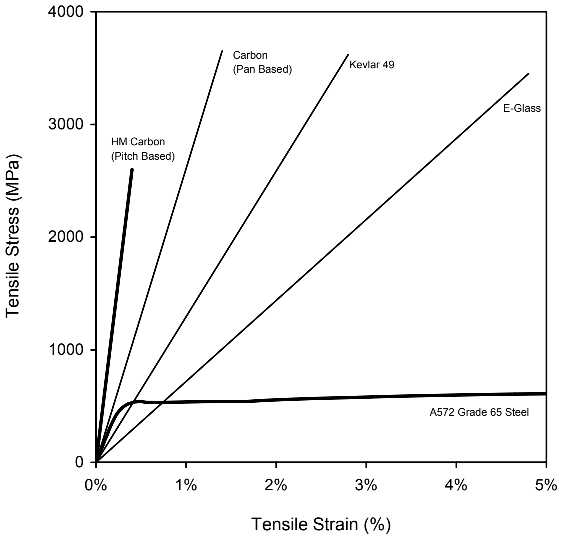

Figure 1 Comparison of tensile fiber stiffness of new, high modulus carbon fiber to other types of fibers and steel

MATERIAL PROPERTIES

This paper deals with a new, high-modulus carbon fiber that has been developed by Mitsubishi Chemical America for use in applications requiring greater stiffness than standard modulus carbon fiber or other types of fibers as shown in Figure 1. 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, with a tensile rupture strength of 2600 MPa and a maximum elongation of 0.4 percent at failure. This fiber is used to manufacture a unidirectional tow sheet that has a width of 330 mm and is suitable for applications requiring a wet lay-up process to conform to the surface configuration of the structure as shown in Figure 2.

Where a greater degree of strengthening is required and flat uniform surfaces are available for bonding, it is often advantageous to adhesively bond CFRP laminate strips to the structure. As such, the same fiber that is 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, as shown in Figure 3. The fiber volume content for these strips that were used in this experimental program, was determined to be 55 percent.

Figure 2 Unidirectional tow sheet manufactured from new, high modulus carbon fiber material

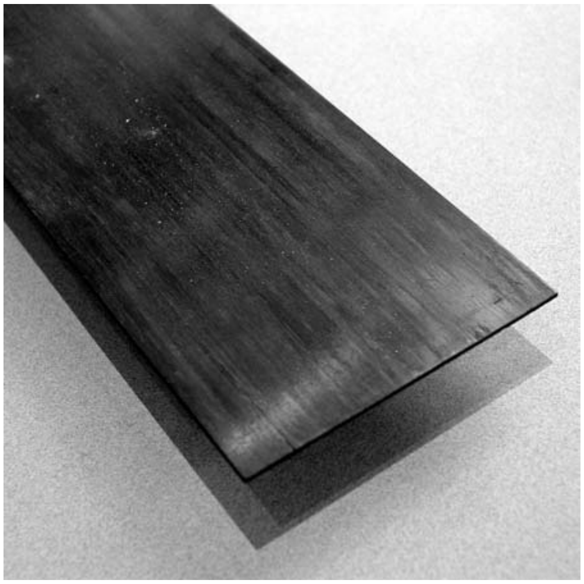

Figure 3 Pre-cured laminate strip manufactured from new, high modulus carbon fiber material

EXPERIMENTAL PROGRAM

The experimental program, currently in progress, consists of three phases. The first phase of testing was conducted to determine a suitable resin for the wet lay-up of unidirectional carbon fiber sheets bonded to steel. Resin selection for the wet lay-up process was determined through testing of double lap shear coupons using ten different resins. The second phase of the experimental program is designed to determine the development length of the sheets used for the wet lay-up process as well as the development length for bonded CFRP laminate strips. For this phase of the program, a super-light beam (SLB) section 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 the 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 third phase of the program consists of testing steel-concrete composite beams scaled from typical steel bridge girders in composite action with the concrete deck slab. The tests are designed to determine the overall performance of the strengthening system and to evaluate different strengthening details. This paper discusses of phases 1 and 2 and the test program planned for phase 3. Results of the experimental program for phase 3 will be reported at the workshop.

PHASE 1(A) RESIN SELECTION FOR WET LAY-UP PROCESS

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 4. These plates were joined together with five tows of the unidirectional carbon fiber sheets on each side of the steel plates with an overlap of 25.4 mm on each of the plates. 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.

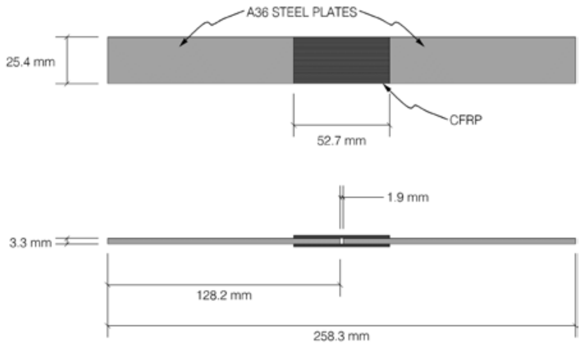

Figure 4 Front and side view of typical double lap shear coupon

The test matrix for evaluation of the wet lay-up resins included ten resins that were cured at room temperature (RT). Table 1 indicates the resins as well as their designation for the study. Testing was completed using a 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 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 stroke at a sample rate of 5 Hz. Load was applied under stroke control at a rate of 0.12 mm/min.

Table 1 Test matrix for wet lay-up adhesive selection

Designation	Resin	Resin Type
DP460.RT	3M DP-460	Amine-epoxy
DP810.RT	3M DP-810	Acrylic
MBSAT.RT	Degussa MBrace Saturant	Amine-epoxy
J121.RT	Jeffco 121	Amine-epoxy
ATP2.RT	Reichhold Atprime 2	Urethane resin
EP1246.RT	Resinlab EP 1246	Acrylic-epoxy blended
S300.RT	Sika Sikadur 300	Amine-epoxy
S330.RT	Sika Sikadur 330	Amine-epoxy
AM22F.RT	SP Ampreg 22 (fast hardener)	Amine-epoxy
AM22S.RT	SP Ampreg 22 (slow hardener)	Amine-epoxy

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 5 with the number of tests for each resin given in parenthesis beside its label. Based on overall performance and constructability aspects, three resins with the highest shear strengths, are discussed in this paper. The complete stress-strain behavior of these coupons is shown in Figure 6.

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 cured FRP material. The average shear strength for these coupons was 12.3 MPa.

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.

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.

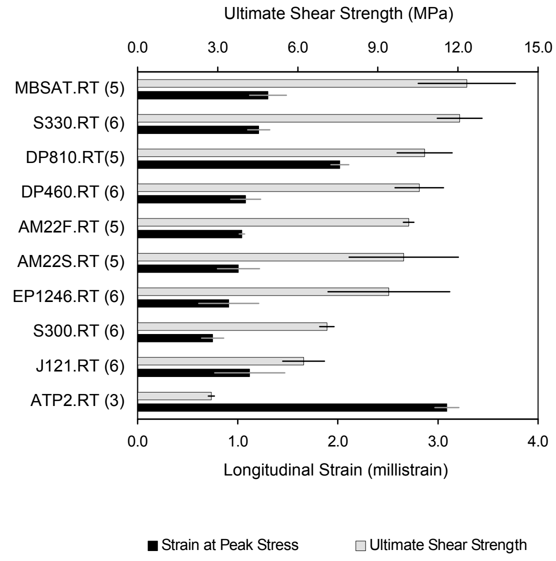

Figure 5 Strain at peak stress and shear strength for wet lay-up resins cured at room temperature (RT)

PHASE 1(B) DEVELOPMENT LENGTH FOR BONDED CFRP STRIPS

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 100 x 5.4) were used as shown in Figure 7 with an additional 6.4 mm thick steel plate welded to the compression flange to simulate the 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 and the thickness was 1.4 mm. Different strip lengths were used to determine the development length for the adhesive bonding process. It is also planned that the development length for the wet lay-up process using the sheets will be completed using this test specimen using both the Degussa MBrace and the Sika Sikadur 330 epoxy saturants.

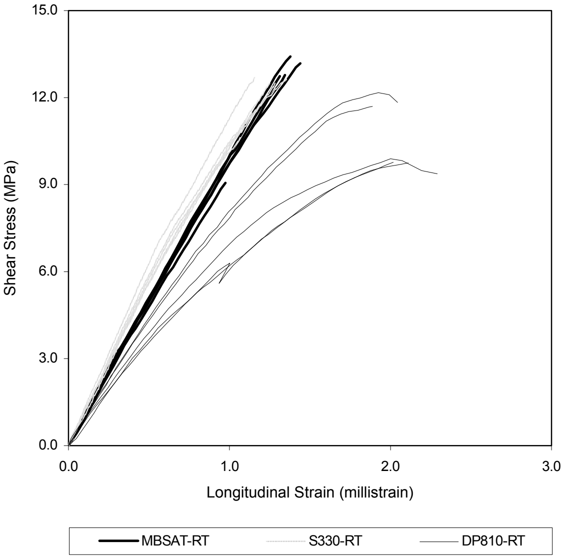

Figure 6 Stress-strain behavior for wet lay-up specimens using three types of resins

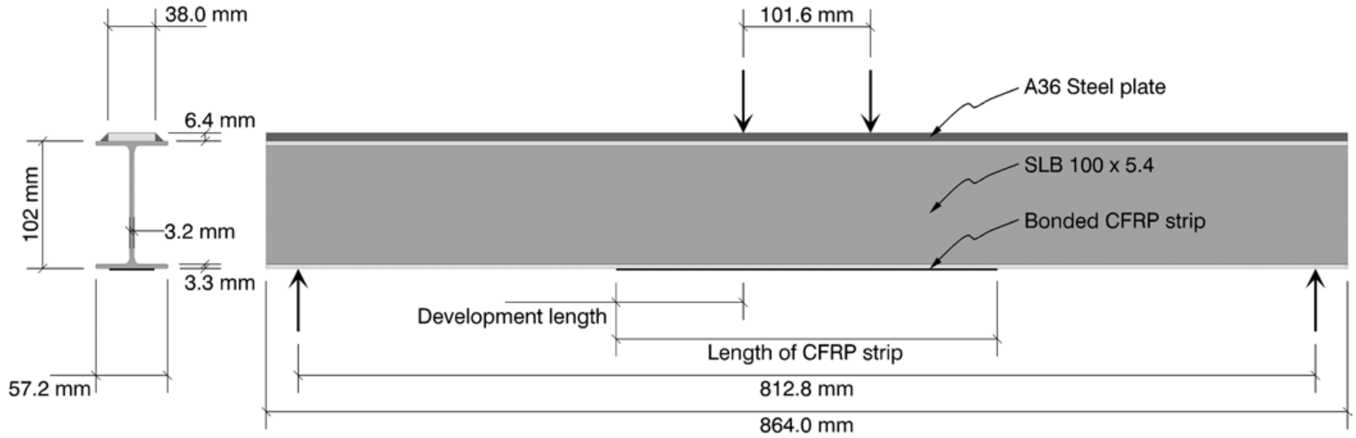

Figure 7 Cross-section dimensions and loading configuration

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 with acetone. 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.

Figure 8 Setup for development length specimens

The beams were simply supported and loaded under four-point loading using a spherically seated bearing block, as shown in Figure 8. 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.

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 control specimen and outside on the CFRP strip for the strengthened beams. Displacement was measured using two linear voltage displacement transducers.

The results of the tests are shown in Table 2, which lists the ultimate strain of the strip at the time of failure either by rupture or debonding of the laminate strip, as shown in Figures 9 and 10 respectively. It can be seen that the specimens with fabricated using the Weld-On SS620 adhesive and the SP Spabond 345 adhesive had the shortest development lengths, being able to develop the ultimate strain in the sheets at approximately 75 mm.

Figure 9 Rupture of CFRP strip for development length specimen using SP Spabond 345 adhesive and 203 mm development length

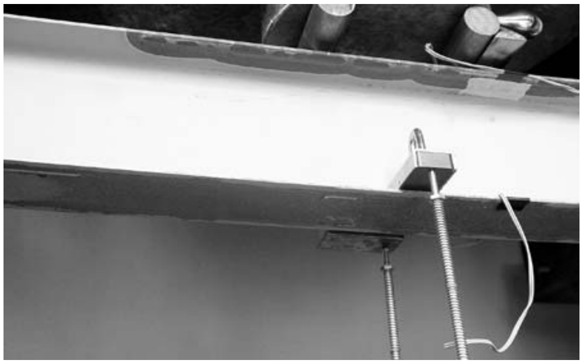

Figure 10 Debonded surface for development length specimen using Sika Sikadur 30 adhesive and 203 mm development length

Table 2 CFRP laminate strip ultimate strain (millistrain) and failure mode for various development lengths (L_d)

Adhesive	L_d = 203 mm	L_d = 152 mm	L_d = 102 mm	L_d = 76 mm
Weld-On SS620	3.08 mε rupture	2.96 mε rupture	3.22 mε rupture	2.76 mε rupture
SP Spabond 345	2.88 mε rupture	2.93 mε rupture	3.29 mε rupture	2.43 mε rupture
Vantico Araldite 2015	3.09 mε rupture	2.98 mε rupture	2.88 mε rupture	2.18 mε debond
Jeffco 121	2.98 mε rupture	3.28 mε rupture	3.00 mε debond	-
Fyfe Tyfo MB2	3.47 mε rupture	3.06 mε debond	2.10 mε debond	-
Sika Sikadur 30	2.81 mε debond	-	-	-

PHASE 2 MONOPOLE BEHAVIOR

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 6096 mm with a dodecagonal, or twelve-sided, cross-section. This cross-section was tapered uniformly along the length, starting at 457 mm from flat to flat at the base and ending at 330 mm at the tip. The thickness of the steel used to fabricate the pole was 4.69 mm. 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 in thickness to allow mounting to the structural wall at the Constructed Facilities Laboratory.

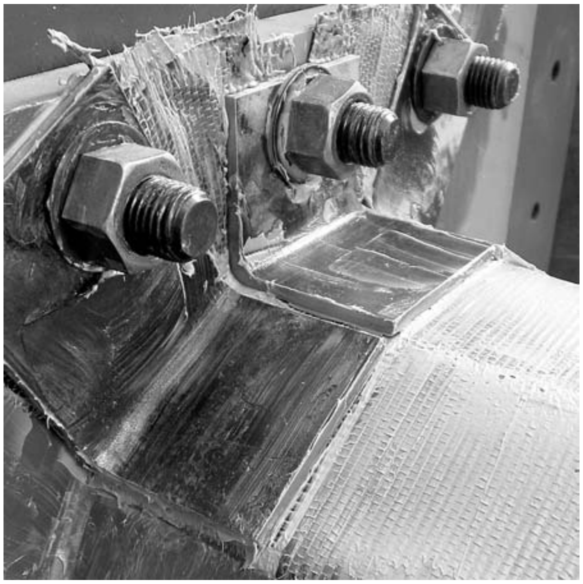

Figure 11 Steel angles used to mechanically anchor longitudinal CFRP plys of first monopole

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 was used to complete the sandblasting and the delivery of the pole was scheduled 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 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, as shown in Figure 11.

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 at the mid-depth of the pole. The transversely oriented sheets were applied continuously from the base to 1200 mm along the length to also delay the onset of local buckling of the steel on the

Figure 12 Gusset plate welded from the corner of two flats on the monopole shaft to the base plate

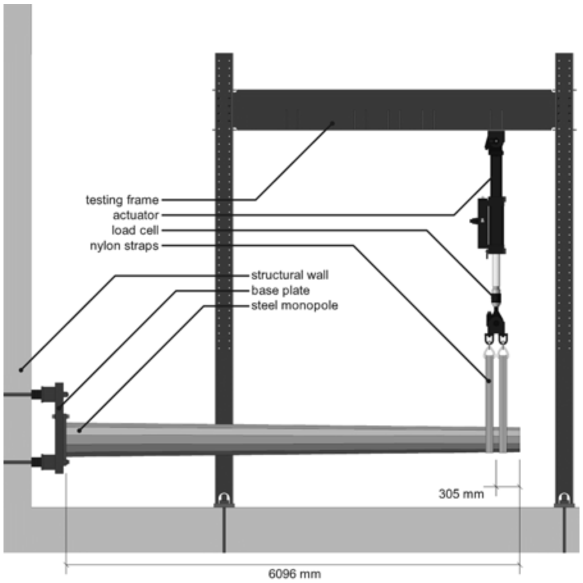

Figure 13 Cantilever setup for monopole tests

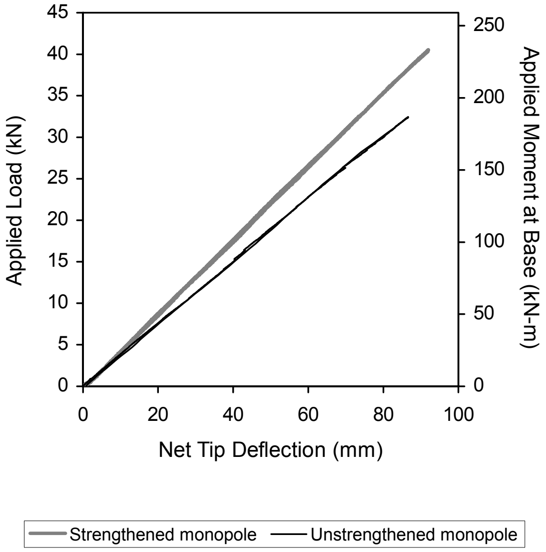

Figure 14 Net tip deflection before and after strengthening using wet lay-up technique

compression side. From this point to the mid-span the transversely oriented sheets were spaced apart from each other.

The second monopole was strengthened by welding gusset plates at the base overlapping with the CFRP strips for a length exceeding the development length as shown in Figure 12. Test results for this monopole will be presented at the workshop.

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 13. 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 tip of the pole from a loading fixture.

After strengthening, the first monopole was loaded to the same load as the same unstrengthened monopole. The monopole was then reloaded to the same mid-pole displacement as the same unstrengthened monopole 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 stroke. 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.

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 14 taking only the net deflection of the

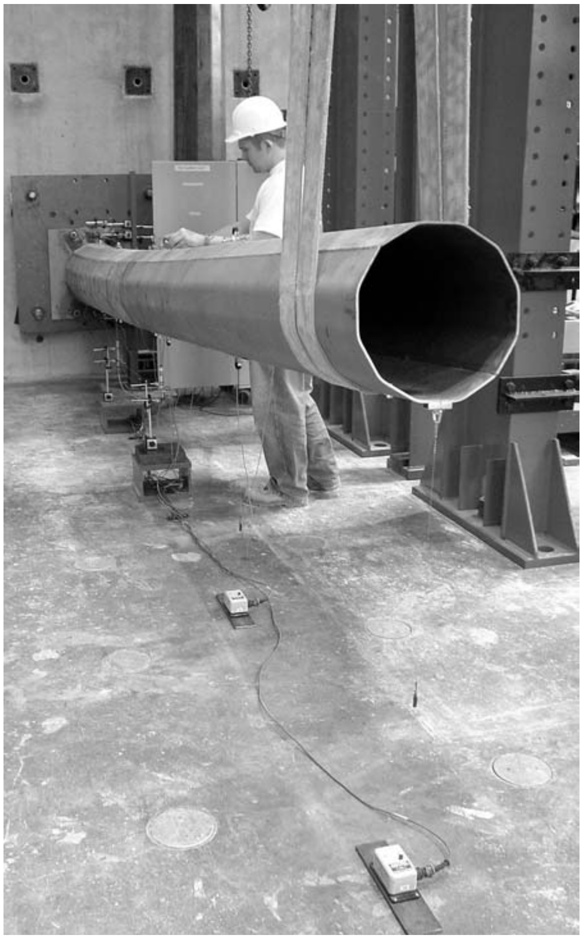

Figure 15 Strengthened monopole deflection at 95% of the ultimate load

Figure 16 Rupture of the CFRP sheets on the tension side of the base

monopole, accounting for the components of deflection resulting from base slip and base rotation. Figure 15 shows the deflection of the monopole at 95% of the ultimate load. The monopole was then reloaded to failure, which occurred due to rupture of the sheets on the tension side underneath the anchorage, as shown in Figure 16. 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 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 with a maximum net deflection at the tip of 129 mm.

PHASE 3 STEEL-CONCRETE COMPOSITE BEAM PROGRAM

The third phase of the experimental program consists of three steel-concrete composite beams that will be strengthened with high modulus CFRP strips using two different techniques. Each of the three beams will be identical in geometry and have been scaled from typical bridge members common in use. The beams consist of a W 12 x 30 cross-section with 19 mm diameter shear studs welded to the compression flange. A concrete deck slab that is 100 mm in thickness will be cast simultaneously from a single concrete batch to minimize differences in concrete behavior. The first beam, with the cross-section shown in Figure 17, will be tested without any strengthening for comparison with the remaining two beams. The second beam will be strengthened by bonding high modulus CFRP strips to the tension flange. The third beam will be strengthened with high modulus CFRP strips that are prestressed during the bonding operation. As expected, there will be a considerable reduction in the amount of CFRP used for the prestressed beams, thereby enhancing the cost-effectiveness of the strengthening. It is also expected that the prestressed beam will have even greater stiffness relative to the beam strengthened with unprestressed strips.

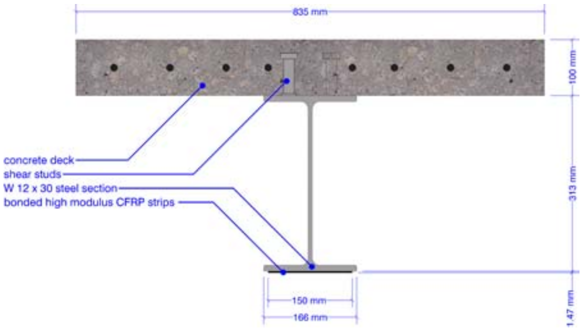

Figure 17 Cross-section of steel-concrete composite beams strengthened with high modulus CFRP

SUMMARY

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 through a development length study, giving the, ultimate CFRP strain, and mode of failure for different bonded lengths.

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