EFFECTIVENESS OF CFRP STRENGTHENING FOR STEEL STRUCTURES

Mina Dawood, Murthy Guddati & Sami Rizkalla
Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, USA, 27695-7533

ABSTRACT

This paper describes a detailed research program that was conducted in two phases to evaluate the bond characteristics and environmental durability of a proposed carbon fiber reinforced polymer (CFRP) system for strengthening steel bridges and structures. The first phase included both double-lap shear coupon and steel beam tests to assess the bond strength of CFRP splice joints. Small scale tests were conducted to characterize the tension and shear strength of the bond interface. A finite element analysis was conducted to evaluate the distribution of stresses near the splice plate ends. The findings of the first phase suggest that a maximum principal stress based failure criterion may be suitable for design of the bonded splice joints. The second phase of the research included 52 double-lap shear coupon tests to evaluate the environmental durability of the system. The findings indicate that the use of a silane adhesion promoter can significantly enhance the bond durability. The findings further suggest that including a glass fiber layer in the adhesive can increase the initial bond strength of the system. This research demonstrates that, with proper detailing, the proposed system can be effectively used to strengthen and repair steel structures and bridges.

Keywords: CFRP, steel structures, detailing, bond, FEM, environmental durability

INTRODUCTION

Significant research has been conducted to study the behavior of steel structures strengthened with carbon fiber reinforced polymer (CFRP) materials [1,2,3]. This early research focused mainly on the use of conventional modulus CFRP materials for strengthening or repair of steel girders. The early research typically indicates that CFRP materials can be effectively used to increase the flexural strength, and post-yield stiffness of typical steel bridge girders. However, due to the relatively low modulus of elasticity of the CFRP materials compared to steel, a significant amount of strengthening material was typically required to enhance the stiffness and overall serviceability of the structure within the elastic range.

A comprehensive experimental and analytical research program has been in progress for the past 6 years to develop a high modulus (HM) CFRP strengthening system for steel bridges and structures. The initial stages of the research focused on selection of a
suitable adhesive to bond the CFRP materials to steel surfaces [4]. A total of six different adhesives were studied using a series of small-scale steel beam tests. The development length of each adhesive to develop the rupture strength of the CFRP was evaluated for one layer and two layers of CFRP plates. Based on the required development length, the observed failure mode and the overall workability of the adhesive, the SP Systems Spabond 345 two-part epoxy adhesive was selected as a component of the proposed strengthening system.

The overall behavior of the system was investigated based on a series of large-scale steel-concrete composite girder tests [4]. The large-scale beams were strengthened with various configurations of high and intermediate modulus CFRP materials and tested monotonically to failure. The test results indicate that the proposed strengthening system increased the flexural strength and elastic stiffness of the beams by up to 45 percent and 36 percent respectively. The research findings further demonstrated that prestressing the CFRP plates prior to installation can further enhance the stiffness of the member and can help to maintain the original ductility of the unstrengthened member.

In a related study the performance of strengthened steel-concrete composite beams under overloading and fatigue loading conditions was considered [5]. The findings demonstrated that, in addition to increasing the flexural strength and stiffness of the beams, the presence of the strengthening system also increased the yield load. This helped to reduce the residual deflections and maintain the serviceability of the strengthened members in the event of overloading conditions. Due to the enhancement of the serviceability the allowable live load level of the strengthened beams could be increased. In the fatigue study two additional beams were tested under a simulated increase of the live load level of 20 percent compared to an unstrengthened beam. Both of the strengthened beams survived three million loading cycles at the increased live load level without showing any signs of failure. Based on the previous research, flexural design guidelines were developed to allow design of the strengthening system for a desired increase of the allowable live load level [6].

This paper presents the further development of the strengthening system. The first phase of the research studied the bond characteristics of the strengthening system. Detailing considerations are described which can be used to approximately double the capacity of bonded CFRP splice joints. The tension and shear strength of the bond interface were studied and a finite element analysis is presented which was used to evaluate the stress distribution near the plate end. The second phase of the research focused on the environmental durability of the strengthening system. Several different techniques were investigated to enhance the durability of the system including use of a silane adhesion promoter or including a glass fiber insulating layer in the adhesive between the steel and the CFRP to prevent galvanic corrosion.

**HIGH MODULUS CFRP STRENGTHENING SYSTEM**

The proposed strengthening system consists of HM CFRP plates and a two-part room temperature cure epoxy. The relatively high modulus of the CFRP materials compared to steel makes them well suited to enhance the serviceability of steel
structures. Several different types of fibers, CFRP plates and adhesives were investigated in the first two phases of the research. Based on the initial trials, the materials presented in Table 1 were selected as components of the system. The table presents the material properties in tension of the dry carbon fibers, the CFRP plates and the epoxy adhesive.

Table 1: HM CFRP strengthening system material properties

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus, E</td>
<td>640,000 MPa</td>
<td>418,000 MPa</td>
<td>2980 MPa</td>
</tr>
<tr>
<td>Ultimate strength, f_u</td>
<td>2600 MPa</td>
<td>1540 MPa</td>
<td>38 MPa</td>
</tr>
<tr>
<td>Rupture strain, ε_u</td>
<td>0.004</td>
<td>0.0037</td>
<td>0.0148</td>
</tr>
</tbody>
</table>

**BOND STUDY**

The following sections describe the details of the experimental and analytical program to study the bond behavior of the strengthening system. The experimental program included double-lap shear coupon tests and large-scale beam tests. Material level tests were conducted to evaluate the strength of the adhesive and the bond strength of the interface between the adhesive and the CFRP. A finite element analysis was conducted to determine the distribution of bond stresses along the bond interface.

**Experimental Program**

Eight double-lap shear coupon tests were conducted in the first part of the experimental program. Figure 1 (a) – (d) show the different joint configurations that were considered. The effect of a steel clamp near the plate end was also studied. The typical setup for the coupon tests is shown in Figure 1(f).

<table>
<thead>
<tr>
<th>End of Splice Plate</th>
<th>Center of Splice Joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square (S)</td>
<td>CFRP Splice</td>
</tr>
<tr>
<td></td>
<td>Main CFRP</td>
</tr>
<tr>
<td></td>
<td>see Figure 1(b)</td>
</tr>
<tr>
<td>Reverse Tapered 1 (T1)</td>
<td>CFRP splice</td>
</tr>
<tr>
<td></td>
<td>see Figure 1(c)</td>
</tr>
<tr>
<td>Reverse Tapered 2 (T2)</td>
<td>see Figure 1(c)</td>
</tr>
<tr>
<td>Rounded &amp; tapered (U)</td>
<td>see Figure 1(d)</td>
</tr>
</tbody>
</table>

Figure 1. (a) Plate end details for tested coupons (b) square (c) tapered, (d) rounded & tapered plate ends (e) double-lap shear coupon test setup
A total of 10 large-scale steel beams were also tested to investigate the behavior of the
splices under flexural loading conditions. Several of the plate end details shown in
Figure 1 were also considered for the beam tests. Different splice plate lengths
ranging from 200 mm to 400 mm were studied. The possibility of increasing the joint
strength by mechanically anchoring the ends of the splice plate was studied. Two
methods of mechanical anchorage were investigated including a transverse CFRP
wrap and a steel clamp.

Experimental Results
All of the tested double-lap shear coupons and splice beams failed due to debonding of
the splice plate. The test results are described in detail elsewhere [10]. The findings
of the experimental program indicate that the reverse tapered configuration, T2,
approximately doubled the bond capacity as compared to the square, S, configuration.
This is likely due to the reduction of the stress concentration near the plate ends which
was confirmed by a finite element analysis. While the other details also increased the
joint capacity, the effect was not as significant. The findings of the beam tests indicate
that both increasing the splice plate length and including mechanical anchorage near
the plate end did not increase the joint capacity.

Bond Interface Strength
A suitable bond failure criterion is currently being developed based on the
fundamental material properties of the adhesive and the characteristics of the bond
interface. Since the adhesive used in the strengthening system is essentially linear,
elastic and brittle in nature, a principal stress based criterion is being adopted. Both
the pure shear strength and the pure tension strength of the adhesive and the bond
interface are being considered.

To determine the pure tension strength of the bond interface, pull-off tests were
conducted as shown in Figure 2(a). The test configuration is shown schematically in
Figure 2(b). The observed failure mode was typically a combination of an adhesive
failure at the CFRP-adhesive interface and an interlaminar failure near the surface of
the CFRP material. This was similar to the observed failure mode of the tested
double-lap shear coupons and splice beams. The average measured bond strength of
the interface was 18 MPa which is approximately five times the typical bond strength
between CFRP and concrete surfaces. Similar pull-off tests were conducted to
evaluate the bond strength between the steel and the adhesive as shown schematically
in Figure 2(c). The failure mode was primarily cohesive within the adhesive layer.
The average measured bond strength was 38 MPa which correlates well with the
measured tension strength of the adhesive.
To determine the pure shear strength of the adhesive and of the bond interface, a specially designed torsion test device, shown in Figure 3 was fabricated. Load was applied to the steel shaft using a torque wrench and the applied torque was measured using an electrical resistance strain gauge based torque transducer. The average measured shear strengths of the adhesive and the bonded interface were 48 MPa and 23 MPa respectively.

**Finite Element Analysis**

A 2-D linear finite element analysis was conducted for the double-lap shear coupons with square plate ends. The results were used to determine the magnitude of the principal stress near the end of the splice plate for the tested coupons immediately prior to failure. The principal stress distributions obtained from the finite element analysis at the adhesive main-plate interface near the plate end are plotted in Figure 4. The stresses were calculated for load levels of 89 kN and 97 kN, which correspond to the minimum and maximum measured failure loads respectively of the tested double-
lap shear coupons with square plat ends. The measured tension strength of the adhesive and the bond interface are also plotted in the figure. From the figure it can be seen that the calculated stress directly at the end of the splice plate was highly affected by the presence of the singularity at this location.

![Figure 4. Principal stress distribution near square plate end prior to failure](image)

For all of the tested specimens, the fabrication process resulted in some amount of adhesive spew near the end of the splice plate. Consequently, the idealized square plate end configuration was not achieved for any of the tested specimens. The actual geometry of the splice plate ends would likely lessen or eliminate the effect of the singularity at the plate end. This is confirmed by the consistency of the measured experimental results for the three 400-S type double-lap shear coupons. Therefore, the maximum principal stress near, but not at, the plate end was considered in the finite element analysis to assess the failure of the joints. The maximum principal stress determined from the FE analysis 0.4 mm away from the plate end was between 32 MPa and 35 MPa for all of the tested coupons. These values are within the range of the measured tension strength of the adhesive and the bond interface. Thus, the average tension strength of the bond interface as measured by pull-off tests can possibly be used as a conservative failure criterion for the design of the bonded joints.

**ENVIRONMENTAL DURABILITY STUDY**

The following sections present the details of the environmental durability study. The experimental program and the results obtained to date are presented and discussed.

*Experimental Program*

A total of 52 steel-CFRP double-lap shear coupons were tested to investigate the environmental durability of the strengthening system. The durability of the bond region is of particular interest. Bond deterioration is typically due to one or a
combination of the following mechanisms: (1) galvanic corrosion of the steel due to coupling with the CFRP materials, (2) ingress of moisture into the interfacial region between the adhesive and the steel surface, and (3) degradation of the material properties of the bulk adhesive. The typical double-lap shear coupon test specimens consisted of two 32 mm wide by 9.5 mm thick steel plates bonded together by two 400 mm long, 19 mm wide by 4 mm thick CFRP splice plates.

Four bond details, shown schematically in Figure 5(a) – (d), were considered. Detail A represents the simplest bond configuration which does not include any additional measures to enhance the environmental durability. For Detail AS the steel surface was pre-treated with a silane coupling agent to enhance the durability of the interfacial region between the steel and the adhesive. A glass fiber layer was inserted in the bond region for Detail AG to prevent direct electrical contact between the carbon and the steel and to prevent the occurrence of galvanic corrosion. Detail AGS included both methods of protection.

Figure 5. Environmental durability specimen details

The test matrix for the environmental durability study is given in Table 2. A total of 14 control specimens were tested under laboratory conditions without any environmental conditioning. An additional 30 coupons were exposed to severe exposure conditions to accelerate the deterioration of the bond interface. This allowed comparison of the test results after a short duration of exposure. The severe exposure consisted of wet/dry cycles in a 5% NaCl solution at a temperature of 100°F. The exposure was cycled on a one week wet/one week dry schedule for 1, 4 and 6 month durations. The remaining coupons were exposed to typical outdoor environmental conditions for 12 months.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Joint Detail</th>
<th>Load</th>
<th>Planned Duration</th>
<th>Repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Laboratory Conditions</td>
<td>A</td>
<td>$T_{uA}$</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>AS</td>
<td>$T_{uAS}$</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>AG</td>
<td>$T_{uAG}$</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>AGS</td>
<td>$T_{uAGS}$</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Accelerated Exposure</td>
<td>A</td>
<td>0</td>
<td>1, 4 &amp; 6 mo.</td>
<td>2</td>
</tr>
<tr>
<td>Wet/Dry Cycling</td>
<td>AS</td>
<td>0.35 $T_{uA}$</td>
<td>1, 4 &amp; 6 mo.</td>
<td>2</td>
</tr>
<tr>
<td>5% NaCl, 100°F</td>
<td>AG</td>
<td>0.35 $T_{uA}$</td>
<td>1, 4 &amp; 6 mo.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>AGS</td>
<td>0.35 $T_{uA}$</td>
<td>1, 4 &amp; 6 mo.</td>
<td>2</td>
</tr>
<tr>
<td>Outdoor Exposure</td>
<td>A</td>
<td>0.35 $T_{uA}$</td>
<td>12 mo.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>AS</td>
<td>0.35 $T_{uA}$</td>
<td>12 mo.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>AG</td>
<td>0.35 $T_{uA}$</td>
<td>12 mo.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>AGS</td>
<td>0.35 $T_{uA}$</td>
<td>12 mo.</td>
<td>2</td>
</tr>
</tbody>
</table>
The effect of sustained load on the environmental durability of the system was also considered. A total of 24 of the accelerated exposure coupons were subjected to a sustained load representing 35 percent of the average ultimate strength of the Detail A control coupons, \( T_{uA} \). All of the coupons exposed to outdoor conditions were also subjected to the same level of sustained load. The applied load level was monitored by two electrical resistance strain gauges on each coupon.

**Experimental Results**

To date a total of 34 coupons have been tested. These include 14 unconditioned control coupons, 10 coupons which were subjected to accelerated corrosion for one month and 10 coupons exposed to four months of accelerated corrosion. The remaining tests are currently in progress. The average measured tension strength and the range of measured strengths for all of the tested coupons are given in Figure 6(a). The error bars in the figure represent the distribution of the test results. All the tested coupons, except for one of the Detail AG control coupons, failed by debonding of the CFRP from the steel surface. The one remaining coupon failed due to yielding of the steel plate. Inspection of the initial results indicates that the presence of the glass fiber layer increased the initial bond strength. The average strength of the AG and AGS control specimens, which all incorporated a glass fiber layer in the adhesive, was about 50% higher than the average strength of the Detail A and AS control specimens which did not include glass. This was likely because the glass fibers acted to reinforce the adhesive layer and possibly also delayed the propagation of cracking. After one month of exposure to accelerated environmental conditions, the bond strength in all cases did not decrease significantly. The variability of the results for this exposure duration was likely due primarily to the inherent variability of the bond strength of the joints.

After four months of exposure one of the Detail A specimens, which did not include any additional environmental protection, failed unexpectedly under the effect of the sustained load. Significant deterioration was observed for the remaining specimens which were subsequently loaded monotonically to failure to determine their remaining strength. After four months of severe exposure the average tension strength of the Detail A specimens decreased by 45% compared to the control specimens. Figure 6(b) shows the failure surface of one of the failed Detail A specimens. Inspection of the failure surface revealed a discolored portion of the adhesive near the edges of the CFRP plate. This discoloration indicated ingress of moisture into the bond interface at the edges of the CFRP plate. While the center of the bond region remained bonded, the discolored outer region was apparently partially debonded. The moisture ingress may have accounted for the observed reduction of strength of the Detail A specimens. The average strength of the specimens which included a silane coupling agent, Detail AS, remained essentially constant for the four month duration. The failure surface of the Detail AS coupons, shown in Figure 6(c), indicated total bond of the CFRP to the steel.

While the use of a glass fiber layer helped to increase the initial strength of the coupons, after four months of exposure the average tension strength of the Detail AG specimens decreased by 50%. Inspection of the failure surface of the test coupons indicated that the glass fibers were not completely impregnated by the adhesive and rust colored stains were observed on the glass fibers. This suggests that the dry fibers
may have possibly acted as a wick, drawing water into the adhesive region and reducing the durability of the system. After four months the average strength of the Detail AGS coupons, which included both glass and silane, only decreased by 12 percent. This further demonstrates the beneficial effect of the silane pretreatment.

CONCLUSIONS

This paper describes a detailed experimental and analytical program that was conducted to evaluate the bond characteristics and environmental durability of a CFRP strengthening system for steel structures. The experimental results of the bond study indicate that implementing a reverse tapered configuration near all plate ends can approximately double the bond strength of typical splice joints. Pull-off tests and torsion tests were conducted to evaluate the tension and shear strength of the bond interface. The results suggest that the maximum principal stress may be an appropriate failure criterion to evaluate the ultimate capacity of bonded splice joints. The results of a finite element analysis indicate that the maximum principal stress in the adhesive of several of the tested double-lap shear coupons was between the measured tension strength of the bond interface and that of the adhesive. This suggests that the tension strength of the interface could possibly be used as a conservative upper limit on the principal stress for design purposes.

The findings of the environmental durability study indicate that the use of a silane adhesion promoter can significantly enhance the durability of the bond between CFRP materials and steel surfaces. The results further suggest that also including a glass fiber layer within the adhesive between the steel and the CFRP can increase the initial bond strength by up to 50 percent. However, a silane pretreatment should still be used.
to enhance the bond durability. This paper demonstrates that, with careful detailing, the proposed system represents a promising technique for repair and strengthening of steel structures and bridges.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the National Science Foundation (NSF) Industry/University Cooperative Research Center (I/UCRC) on Repair of Buildings and Bridges with Composites (RB²C). The generous support and contributions of Mitsubishi Chemical FP America Inc. and Fyfe Co. LLC are also greatly appreciated.

REFERENCES