ENVIRONMENT-ASSISTED SUBCRITICAL DEBONDING OF EPOXY-CONCRETE INTERFACE

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Abstract

Interface debonding can grow slowly within the FRP-to-concrete interface in aggressive environments, even though the energy release rate at the crack tip is only a fraction of the critical energy release rate of the interface. This slow debonding process is called environment-assisted subcritical debonding, which may be a dominant mechanism for the failure of the FRP-to-concrete interface under service loads in aggressive environments. In this study, environment-assisted subcritical debonding of the epoxy-concrete interface was first observed and characterized using wedge-driven test. It has been found that aggressive environments can substantially increase the debonding growth rate along the epoxy-concrete interface. Fracture surface analysis suggests that the debonding mode can change from the cohesive failure within the concrete in critical debonding to the adhesive failure along the epoxy-concrete interface in subcritical debonding.

Keywords: fiber reinforced polymers; concrete; interface fracture; environment-assisted subcritical debonding; durability; environmental species

1. Introduction

The long-term durability of the FRP-to-concrete interface still remains unaddressed. A number of studies have been dedicated to the durability of the FRP-to-concrete interface [1, 2]. In these studies, testing specimens were first conditioned in typical civil infrastructure environments, and then were loaded to failure to measure the deteriorated mechanical properties. Two general observations can be obtained from those studies: a) varying degrees of deterioration of structures are induced by environmental conditioning; b) structural failure due to interface debonding occurs more frequently in conditioned structures than in unconditioned structures. When interface debonding occurs, its debonding locus can shift from within the concrete in its dry state.
to along the adhesive-concrete interface in its wet state. These observations suggest that the durability of the FRP-to-concrete interface plays a critical role in the durability of the FRP strengthened structures.

An inherent shortcoming of all existing studies is that only the loads occurred at the time of catastrophic failure are measured. The most distinct feature of these slow cracks is that they grow at a very slow rate under an energy release rate $G$ which is only a fraction of the critical energy release rate $G_c$ if reactive environmental species exist. This slow crack growth is a long-term process of synergistic action of environments and mechanical loads. The catastrophic interface debonding (critical crack) is only the ending point of this process. For any structure requiring long-term performance, a resistance to this slow crack growth would be needed. To understand the degradation mechanism of the interface and gain the ability to accurately predict the long-term durability ultimately requires quantification and appropriate analysis of the slow debonding growth process. The current FRP research literature seems to neglect the significant role of this slow debonding growth, which could be a dominant mechanism for the failure of the FRP-to-concrete interface in service loads and aggressive environments. No study on it has been reported to date.

2. Environment-assisted subcritical cracking

The slow crack growth in adhesive joints in aggressive environments is referred to as environment-assisted subcritical debonding, or cracking, corresponding to critical cracking at the catastrophic failure [3]. Following the classic work of Wiederhorn [3], the environment-assisted subcritical debonding can be treated as a synergistic interaction between strained adhesion bonds and environmental species. A schematic illustration of debonding growth rate ($da/dt$) vs. driving energy release rate at the crack tip ($G$) curve is shown in Fig. 1. This curve consists of three debonding growth regions and a threshold energy release rate ($G_{th}$). If the energy release rate $G$ is less than $G_{th}$, subcritical debonding will not occur. In Region I, the debonding growth is so slow that the environmental species have enough time to reach the crack tip to enable the environmental attack mechanism. As a result, the debonding growth rate is dependent on both the reaction rate and the energy release rate $G$. In Region II, the debonding grows faster so that the debonding growth rate is only controlled by the availability of the environmental species. Consequently, the debonding growth rate is almost independent of the energy release rate $G$. In Region III, the debonding growth is much faster than the transport rate of environmental species so that environmental species cannot reach the crack tip. In such a case, the debonding growth rate is only dependent on $G$. Measurements in this region do not provide any information about the interaction with environmental species at the crack tip. Clearly, Region III describes the critical debonding growth in the adhesive joint and the corresponding $G$ is the critical energy release rate $G_c$.

Existing studies on the strength and durability of FRP-to-concrete interface in aggressive environments only focused on Region III. Region I and II have been completely ignored. Since no environmental species can reach the crack tip in Region III, existing studies have to adopt a two-step approach. In the first step, testing specimens are conditioned in designed accelerated environments so that environmental species can reach the interface through diffusion and capillary action. In the second step, the residual strengths of the conditioned specimens are measured at catastrophic failure (Region III).

The major drawback of this method is that the real mechanism of deterioration is masked.
The accelerated aging test can be inaccurate or even misleading. Since the interaction between the environmental species and mechanical loads is lost in the existing critical failure-based testing, little information of the degradation mechanism of the interface under environmental species attack can be obtained from the testing. Consequently, very little new information can be produced by this method to improve the durability and long-term performance of the structure. It has also been shown that critical failure-based testing can lead to a different failure mode from that of real applications. As demonstrated in many studies [4], interface debonding may shift from adhesive failure at slow growth rate under service loads to cohesive failure at high growth rate under critical failure.

![Fig. 1 Schematic of typical environment-assisted debonding](image)

Log(G<sub>th</sub>)

I
II
III
Reaction controlled
Transport controlled
G<sub>c</sub>

To date, no study has been published on the environment-assisted subcritical debonding of the FRP-to-concrete interface. To address this significant research gap in long-term durability of the FRP-to-concrete interface and overcome the drawbacks in existing approach, this study conducted a systematic experimental study on the environment-assisted debonding growth along the FRP-to-concrete interface under service loads. The focus of this study was on the subcritical debonding growth (regions I and II) because our knowledge on it is virtually nonexistent.

3. Materials and Testing

Water has been identified as the primary environmental species in the degradation process of adhesive bonds [5]. Water molecules can permeate the adhesive or concrete and preferentially migrate to the interfacial region. These water molecules can reduce the bonding strength of the adhesive-concrete interface through a displacement mechanism. To understand and quantify the role of moisture on the degradation of the FRP-to-concrete interface, subcritical debonding testing was first carried out in water. Although there are many other environments which can induce adverse effects on the FRP-concrete interface, only deicing salt and alkaline solutions were considered in this study. Other environments will be studied in the future.

Wedge-driven testing specimens shown in Fig. 2 were manufactured through bonding CFRP strips (Aslan 400 CFRP Laminates with dimension of 1.40 mm × 50.8 mm × 165 mm to concrete blocks (50.8 mm × 50.8 mm × 165 mm) with compressive strength of 21 MPa. To allow better bonding with structural adhesive, one side of the CFPR plates was sanded by the manufacturer. The mean tensile strength and modulus of elasticity of the CFRP are 2.41 GPa and 131 GPa, respectively. Tyfo TC is used as adhesive as recommended by the manufacture. Tyfo TC is a two-component adhesive, based on a combination of epoxy resins and special filler. After cured for seven days at room temperature, the compressive, tensile strength and tensile modulus of
Tyfo TC are 28.1 MPa, 22.7 MPa and 1.20 GPa, respectively. Before bonding, the concrete surface was sand blasted to expose the coarse aggregates slightly. The thickness of the adhesive layer is 1 mm. To ensure the maximum adhesive strength is achieved, the plated concrete specimens were cured for 7 days before testing.

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Testing set-up is shown in Fig. 3. The specimen was first fixed in a home-made fixture. A steel wedge with a thickness of 3.18 mm was then inserted into a pre-crack between the epoxy and the concrete of the specimen. A MTS 810 material testing system was used to slowly drive the wedge into the crack at a very low speed. A digital camera was used to take pictures of the crack tip every 10 seconds, which were then used to determine the crack length. A transparent glass vessel was used to enclose the whole specimen and the load fixture (Fig. 3(b)). After filling this vessel with water or other aggressive chemical solutions, the whole specimen was submerged in these fluids. In this way, we were able to apply both the mechanical forces and the environmental loading simultaneously to the specimen. Compared with the FRP-epoxy layer, the concrete substrate is much stiffer. Therefore, the concrete block can be modeled as a rigid body. Then the energy release rate at the crack tip in Fig. 1 can be calculated as:

$$ G = \frac{9D \Delta^2}{2a^2} $$

where $D$ is the bending stiffness of the FRP-epoxy composite beam; $a$ is the effective crack length shown in Fig. 1; and $\Delta$ is the thickness of the wedge.

Subcritical debonding tests were conducted in ambient environment, in tap water, in deicing salt solutions, and in alkaline solutions. Three specimens were tested for each environmental exposure. When tested in aqueous conditions, the specimen was conditioned in the solutions for
24 hours before applying mechanical loading to ensure the crack tip is saturated with the fluids. Saturated calcium chlorides solution is used to simulate the maximum deleterious effect of the de-icing salt on the FRP-concrete interface. Saturated calcium chlorides solution is prepared by mixing deicing salt with water at a weight ratio of 40:100. The FRP-to-concrete interface can also be deteriorated by naturally occurred alkaline solution due to the presence of concrete pore water. This solution has high PH value (as high as 13.5), which can attack the adhesive. The alkaline solution is prepared by mixing sodium hydroxide with water at a weight ratio of 42:100.

To evaluate their effects on the durability of the epoxy-concrete interface, the subcritical debonding tests were conducted in the sodium-hydroxide solutions with PH = 13. All tests conducted in this study were carried out at a nominal room temperature of 21ºC.

4 Testing Results and Discussion

Testing results for specimens exposed to ambient environment are shown in Figs. 4 to 5. Figure 4(a) shows the interface debonding grows very slowly and stably for the specimen tested at the slow driven rate for a fairly long time until a sudden jump of crack length is observed. This jump of crack length indicates that critical crack occurs. The energy release rate at the crack tip of the slow test specimen varying with the time is shown in Fig. 4(b). It shows that the energy release rate is also slowly increasing until it reaches a maximum value where critical cracking occurs. Since this maximum value of energy release rate (2.59 N/mm) triggered the critical crack, it is the fracture toughness of the interface. Figures 4 suggest that the interface crack is slowly growing even though the energy release rate at the crack tip is well below the critical value. This phenomenon confirms that the subcritical crack growth exists within the FRP-concrete interface. The relationship between the crack growth rate and the driven energy release rate is shown in Fig. 5. It clearly exhibits two distinct regions (Regions I and II).

Results of subcritical debonding testing in tap water, deicing salt solution and alkaline solutions are presented in Figs. 6. Similar to the case in ambient environment, interface debonding growth is observed although the driven energy release rate is much lower than the critical value. It can be seen that two distinct regions exist on the crack growth rate vs. energy release rate curves. Compared with the case in ambient environment, we can find that the energy release rate needed to drive the subcritical debonding in aqueous conditions is much lower, even though the crack growth rate is much faster than in ambient environment. Clearly, environmental species (water and aggressive chemicals) makes the subcritical debonding along the epoxy-concrete interface much faster due to the interaction between the environmental species and the strained adhesion bonds between the epoxy and the concrete. Environmental species are much more abundant at the crack tip in aqueous condition than in ambient environment. As a result, more epoxy chains strained by the wedge can be displaced by the water molecules, leading to much fast subcritical debonding in water [6, 7]. It is also noticed that although the concrete substrates have different strengths, their effects on the subcritical debonding in aqueous condition is very insignificant, as shown in Fig. 6. This is because that the subcritical debonding locus is mainly along the epoxy-concrete interface. As a result, the strength of the concrete substrate is not as important as it is in the critical debonding.

The debonded epoxy sides of the specimen surfaces are shown in Fig. 7. In this figure, the regions within the red rectangles are the initial crack surfaces induced by fast driving. Most of this region is covered by concrete for all testing conditions, suggesting that debonding is a cohesive failure within the concrete for fast driving cracking. This is in agreement with the
existing critical debonding-based studies. In the subcritical debonding region of the specimen tested in ambient environment, there is much less concrete attached to the epoxy surface, indicating a change of failure mode from the cohesive failure in concrete to mainly adhesive failure along the epoxy-concrete interface. This change of failure mode can be seen more clearly in specimens tested in aqueous conditions, as shown in Fig. 7. There is very little concrete attached to the epoxy layer of specimens tested in aqueous conditions, suggesting that debonding occurs along the epoxy-concrete interface in these specimens.

![Fig. 4 subcritical crack growth in ambient condition: (a) crack growth length: (b) energy release rate varying with time](image)

![Fig. 5 Subcritical debonding of the epoxy-concrete interface in ambient environment](image)

![Fig. 6 Comparisons of subcritical debonding of the epoxy-concrete interface in various aqueous environments (all strength groups are included)](image)
There are two reasons for the change of failure mode from the cohesive failure within the concrete in fast crack growth to adhesive failure in slow (subcritical) crack growth. First, the interaction of water molecules with the chemical bonds (most likely hydrogen bonds [7]) between the epoxy and the concrete is allowed in subcritical debonding, significantly deteriorating the epoxy-concrete interface. Second, the strength of the chemical bonds (hydrogen bonds) between the epoxy and the concrete increases with the loading rate, as shown in [8]. For these two reasons, it is possible that epoxy-concrete interface is weaker than that of the adjacent concrete layer in the environment-assisted subcritical debonding, leading to the adhesive failure of the bond. In the existing critical debonding-based studies, the specimens are loaded much faster and there is no interaction between environment species and epoxy-concrete interface bond. As a result, the epoxy-concrete interface is stronger than the adjacent concrete layer, leading to cohesive failure in concrete as observed in the existing studies. Long-term durability testing on the FRP-to-concrete interface [1, 2] also suggested that the debonding mode shows a transition from cohesive purely in the concrete before aging to adhesive at the final stages of aging. This is because the specimens used in these studies have been conditioned sufficient long time before testing so that environment species are available, making the epoxy-concrete interface weaker than the adjacent concrete. The difference in debonding mode of the FRP-to-concrete interface in critical and environment-assisted subcritical debonding may imply that the existing critical debonding-based approach is unsuitable to predict the long-term durability of the FRP-to-concrete interface.

Fig.7. Fracture surfaces of wedge-driven tests: (a) in ambient condition; (b) in tap water; (c) in deicing salt solution; (d) in alkaline solution

5 Conclusions

Environment-assisted subcritical debonding tests of the epoxy-concrete interface were carried out using driven wedge specimens in an ambient environment, tap water, deicing salt, and alkaline solutions. The subcritical debonding growth along the epoxy-concrete interface was observed for the first time. Testing results suggest that water, alkaline, and deicing salt solutions can substantially reduce the energy release rate at the crack tip needed to drive the subcritical debonding growth along the epoxy-concrete interface. Under the same mechanical driving energy, water, deicing salt, and alkaline solutions can accelerate the subcritical debonding growth along the epoxy-concrete interface by many times. The major debonding mode of the environment-assisted subcritical debonding in aqueous conditions is mainly adhesive along the epoxy-concrete interface, which is different from the cohesive failure within the concrete.
observed in the critical debonding-based studies. This change of failure mode is caused by two possible reasons: low loading rate in the test and interaction with environmental species.

Environment-assisted subcritical debonding testing provides a new approach to characterizing the long-term durability of the FRP-to-concrete interface. It not only closely simulates the failure occurring in the service-life of the interface, but also accounts for the synergistic interaction between strained adhesion bonds and environmental species at the crack tip, providing new way to delve into the mechanism of the debonding growth along the FRP-to-concrete interface exposed to aggressive environments under service loads.

It should be pointed out that the observation obtained in this study is based on the used specimen, which is mainly mode-I debonding. However, it can be used to assess the long-term durability of the interface since mode-I and model-II debondings are related. As environment-assisted cracking is also referred to as static fatigue, the results of subcritical debonding testing can be used to predict the service life of FRP-concrete interface in the similar fashion as fatigue crack.

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