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Effect of web bonded CFRP shear reinforcement on internal steel stress

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ABSTRACT: A four-point iosipescu shear test is used to evaluate the effects of FRP reinforcement on crack width development and the combined effects of FRP and steel reinforcement. The test program indicates that the steel reinforcement yields following cracking in a concrete test specimen containing a single No. 13 - 400 MPa yield strength reinforcing bar. FRP bonded to the face of both precracked and uncracked test specimens resulted in the steel strain reaching and average of approximately 45 percent of the yield strain prior to failure of the FRP/concrete interface. This research concludes that it is not prudent to assume that the steel yields when bonded FRP is present. The recommended stress in internal steel reinforcement used in combination with externally bonded CFRP is limited to 200 MPa for shear applications.

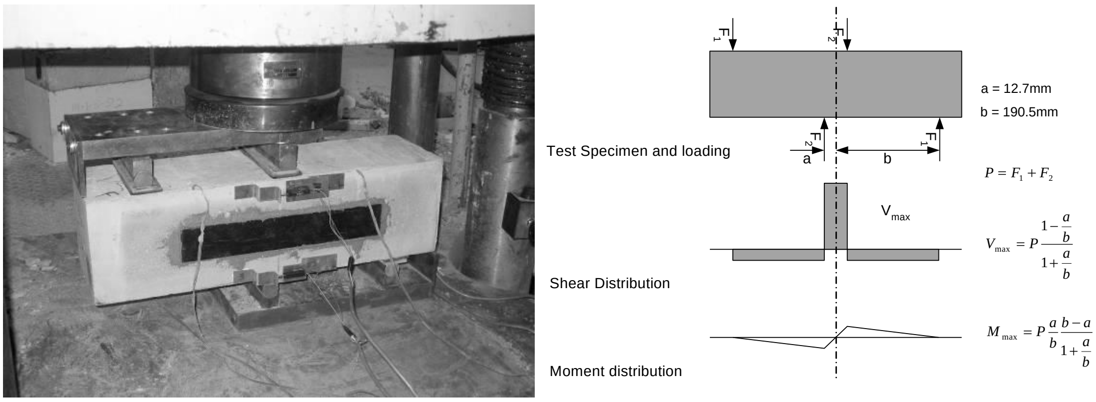
1 INTRODUCTION

Fiber reinforced polymer (FRP) laminate or fabric reinforcement is adhered to the web of concrete members to increase the member shear capacity. It can be used as reinforcement when designing a member or as supplemental reinforcement to repair damaged or under-strength members. It is commonly used to repair concrete structures in the United States and has been shown to increase the shear capacity of a member by 5 to 17% (Deniaud 2000, Khalifa et al 1998, Chaallal & Perraton 1998, Triantafillou 1998, Malek & Saadatmanesh 1998). Researchers have developed behavioral models and material test methodology for evaluating shear strength in plain concrete and concrete members with steel reinforcement (ACI 440.2R-02 2002). However, the load distribution in members reinforced with both steel and FRP is less well defined. The goal of this research was to determine if the addition of FRP limits cracks from opening in concrete specimens with steel reinforcement and determine the corresponding strain in the steel reinforcement.

The design process for determining the nominal shear capacity of steel reinforced concrete members assumes the steel reinforcement yields and carries the load according to ACI 318-02 Building Code for Concrete Structures (2002). However, when FRP is added in addition to the steel reinforcement, the load sharing mechanism is less well known. Previous research has shown bonded FRP will alter shear cracking, deflections, and consequently load sharing between the concrete, steel reinforcement and the FRP. Confinement provided by the FRP, combined with aggregate interlock, provides internal frictional resistance to shear. As the two surfaces slide relative to each other, the surface roughness opens the crack and strains the steel reinforcement similar to the shear friction model proposed by Birkeland (1966). The shear friction model suggests that the aggregate forces the crack open and that the opening is sufficient to yield the steel.

2 EXPERIMENTAL APPROACH

Concrete specimens are prepared with a single No. 13 Grade 40 steel reinforcement bar in the center of the specimen or a single No. 13 Grade 40 bar plus FRP reinforcement. The concrete specimens are fabricated and tested according to the four-point iosipescu shear test refined by Ross (2002). The four-point loading generates a high shear stress at the center of the specimen, nearly zero moment, and forces the specimen to fail along a nearly vertical shear crack. Figure 1 illustrates the test setup, loading, and shear and moment diagrams associated with the four-point iosipescu shear test. The arrangement of the test specimen allows reinforcement to be placed perpendicular to the crack along the longitudinal axis of the test specimen and instrumentation to be installed at a known location relative to the crack.



a) Instrumented test specimen

b) Test set-up, shear, and moment

Figure 1. Four Point Iosipescu Test Specimen

During loading, strain in the steel reinforcement is monitored by four strain gages. The steel reinforcement is prepared for the strain gages by grinding and polishing four locations on the bar for the application of the strain gages. Two gages were located opposite each other at 229 mm and 305 mm. This spacing assured that the gages were on opposite sides of the crack and within 20 mm of the crack. The steel reinforcement tensile characteristics were confirmed experimentally in a tension test to failure. A yield strength of 350 MPa was obtained for steel with a specified yield of 276 MPa. The computed modulus of elasticity was 179 GPa and suggests there was slight slippage in the extensometer. Crack widths were measured by four linear potentiometers placed at top and bottom of the longitudinal center of the specimen.

Two concrete mixtures are evaluated. One mixture was a standard bridge deck design and has 19 mm aggregate and an average compressive strength of 31 MPa. The second mixture is a pea gravel (7 mm aggregate) mix with an average compressive strength of 39 MPa.

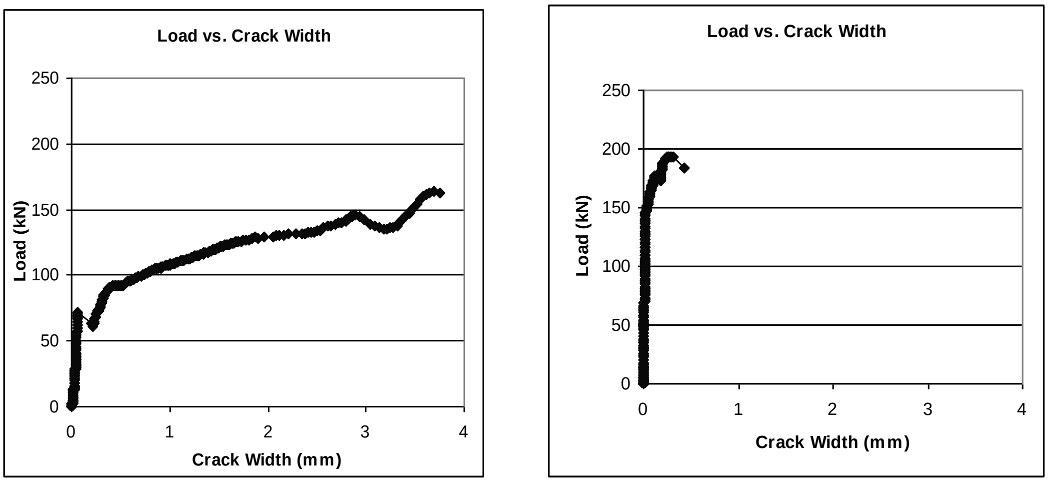
Six specimens measuring 152 x 152 x 533 mm used the pea gravel concrete mix and twelve used the bridge deck concrete mix. Two specimens from each mix contained only steel reinforcement. Ten specimens with 19 mm aggregates are reinforced with both steel and FRP, and four pea gravel mix specimens are reinforced with both steel and FRP.

Two brands of carbon FRP (Sika Carbodur and Aslan 400 CFRP Laminate) are used to strengthen the specimens. Each FRP laminate is 50 mm wide and had a tensile strength well in excess of the concrete substrate shear capacity. The concrete specimens are lightly sandblasted and vacuum cleaned. Both FRP materials were applied with a two-part Sika 30 epoxy following the manufacturer’s instructions. All FRP is applied with a minimum 100 mm development length on either side of the crack. Research has shown this is a sufficient length to mobilize the concrete bond strength (Ross 2002).

3 RESULTS

Figure 2 presents the crack width in the specimens versus the applied load. The steel only reinforced specimen, Fig. 2a, forms a significant crack, whereas the FRP and steel reinforced specimen Fig. 2b, develops a much smaller crack width. The crack width alone suggests that the steel may not have yielded in the specimen with supplemental FRP reinforcement.

Figure 2 additionally shows the effect of the bonded FRP on the strength of the specimens. In the steel only reinforced specimen, the load increases rapidly with little strain in the steel until the specimen cracks at about 75 kN, Fig. 2a. The steel reinforcement is then engaged and the steel strain increases with load to a maximum strength of approximately 160 kN. Figure 2b shows the effect of the FRP. The load increases rapidly to about 200 kN and the corresponding steel strain remains low because the FRP inhibits the crack from opening and engaging the steel reinforcement**.** In this case, the steel and bonded FRP leads to an overall increase in shear capacity of approximately 12 percent. Strain gage data shows the steel contributes to the strength of the FRP and steel reinforced specimens; however, the steel does not contribute nearly its ultimate capacity when combined with FRP reinforcement. Lastly, the failure mode has transitioned from a ductile failure in Fig. 2a to a brittle failure in Fig. 2b. The brittle nature of the failure can be seen in Fig. 3.



a) Steel reinforced specimen b) FRP and steel reinforced specimen

Figure 2. Comparison of crack width versus load

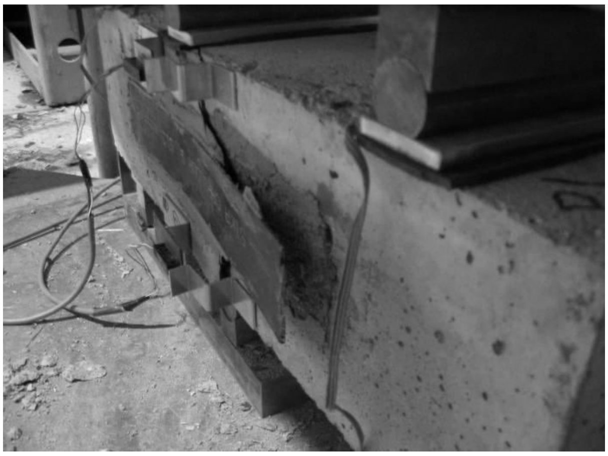
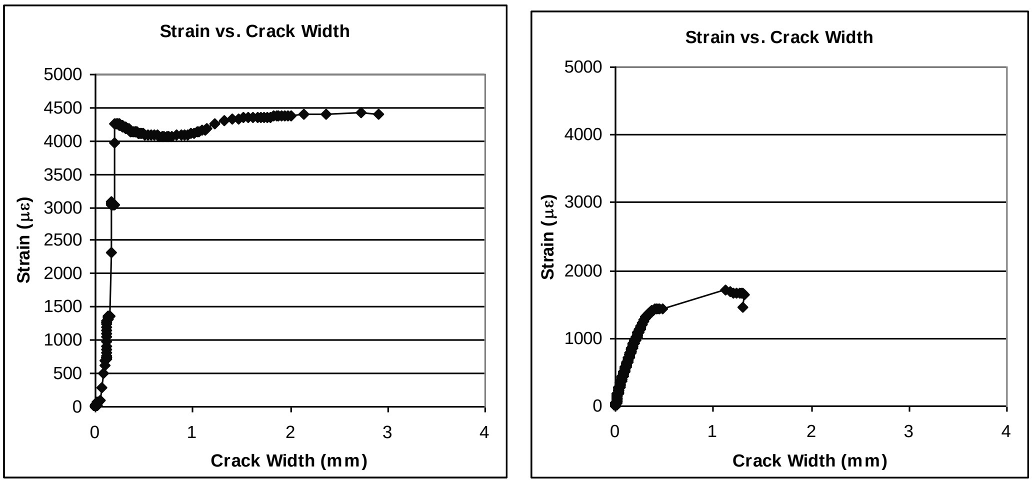


Figure 3. Brittle bond failure of FRP reinforced specimen

Figure 4 shows the relationship between strain and crack width. Figure 4a indicates the steel in a sample without FRP supplemental reinforcement yields, $\varepsilon_y = 2000\ \mu\varepsilon$, at a crack width approximately 0.2 mm wide. Figure 4b indicates that at a crack width of 0.2 mm the steel is approximately 75 % of the yield strain.



a) Steel reinforced specimen

b) FRP and steel reinforced specimen

Figure 4. Comparison of steel strain and crack width

The test results demonstrate that FRP inhibits cracks from initially forming and, in the condition where the cracks are preformed, limit the crack width opening. The small crack width prevents the steel reinforcement from yielding prior to delamination of the FRP. The steel reinforcement did not yield in any of fourteen specimens with externally bonded FRP. Steel in three of the four specimens without externally bonded FRP yielded. The one specimen failed prematurely and, therefore, yield data is unavailable.

4 CONCLUSIONS AND RECOMMENDATIONS

Specimens with only steel reinforcement have a final average crack width of 6 mm. This crack width is recorded at the conclusion of the shear test and reflects the ductility of the steel reinforcement. The average maximum crack width with steel reinforcement and FRP is 3.5 mm, recorded just as the FRP separates from the concrete. Following delamination of the FRP, the load drops off to the value of the steel only specimen at the corresponding crack width. Three of four concrete specimens with only steel reinforcement yielded, while none of the steel yielded in all fourteen specimens with both FRP and steel. The one steel reinforced specimen that did not yield failed prematurely. Test results are summarized in Table 1. The data shows the FRP inhibits cracks from opening and does not allow the steel reinforcement to yield. Furthermore, the average strain in the steel and FRP reinforced specimens was 43% of the yield strain. Based on these tests, the stress in internal steel stirrups should be limited to 850 $\mu\varepsilon$ for members strengthened with externally bonded FRP. There was no perceptible difference between the two brands of FRP used in this test program.

5 ACKNOWLEDGEMENTS

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Table 1. Crack width, strain, and load data

	Sample #	**Max Crack Width (mm)**	**Max Strain (x1000)**	**Strain yield strain (%)**	**Max Load (kN)**
FRP & Steel specimens	b14-frp	1.1	313	16	204
	b11-frp	2.8	753	38	277
	b12-frp	2.8	63	3	282
	b13-frp	1.0	896	45	277
	b15-frp	1.0	1521	76	194
	b16-frp	5.8	411	21	231
	p1-frp	1.5	1315	66	273
	p2-frp	3.5	1198	60	272
	b2-frp	7.4	797	40	186
	b6-frp	-	1145	57	239
	p5-frp	1.0	610	31	298
	p4-frp	2.6	867	43	222
	b3-frp	3.6	546	27	212
	b5-frp	1.3	1702	85	312
	Average	2.7	867	43	248
Steel only specimens	p6	2.9	4425	221	195
	p3	8.9	7299	365	164
	b4	9.4	3731	187	166
	b1	4.7	1052	53	134
	Average	6.5	4127	206	165