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Bond behavior and durability of a CFRP strengthening system for steel structures

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ABSTRACT: This paper describes a research program that was conducted in two phases to study the behavior of a high modulus CFRP system for strengthening steel structures. The first phase of the research consisted of an experimental program and finite element analysis to study the bond characteristics of the system. The findings indicate that a reverse tapered plate end detail can effectively increase the joint capacity. The second phase of the research focused on the environmental durability of the system. Initial test results, after only one month of exposure to severe environmental conditions shows insignificant reduction of the bond capacity. Findings of the research program indicate that the proposed CFRP system can be effectively used for strengthening and repair of steel buildings and bridges.

1 INTRODUCTION

A new high modulus CFRP system has been developed to strengthen steel structures (Rizkalla et al., in press). Due to the high stiffness of the CFRP material, plate end debonding was found to be of particular concern for long span structures which require splice joints. Analysis indicates that implementing a reverse taper near the plate ends can significantly reduce bond stress concentrations and potentially increase joint capacity (Adams, et al., 1986; Hildebrand, 1994; Belingardi et al. 2002). However, experimental evidence of this behavior is limited.

The environmental durability of the CFRP materials for strengthening steel structures has also been questioned. Some researchers have concluded that a thin layer of epoxy between the steel and the CFRP can sufficiently reduce galvanic corrosion rates between the two materials (Tavakkolizadeh & Saadatmanesh, 2001). Other researchers recommend the use of a glass fiber layer to electrically isolate the materials (West, 2001). Research also demonstrates that the use of a silane adhesion promoter can significantly enhance the moist durability of steel-adhesive bonds (Comyn et al, 1990; West, 2001). This paper presents a comprehensive experimental and analytical study which was conducted to study the bond behavior and environmental durability of CFRP materials proposed for strengthening steel structures.

2 CFRP STRENGTHENING SYSTEM

The proposed strengthening system consists of high modulus CFRP strips and a two-part room temperature cure epoxy adhesive. The average material properties, determined according to ASTM D3039 and ASTM D638 for the CFRP and adhesive respectively, are given in Table 1.

Table 1. Strengthening system material properties

Material Property	CFRP Plate	Adhesive
Elastic Modulus, E	418,000 MPa	2980 MPa
Ultimate Strength, f_u	1490 MPa	37.9 MPa
Ultimate Strain, ε_u	0.0035	0.015

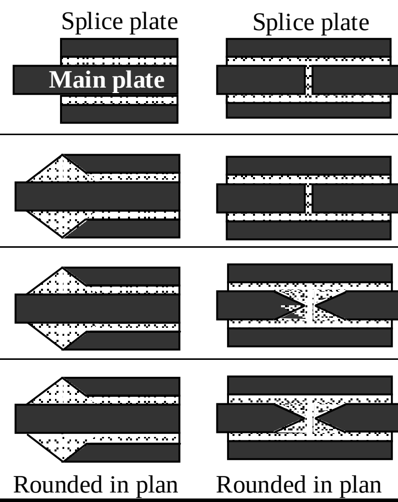
3 PHASE I: BOND BEHAVIOR

This section presents the findings of a comprehensive experimental program, which was supported by an analytical study, to examine the bond behavior of CFRP strips bonded to steel structures. The program consisted of eight double-lap shear coupon tests and 10 large-scale steel beam tests. The experimental program is described in detail by Rizkalla et al. (2008).

3.1 *Experimental program*

In the first part of the experimental program, seven CFRP double-lap shear coupons were tested. Several different plate end configurations, shown in Figure 1 (a) – (d), were considered. All of the specimens consisted of two 8 mm thick by 38 mm wide CFRP main plates which were bonded together by two 4 mm thick by 38 mm wide by 400 mm long CFRP splice plates.

	No. of Specimens	End of Splice Plate	Center of Splice Joint	Failure load (kN)
Square (S)	3			89-97
Reverse Tapered 1 (T1)	1			160
Reverse Tapered 2 (T2)	2			157
Rounded & tapered (U)	1			191-228



(a)

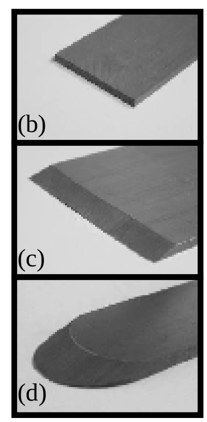


Figure 1: (a) Plate end details for tested coupons (b) square (c) tapered, (d) rounded & tapered

All of the tested double-lap shear coupons failed due to debonding of the splice plate. The test results are described in detail by Rizkalla et al. (2008). The measured failure loads for the tested coupons are presented in Figure 1. The results indicate that the presence of the reverse tapered plate detail, T2, doubled the bond capacity as compared to the square, S, plate end detail. This is likely due to the reduction of the stress concentration near the plate ends which was confirmed by the finite element analysis. While the T1 and U details also increased the joint capacity, the effect was not as significant.

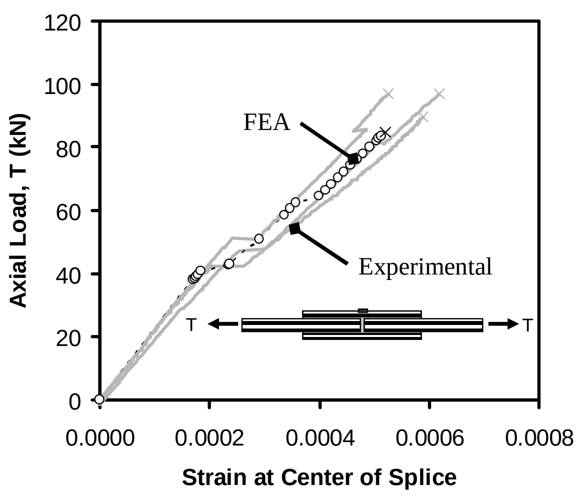
A total of 10 large-scale steel beams were also tested to investigate the behavior of the splices under flexural loading conditions (Rizkalla et al., 2008). The typical test beams consisted of a steel W12x30 wide flange beam with a C9x15 or C9x13.4 channel welded to the top flange to simulate the presence of a reinforced concrete bridge deck. The beams were strengthened by a 4 mm thick by 100 mm wide CFRP plate which was bonded to the tension flange. The main CFRP plate was discontinuous and a splice cover plate was bonded at the midspan of the beam. The splice plate configurations S, T2 and U, shown in Figure 1, were also considered for the beam tests. The influence of the splice plate length was also studied. Two methods of mechanical anchorage near the plate end were also investigated including a transverse CFRP wrap and a steel clamp. The beams were tested in four-point bending with a span of 4572 mm and a 1600 mm long constant moment region. The findings of the beam tests confirmed that the reverse tapered, T2, plate end configuration approximately doubled the joint strength compared to the square, S, configuration. The beam tests further indicated that both increasing the splice plate length and including mechanical anchorage near the plate end did not increase the joint capacity.

3.2 *Finite Element Analysis*

A 3-D non-linear finite element analysis (FEA) was conducted to study the behavior of the tested double-lap shear coupons. Three of the tested coupons with the square plate ends, 400-S(1) – (3), were modeled using the ANSYS software package. The CFRP plates were modeled using the ANSYS SOLID45 8-node brick element. The adhesive was modeled using the ANSYS SOLID65 element which has built-in cracking capabilities. A maximum element size of 1 mm was used in all three principal directions.

The tension strength of the CFRP-adhesive interface was obtained from pull-off tests. A total of four tests were conducted. Typically a combined interfacial/interlaminar failure was observed near the surface of the CFRP material which was similar to the observed failure mode for the double-lap shear coupon and beam tests. The average and maximum measured bond strengths were 18.4 MPa and 20.2 MPa respectively. The maximum measured pull-off strength was used as the specified tension strength of the bond interface in the FEA. Cracking of the adhesive within the center of the splice joint was modeled using the measured tensile properties of the adhesive given in Table 1.

Figure 2 compares the FEA and measured load-strain relationships at the center of the splice joint at the surface of the CFRP splice plate for configuration 400-S. The figure indicates that the FE model accurately predicted the initial stiffness of the uncracked splice joint. The model predicted a gradual debonding failure. Initial cracking of the adhesive was observed within the center of the joint at a load level of 41 kN which closely matches the experimental results. At an applied load level of 62 kN the FE model predicted additional cracking at the center of the joint which is shown in Figure 2(a) by the sudden increase of the strain at that load level. This was accompanied by initial debonding near the end of the CFRP splice plate which extended approximately 30 mm from the plate end. The FEA predicted total debonding of the splice plate at a load level of 85 kN. The tabulated values presented in Figure 2(b) demonstrate the close correlation between the finite element prediction and the measured cracking and failure loads of the three similar tested coupons.



	Cracking	Failure
400-S(1)	41 kN	89 kN
400-S(2)	47 kN	97 kN
400-S(3)	51 kN	97 kN
FEA	42 kN	85 kN

Figure 2: Comparison of FEA results and experimental results for double-lap shear coupons 400-S

A linear, 3-D FEA of the tested beams was also conducted to investigate the adhesive bond stress distribution near the end of the splice plates for the square and reverse-tapered joint configurations. The beams were modeled using the ANSYS SOLID95 20-node brick element. Only the constant moment region of the beams was modeled and quarter model symmetry was employed. A stress gradient was applied at the end of the beam section to simulate an equivalent total applied load of 80 kN. A maximum element edge length of 5 mm was used throughout the model.

The FEA indicated that increasing the length of the splice plate did not affect the stress distribution near the end of the plate. This is consistent with the findings of the experimental program. Further, the analysis indicated that the presence of the reverse-tapered joint configuration significantly decreased the magnitude of the principal bond stress in the adhesive near the end of the joint. Figure 3 (a) and (b) show the shear, normal and principal stress distributions in the adhesive near the end of the splice plate for beam configurations 800-S and 800-T2 as determined from the FEA. Inspection of the figure indicates that the reverse-tapered plate end effectively eliminated the normal (peeling) stress concentration and also moderately reduced the magnitude of the peak shear stress near the end of the plate thus reducing the maximum principle stress by approximately 60 percent. This reduction of the principle stress can explain the increase of the joint capacity due to the reverse taper which was measured in the experimental program.

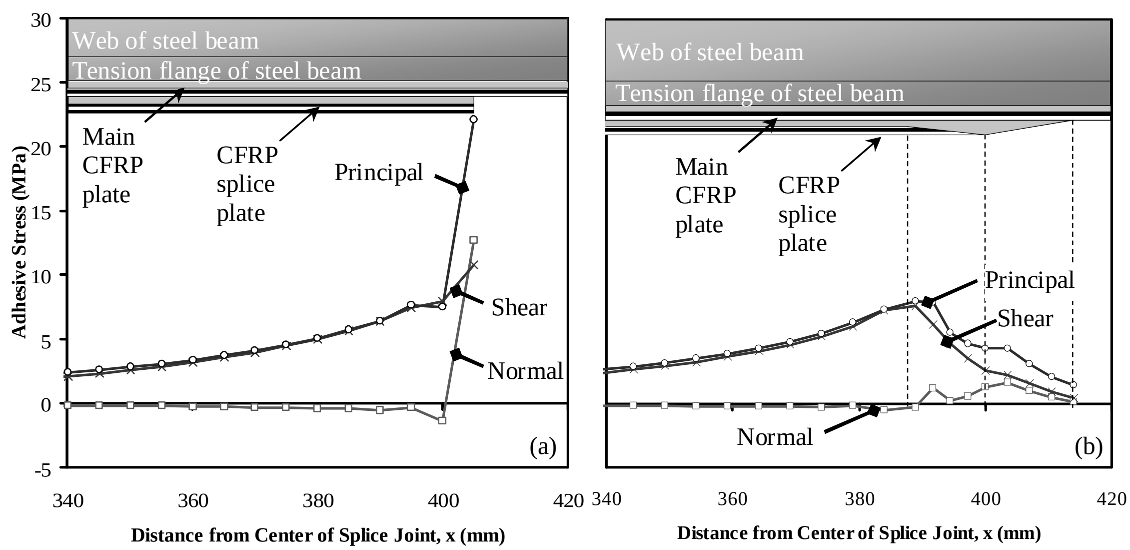


Figure 3: Bond stresses obtained by FEA near the splice plate end for beams (a) 800-S and (b) 800-T2

4 PHASE II: ENVIRONMENTAL DURABILITY

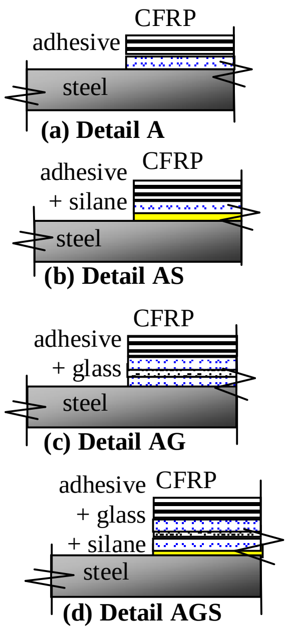
The following sections present the details and initial results of an experimental program to study the environmental durability of the CFRP strengthening system.

4.1 *Experimental Program*

The experimental program consists of 52 steel-CFRP double-lap shear coupons to investigate the environmental durability of various bond configurations. The study is designed to investigate three modes of possible bond deterioration including galvanic corrosion between the steel and CFRP materials, ingress of moisture into the interfacial region between the adhesive and the steel surface and degradation 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 4 mm thick by 19 mm wide by 400 mm long CFRP splice plates. The bonding technique had previously been shown to result in a cured adhesive thickness of 0.1 mm.

Four bond details, shown schematically in Figure 4(a) – (d), were considered. The first detail represents the simplest bond configuration. For Detail AS the steel surface was treated with a silane coupling agent prior to bonding the CFRP to enhance the durability of the interfacial region. To electrically isolate the carbon from the steel, a glass fiber layer approximately 0.5 mm thick was inserted in the bond region for Detail AG. Detail AGS included both methods of protection.

Figure 4(e) presents the test matrix for the environmental durability study. A total of 14 control specimens were tested under laboratory conditions without any environmental conditioning. The average ultimate strength of each detail was determined; for example. T_{uA} represents the average measured ultimate strength of the Detail A control coupons. An additional 30 coupons were subjected to one week wet/one week dry cycles of 5% NaCl solution at a temperature of 100^{o}F for 1, 6 or 12 month durations. The remaining coupons were exposed to outdoor environmental conditions. Material coupons of the steel, adhesive and CFRP were also prepared to assess the effect of the exposure on the bulk material properties.



Environment	Joint Detail	Load	Duration	Repetitions
Control Laboratory Conditions	A	T_{uA}	-	3
	AS	T_{uAS}	-	3
	AG	T_{uAG}	-	4
	AGS	T_{uAGS}	-	4
Accelerated Exposure Wet/Dry Cycling 5% NaCl 100^{o}F	A	0	1, 6 & 12 mo.	2
		0.35 T_{uA}	1, 6 & 12 mo.	2
	AS	0.35 T_{uA}	1, 6 & 12 mo.	2
	AG			
	AGS			
Outdoor Exposure	A	0.35 T_{uA}	12 mo.	2
	AS			
	AG			
	AGS			

(e) Test matrix

Figure 4. Details of the environmental durability study

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 ultimate strength of the Detail A control specimens, T_{uA}. All of the coupons exposed to outdoor conditions were also subjected to a sustained load. The applied load level was monitored by two electrical resistance strain gauges on each coupon.

4.2 *Experimental Results*

To date the control specimens, and the one-month exposure duration specimens have been tested. The six-month and twelve-month duration tests are on going.

All but one of the tested coupons failed due to debonding of the CFRP strip. One of the Detail AG control coupons failed due to yielding of the steel prior to debonding. Consideration of the test results of the control specimens yielded several interesting findings. Comparison of the average strength for the Detail A and Detail AS tests indicated that the silane adhesion promoter did not significantly affect the initial bond strength. A similar conclusion was drawn by comparing the Detail AG and Detail AGS test results. However, comparison of Details A and AS to Details AG and AGS respectively indicates that the glass fiber increased the average bond strength by approximately 40 percent. This could possibly be because the glass fibers acted as reinforcements for the adhesive thereby increasing the strength of the material. However, the standard deviation of the strength was approximately doubled which should be considered in the design of the system.

Similar trends were observed for the specimens subjected to one month of exposure to the extreme environmental conditions. The ultimate failure load of the one month specimens was comparable to or, in some cases, slightly higher than the capacity of the control specimens. The material tests indicate a reduction of the strength of the bulk materials ranging from 2 to 5 percent. The findings indicate that one month was not a sufficient time frame to observe significant degradation of the bond.

5 CONCLUSIONS

This paper presents a detailed experimental and analytical program that was conducted in two phases to study the bond behavior and environmental durability of a CFRP system for strengthening steel structures. The findings of the first phase of the research indicate that the bond capacity of the system can be approximately doubled by implementing a reverse tapered detail at all plate ends. Increasing the splice plate length and including mechanical anchorage near the plate ends was not found to be an effective method to increase the joint capacity. The finite element analysis indicates good correlation with the experimental results of the double-lap shear coupon tests. The analysis also indicates that the reverse tapered plate end significantly reduced the normal and shear stress concentrations in the adhesive near the plate ends which could possibly account for the observed increase of the joint capacity.

The second phase of the research, investigated the environmental durability of the system. The findings indicate that the silane adhesion promote did not affect the initial bond strength. However the presence of a glass fiber layer in the adhesive increased the average bond strength by approximately 40 percent. The tested specimens did not indicate any significant degradation of the bond capacity after one month of exposure to extreme environmental conditions. The findings of this research demonstrate that the proposed CFRP system can be effectively used for strengthening and repair of steel bridges and structures.

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