Effect of primer and substrate concrete on the FRP-concrete bond properties

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1. Introduction

The externally bonded Fiber Reinforced Polymer (FRP) method is one of the most popular strengthening methods for the RC structures. The key issue in this method has always been the interface between concrete and FRP as it is the weakest link in the whole composite system. The premature failure of the interface is hindering the effective utilization of the high strength FRP sheet. Since the bond plays a vital role in stress transfer between concrete and FRP, the sound knowledge of the mechanism and the interface behavior should be clearly understood in order to achieve a safe and economical strengthening method for the RC structures. The quality of bond between FRP and concrete is influenced by various factors such as condition of existing concrete, surface preparation of the substrate concrete, quality of the FRP application, quality of the FRP itself and durability of the resin (fib, 2001). Past researchers have tried to address many of the above factors but there are some of the issues which still need more detailed study on the role of high strength concrete and effect of different types of resin on the interface properties. The resin here indicates primers, adhesives and impregnating matrices. Dai (2003) performed extensive research on different types of adhesives to know the effect of adhesive elastic modulus and thickness on the interfacial properties and found that either increasing the adhesive layer thickness or decreasing the adhesive elastic modulus leads to the improvement of interfacial bond forces. But the importance of using appropriate type of primer in terms of the bond strength and its effect on the failure mode has not been addressed properly by any researcher. Therefore discussions on the effect of concrete strength and the types of primers on the interface properties will be presented in this paper however the main objective of this ongoing study is to address one of the key durability related issue which is to investigate the effect of moisture in the bond properties between FRP and concrete interface.

To evaluate the FRP-concrete bond performances, various kinds of test methods have been adopted in past such as single lap shear test (Dai, 2003), double lap shear test (Sato, Asano, & Ueda, 2001), shear bending tests etc. Every method has its own advantages and disadvantages however single lap shear test is selected for the present study considering the simplicity of the testing procedure.

2. Experimental Program

The experimental program consists of mechanical test of the materials (tensile and shear strength test of resin) and the single lap shear test of FRP-concrete composite. The casting of tensile and shear specimens were done at the same time while preparing the bond specimens. Tensile and shear specimens were prepared in accordance with JIS K 7113 (1995) (Figure 1) and JIS K 6850 (1999) (Figure 2) respectively. For the preparation of the bond specimens (Figure 3), 150mm×150mm×300mm concrete specimens were casted and cured. The surface preparation was done by concrete disk sander till the coarse aggregates were exposed on the surface. An air compressor was then used to remove the tiny dust particles. After that thin layer of primer was applied on the treated surface and allowed to cure for 24 hours in the room temperature before attaching carbon fiber sheet. The wet layup bonding technique was applied and same epoxy resin FR-E3P was used as adherent and impregnating matrix for FRP sheet.

In the current study, 2 different types of epoxy primers were used namely FP-NS and E-200. FP-NS is the commercially used primer for the FRP composites to provide a better bond between FRP and concrete whereas E-200 primer is also used as a bonding agent but for different purposes such as to anchor the steel rod into the concrete and provide good bond between old and new concrete. To examine the effect of substrate concrete, both normal and high strength concrete were used. The ready-mixed concrete of cylindrical compressive strength 40.48 MPa was used as the normal strength whereas high strength concrete of cylindrical compressive strength 90.85 MPa was mixed in the laboratory by using water reducing super plasticizers. The total FRP bond length was set as 200 mm and an unbonded length of 25 mm was set by using vinyl tape to separate the concrete and FRP sheet to avoid the local damage of the concrete block. Electric resistance strain gauges were attached in the bond specimens at an interval of 20 mm along the bond length to record the strain of FRP sheet and LVDT (Liner Variable Differential Transformer) displacement transducer were used to measure the relative slips between FRP sheet and the concrete at the upper bonded end. Testing of all the specimens were carried out in 250 kN universal testing machine with displacement control. The overall parameters and number of specimens are shown in Table 1. The naming for the specimens is done by combination of following letters B (Bond), T (Tensile), S (Shear), E (E-200), F (FP-NS), N (Normal strength concrete), H (High strength concrete) and numbers indicating specimen number.

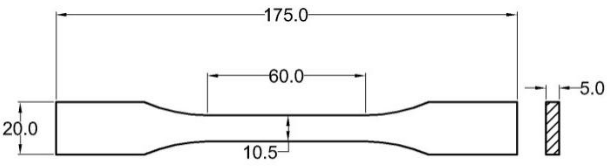

Figure 1 Tensile specimen

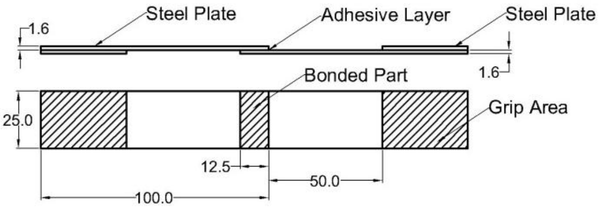

Figure 2 Shear specimen

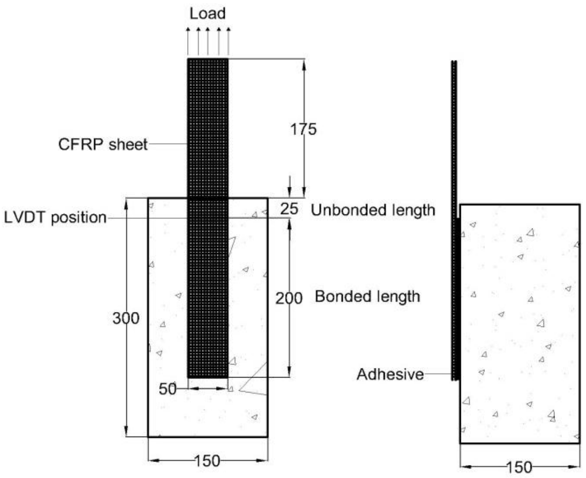

Figure 3 Single lap shear specimen

Table 1 Study parameters and number of specimens

Type of test	Resin Name	Tensile	Shear
		No. of specimens	
Material	E-200	2	2
	FP-NS	2	2
	FR-E3P	2	2
Bond	Single lap shear test		
	Primer Type	Concrete Strength	No. of specimens
	E-200	Normal	2
		High	1
	FP-NS	Normal	2
		High	1

3. Results and Discussions

3.1 Mechanical properties of the resins

Table 2 shows the test results of the mechanical properties such as the tensile strength, elastic modulus and shear strength of different resins adopted for the test. The test indicates that the E-200 primer has comparatively lower tensile and shear strength but higher elastic modulus compared to the FP-NS primer. The correlation of these properties will be made in the later part of the discussion.

Table 2 Mechanical properties of resin

Resin Type	ID	Tensile Strength	Young's Modulus	ID	Shear Strength
		MPa	GPa		MPa
E-200	TE1	29.37	4.30	SE1	11.97
	TE2	30.31	4.20	SE2	11.39
FP-NS	TF1	43.22	3.40	SF1	13.83
	TF2	44.61	3.50	SF2	13.24
FR-E3P	TR1	42.30	2.90	SR1	14.74
	TR2	43.01	3.00	SR2	13.60

3.2 Failure modes

The failure mode varied with types of primer and the strength of concrete. As in the case of normal strength concrete with E-200 primer, the failure occurred by shearing of concrete in which thin uniform layer of concrete was attached on to the FRP sheets. Whereas in case of specimens with FP-NS primer, the failure was a combined interfacial failure which means that the failure is neither a pure concrete shear nor a pure concrete adhesive interface failure. These above 2 different kinds of failure modes (Figure 4) are very common types of failure for the normal strength concrete and were frequently observed by many past researchers. (Dai, 2003; Ching Au, 2006)

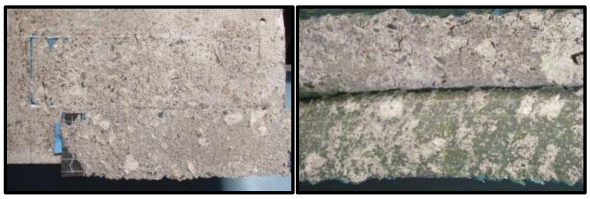

Figure 4 Failure surfaces for E-200 and FP-NS respectively for normal strength concrete substrate

In case of specimens with high strength substrate concrete, failure observed was concrete-primer adhesion failure (Figure 5) irrespective of types of primer used. This kind of failure is possible when the shear strength of concrete is higher than that of adhesive resin. Similar type of failure mode was also reported by Katz (2007) when high strength concrete of 83.8 MPa was used.

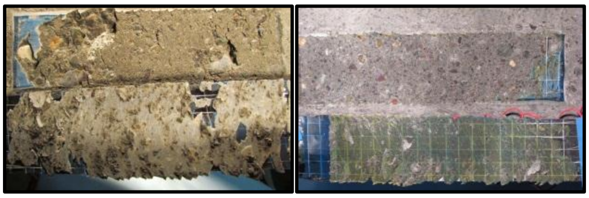

Figure 5 Failure surfaces for E-200 and FP-NS respectively for high strength concrete substrate

3.3 Effect of substrate concrete strength

Concrete strength is a key factor affecting the interface properties as the failure occurs normally in the thin concrete layer near the interface. Therefore some researchers observed that bond strength increased with increase in the strength of concrete. Chajes et. al (1996), Nakaba et. al (2001) and Sato et. al (2001) reported that the bond strength is proportional to $(f_c')^{1/2}$, $(f_c')^{0.19}$ and $(f_c')^{0.20}$ respectively. But this is only true if concrete shear failure occurs. When the failure mode shifts from the concrete shear failure to the primer-concrete adhesion failure with high strength concrete, the bond strength is not dependent on the strength with concrete but on the shear strength of the primer. Therefore primer of higher shear strength should be used in case of adhesive failure in order to achieve higher bond strength. In the current study, even though the strength of concrete varied from 40.48 MPa to 90.85 MPa, there is a mere increase in bond strength for the BFH1 specimen compared to normal strength specimens BFN1 and BFN2. With an increase of concrete strength, the shear strength of the concrete also increases which prevented the shear failure of concrete in BFH1 specimen while inducing primer adhesive failure, where mechanical interlocking action between primer and concrete weakens in case of high strength concrete. Normally when the primer is applied on to the concrete surface, it penetrates through the concrete layer forming a good mechanical interlock between the concrete and primer layer and this is the reason for failure in thin concrete surface layer. This kind of behavior can be observed in normal strength concrete but in contrast, the high strength concrete consists of closely packed cement grains and reduced amount of pores makes difficult for the primer to penetrate inside the concrete which results in comparatively weaker chemical as well as mechanical adhesion between primer and the concrete, and therefore the failure occurs at primer-concrete interface. In case of BEH1 specimen, bond strength was higher than BEN2 specimen but lower than BEN1 case. Interestingly BEH1 showed lower bond strength than BFH1 even though failure modes in both the cases were similar i.e. concrete-primer adhesion failure. This could be because of the lower shear strength of E-200 primer compared to the FP-NS primer. The ultimate load for all the specimens are shown in Figure 6.

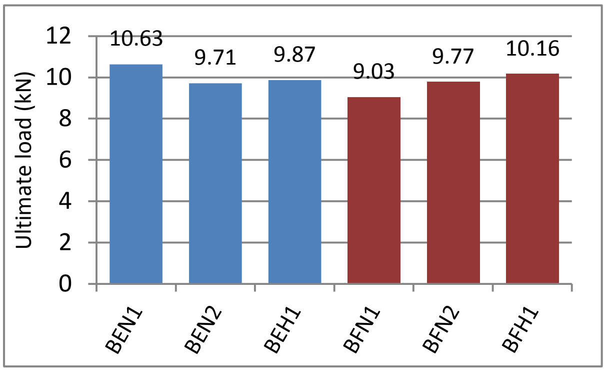

Figure 6 Ultimate interfacial load for single lap shear test specimens

3.4 Strain Distribution

The typical strain distribution along the bond length is shown in Figure 7. Near the loaded end, there is not much change in strain until a certain region after the initiation of peeling. The decreasing strain following this region represents the active bonding zone where transfer of stresses occurs between concrete and the FRP sheet. The horizontal projection of this active bond zone is the effective bond length which indicates that beyond this length there is no significant increase of the ultimate bond strength. The effective bond length for the study was found to be varying from 40mm-60mm in most cases.

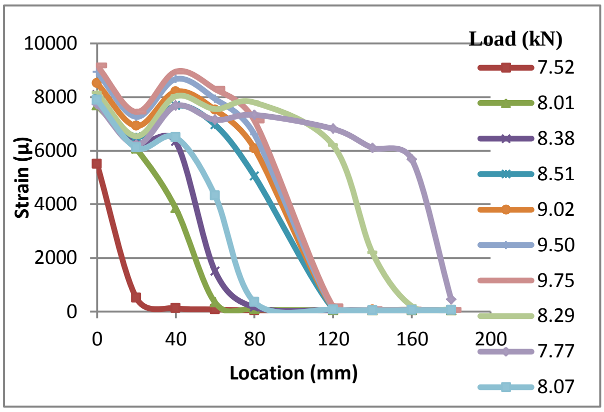

Figure 7 Strain distribution along the bonded length for specimen BFN1

3.5 Bond Stress

Figure 8 shows the bond stress distribution representing propagation of bond stress along the bonded length. The maximum average bond stress for normal strength concrete with E-200 and FP-NS primers are 5.06 MPa and 5.93 MPa respectively whereas for the case of high strength are 7.12 MPa and 7.86 MPa respectively. The average maximum bond stress for specimen with FP-NS primer was higher compared to the E-200 primer.

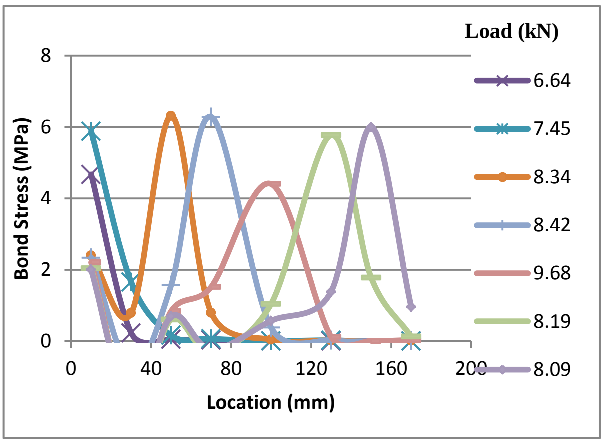

Figure 8 Bond stress distribution specimen BFN1

4. Conclusions

The role of primer type and concrete strength on the failure modes and the ultimate bond strength was examined and the following conclusions were made.

1. The failure mode observed for two types of primers were completely different for normal strength concrete. The failure in the case of E-200 primer was concrete shear (cohesion) failure but in case of FP-NS primer it was combined failure i.e. neither complete shear failure nor primer-concrete adhesion failure.
2. The failure mode changed to concrete-primer adhesion failure when the higher strength concrete was used irrespective of the types of primer.
3. Increasing the strength of concrete beyond a certain limit does not significantly increase the ultimate interfacial load as the mode of failure changes from concrete shear failure to the adhesion failure of concrete and primer interface. Therefore the primer with higher shear strength should be used in case of high strength concrete to achieve higher ultimate interfacial load.
4. In terms of performance, both E-200 and FP-NS did not show much difference in the ultimate interfacial load although different failure modes were observed.

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