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NUMERICAL SIMULATION OF BOND DETERIORATION BETWEEN CFRP PLATE AND CONCRETE IN MOISTURE ENVIRONMENT

Zhenyu Ouyang
(Ph.D. Student, Marquette Universit, Milwaukee, WI, USA)

Baolin Wan
(Assistant Professor, Marquette Universit, Milwaukee, WI, USA)

ABSTRACT
This research investigated the effect of interface region relative humidity (IRRH) on the bond between CFRP and concrete using computer simulation technique. After FRP is peeled off concrete substrate, there is a layer of residue concrete on the detached FRP if the bond is sound. The experimental program related to this research found that the residual thickness of concrete (RTC) was directly related to the IRRH. A constitutive equation, which calculated the RTC from IRRH, was proposed in this research based on the experimental data. The calculated RTCs were used to build a series of finite element models and the virtual crack closure technique (VCCT) was used to calculate the bond fracture energy G_f for debonding. Through the RTC, the bond fracture energy G_f was related to the interface region relative humidity (IRRH). The model and FEM results had excellent agreement with the experimental data. These models can be used to simulate the bond degradation for CFRP bonded concrete specimens suffering from moisture attack.

KEYWORDS
Bond, CFRP, Deterioration, Moisture, Numerical simulation

1. INTRODUCTION

Externally bonding fiber reinforced polymer (FRP) composite materials to concrete beams in order to strengthen or rehabilitate structures is receiving worldwide attention and application. However, many experimental studies (Karbhari et al.,1997; Nguyen et al., 1998; Wan et al., 2006; Ouyang and Wan, 2006) conducted in the past decade show that the water can seriously deteriorate the bond between FRP and concrete. Normally, the fracture mode shifts from cohesive failure in concrete to adhesive failure in interface, where it is the weakest part of bonded structures, in moist environment. Since the vast majority of advanced structural adhesives are epoxy based, they have the propensity to absorb moisture, which can lead to undesirable changes in strength, stiffness and interfacial adhesion. Therefore, the bond durability in moist environment is one of the most important issues for extensive field application of FRP repairing technique in future. Although a lot of experimental researches have been conducted, the mechanism for bond deterioration due to moisture attack is still not clear and how to model such deterioration is still a problem needed to be solved.

Fracture mechanics has been widely used to study the debonding phenomena. The fracture mechanics parameter, fracture energy G_f, includes both crack length and load information for a specimen with crack. Therefore, it is a good criterion to study the bond performance of the FRP bonded concrete members. Besides of the material properties, the critical fracture energy is also considered as an important parameter for modeling FRP debonding from concrete (Coronado and Lopez, 2005). After FRP is peeled off concrete substrate, there is a layer of residue concrete on the detached FRP if the bond is sound. The experimental program related to this research (Ouyang and Wan, 2006) found that the residual thickness of concrete (RTC) remaining on the FRP after it was peeled off concrete substrate was directly related to the interface region relative humidity (IRRH). It was also found that bond fracture energy G_f of FRP-concrete system was directly related to the RTC. This research proposed a constitutive equation and built a series of finite element models to connect IRRH, RTC and G_f.

2. RESEARCH SIGNIFICANCE

A constitutive equation, which calculated the RTC from IRRH, was proposed in this research based on the experimental data. The calculated RTCs were used to build a series of finite element models to calculate the bond fracture energy G_f for debonding. Through the RTC, the bond fracture energy G_f was related to the interface region relative humidity (IRRH).

3. NUMERICAL MODELS

3.1 Constitutive Equation to Calculate RTC from IRRH

As observed in experimental program (Ouyang and Wan, 2006), the fracture energy G_f of control specimens was not significantly affected by the residual thickness of concrete (RTC) in dry environment. After the specimens were submerged in water for different durations, RTC decreased with the increase of interface region relative humidity (IRRH). In this situation, even small change of RTC could cause significant decrease of bond fracture energy due to the moisture at the interface region.

When FRP was peeled off concrete substrate, the crack tip actually located at the place with a distance of RTC from the nominal interface bond line as shown in Figure 1. Since the bond fracture energy G_f is sensitive to RTC after specimens are attacked by moisture, the deviation of crack tip location from nominal bond-line should not be neglected in the debonding analysis models. It is shown in Figure 2 that RTC does not change significantly when the interface is relatively dry. However, it decreases proportionally with the increase of IRRH after IRRH is higher than certain value. Therefore, a bi-linear relation between RTC and IRRH is proposed as Equation 1.

$$RTC = \begin{cases} RTC_c - \left(\frac{IRRH - IRRH_c}{IRRH_0 - IRRH_c}\right) \times RTC_c & \text{For } IRRH \geq IRRH_c \\ RTC_c & \text{For } IRRH < IRRH_c \end{cases} \quad (1)$$

where $IRRH_c$ is the critical value of IRRH to start decreasing the RTC; RTC_c is the constant value of RTC when IRRH is less than the $IRRH_c$; and $IRRH_0$ is the IRRH value when perfect interface adhesive failure happens (RTC = 0). This equation assumes that the change of RTC will cause the change of the fracture energy G_f only when IRRH is greater than $IRRH_c$.

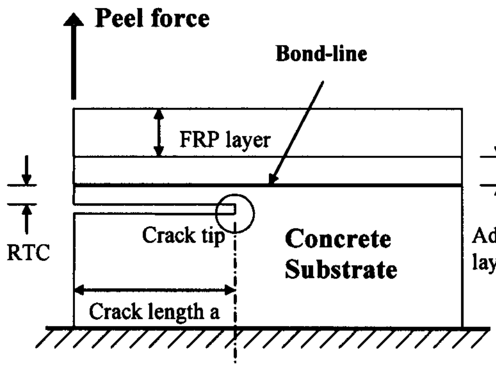

Figure 1: Crack tip location determined by RTC

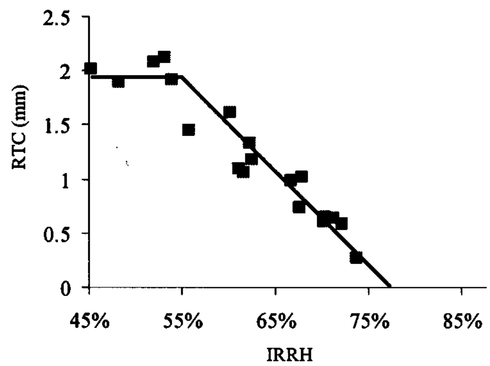

Figure 2: RTC vs. IRRH

The RTC might be different for different loading modes and material properties. All specimens were tested by Mode I (peeling) loading in this study. It is shown in Figure 2 that $IRRH_c$ was 55% and RTC_c was 2.0 mm for the specimens in this research. It can also be found in the figure that IRRH is 77% if the line is extended to intercept with the IRRH axis where the RTC is 0. Thus, $IRRH_0$ was set to be 77% in this study. Equation 2 was used to calculate the RTC for finite element models in this study.

$$RTC = \begin{cases} 2.0 - \left(\frac{IRRH - 0.55}{0.77 - 0.55}\right) \times 2.0 & \text{For } IRRH \geq 55\% \\ 2.0 & \text{For } IRRH < 55\% \end{cases} \quad (2)$$

3.2 Virtual Crack Closure Technique (VCCT)

The virtual crack closure technique (VCCT) is widely used to calculate the interfacial energy release rates from finite element models through a single geometric model for crack propagation. A modified virtual crack closure integral for square-root singularity elements was derived by Sethuraman and Maiti (1988) in order to compute the strain energy release rate by moving the mid-side node position of the isoparametric quadratic element to the quarter location. This method can increase the accuracy of strain energy calculation for linear elastic analysis. The strain energy release rate, G, can be expressed as,

$$G_I = \frac{(u_{yk} - u'_{yk})}{\Delta a}[F_{yj} + (1.5\pi - 4)F_{yi}] \quad (3)$$

$$G_{II} = \frac{(u_{xk} - u'_{xk})}{\Delta a}[F_{xj} + (1.5\pi - 4)F_{xi}] \quad (4)$$

where (F_{xi}, F_{yi}) and (F_{xj}, F_{yj}) represent the nodal forces at nodes I and J, respectively; and (u_{xk}, u_{yk}) and (u'_{xk}, u'_{yk}) represent the nodal displacements behind it as shown in Figure 3. The total energy release rate is the sum of G_I and G_{II}. In this study, the modified virtual crack closure integral was used to calculate the bond fracture energy G_f of FRP bonded concrete specimen.

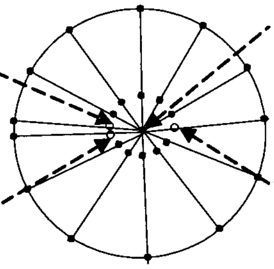

Figure 3: Nodes and elements generated around the crack tip in FE model for energy release rate analysis.

Figure 1 was used to build the geometric model in FE analysis. The dimension of the concrete specimen was 76 x 76 x 191 mm. The width of CFRP plate was 51 mm and the thickness of it was 2 mm. The ultimate tensile strength and tensile modulus in the principal fiber direction were 2.02 GPa and 139 GPa, respectively. The tensile modulus and tensile strength of the epoxy adhesive used in the study were 3.18 GPa and 72.4 MPa respectively. The crack length was set as 33 mm which was the typical first crack length in the tests. The load recorded in the test was applied to the FE model. The RTC, which is the distance from nominal bond line to the crack in FE models, was calculated by Equation 2 for different IRRH values. Ansys 10.0 was used to do finite element analysis and Plane 183 element was selected to mesh the geometric model. All materials were assumed to be linear elastic. It was found that materials' moduli did not have significant effect on G_f for linear elastic analysis (Wan and Ouyang, 2006). Therefore, the material properties change due to moisture attack was not considered in this research.

4. NUMERICAL RESULTS AND DISCUSS

The FEM and experimental results of bond fracture energy G_f is plotted versus residual thickness of concrete as shown in Figure 4. It is shown that the FEM results had excellent agreement with the experimental data. The G_f value decreased with the decrease of RTC value. When the fracture location was moved closer to the bond line (RTC = 0), G_f was significantly lower than that of control specimens. This phenomenon is consistent with the common experimental result that adhesive failure has lower bond strength than cohesive failure. It can also be seen in Figure 4 that slope of the trend line changed around the RTC value of 1.5 mm. When RTC was less than 1.5 mm, the G_f value was very sensitive to the change of RTC value. However, the increase of RTC did not result the significant increase of G_f when RTC was greater than 2 mm.

The relation between bond fracture energy and interface region relative humidity is shown in Figure 5. When IRRH was smaller than 55%, there was no significant change in fracture energy. The FEM result with RTC value of 2.0 mm showed good approximation for this stage. When IRRH was larger than 55%, the reduction of fracture energy with the increase of IRRH was very obvious. As shown in Figure 5, the FEM results agreed well with the experimental data although the G_f values calculated from FEM were slightly larger than the corresponding experimental results. This was due to the local nonlinearity at the crack tip while the finite element model was based on linear elastic fracture mechanics. Figure 5 shows a nonlinear relation between IRRH and fracture energy although the linear relation was assumed between RTC and IRRH in Equations 1 and 2. When the interface was relatively dry (IRRH < 55%), the G_f kept relatively constant. G_f value decreased significantly with the increase of IRRH when it was higher than 55%.

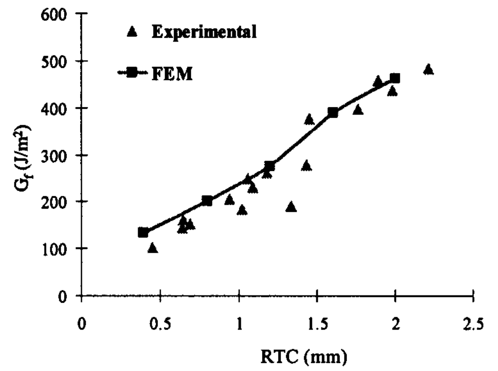

Figure 4: G_f vs. RTC

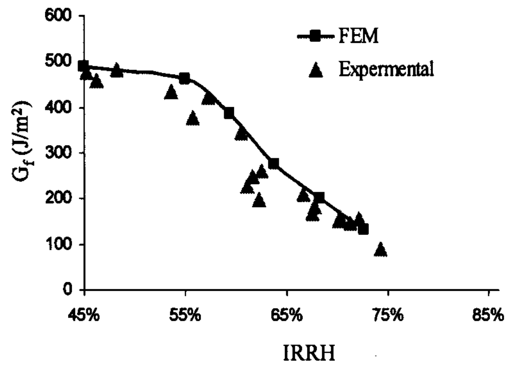

Figure 5: G_f vs. IRRH

5. CONCLUSION

A constitutive equation was proposed in this research to calculate the residual thickness of concrete (RTC) from the value of interface region relative humidity (IRRH). Using this equation and finite element models, the relation between bond fracture energy and the IRRH of the FRP bonded concrete specimens was successfully established.

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