FRPRCS-14, Belfast - June 2019

Experimental study of the long-term durability of FRP-to-concrete joints subjected to cyclic temperature, moisture and aqueous salt environmental conditions

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Abstract

The debonding resistance of FRP-to-concrete joints is compromised under environmental conditioning. In this paper, an experimental investigation is performed to study the interfacial bond behaviour of the FRP-to-concrete joint under cyclic temperature, moisture and aqueous salt solutions over a long-term duration. Three FRP/adhesive combinations, namely pultruded plate with high viscosity adhesive, pultruded CFRP plate with low viscosity adhesive and CFRP fabric with low viscosity adhesive are tested under direct lap shear. The global load-slip behaviour and extracted local bond stress versus slip parameters are analysed and failure modes are discussed in terms of influence of environmental condition and exposure duration. The results show that the failure mode of specimens under all environmental conditions transitioned from cohesive failure towards interfacial failure regardless of the conditioning regimes.

Keywords: ***Long-term durability; FRP strengthening, aggressive environments; bond stress-slip behaviour***

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Introduction

Bonding fibre-reinforced polymers (FRP) to reinforced concrete (RC) members has become a popular means for enhancing load carrying capacity and extending service life of concrete structures. However, there is uncertainty surrounding the long-term durability of flexurally strengthened concrete members with externally bonded FRP. Over the last few decades, the impact of aggressive environmental conditions on FRP-to-concrete joints has been investigated by several research teams [1-8]. Two main exposure conditions have been typically studied, namely temperature and moisture. Despite numerous experimental investigations conducted to date, there remains a discrepancy in the performance of joints under environmental conditioning. Further, the majority of studies that have investigated the durability of FRP-to-concrete joints have reported only the change of maximum debonding force due to environmental exposure. Very few studies report the full range of the bond stress versus slip relationship. Such a relationship is needed for the development of an interfacial joint degradation model [7,8]. In this paper, an experimental investigation is performed to study the interfacial bond behaviour of the FRP-to-concrete joint under cyclic temperature, moisture and aqueous salt solutions over a long-term duration.

Experimental Program

The direct lap shear experimental program involved three FRP/adhesive combinations, namely pultruded plate with high viscosity adhesive (Plate HV), pultruded CFRP plate with low viscosity adhesive (Plate LV1) and CFRP fabric with low viscosity adhesive (3-ply sheet LV2). In total, 135 single lap shear test (SLS) specimens were cast and tested to failure. Environmental conditioning was carried out for durations of 0, 3 and 12 months. For samples conditioned under cyclic temperature, the temperature was cycled between 10 °C to 40 °C inside a temperature controlled chamber with 50% humidity setting. Exposure to cyclic wet-dry conditions was considered for both potable water and sodium chloride (NaCl) solution (5 % NaCl by weight). Wet-dry cycling involved full-immersion for seven days followed by seven days exposure to ambient laboratory conditions (approximately constant 20°C). At the end of each cycle, the water or salt solution was replaced to ensure the pH remained relatively constant. The debonding resistance of FRP-to-concrete joints is tested via the single lap shear (SLS) test set. FRP plates/sheet were bonded to the concrete substrate with a bonded length of 220mm and unbonded length of 40mm at the loaded end to avoid stress concentrations during testing. Normal grade concrete with a target strength of 25MPa was used for the concrete substrate. The adhesives used were two-part epoxies, consisting of bonding and hardener components. One epoxy was of high viscosity (HV) while two were of low viscosity (LV1, LV2). The mechanical properties for tensile strength, elastic modulus and elongation at failure of the pultruded plate and wet lay-up fabric were 2,590MPa, 177GPa, 1.46%, and 727MPa, 57GPa and 1.28% respectively.

Results and Discussion

Failure modes

Considering the failure modes, for the control specimens, failure occurred within the concrete substrate (cohesive failure) with a negligible portion of the plate undergoing debonding between the adhesive layer and concrete substrate (interfacial failure). In order to determine the change in failure mode from cohesive to interfacial failure, an image processing tool was used to determine the quantity of the debonded plate without concrete attached. As seen in figure 1, the area of interfacial failure, that is the proportion concrete substrate no longer attached to the FRP plate at debonding, increased with environmental exposure time. From the analysis of the quantity of the debonded plate without concrete attached the results show that the failure mode of specimens under all environmental conditions transitioned from cohesive failure towards interfacial failure regardless of the conditioning regimes. However, it was found that for the cyclic thermal condition the transition from cohesive failure to interfacial failure is due the reduction of the adhesive strength, whereas for cyclic wet-dry the change is in failure mode is due to the combination of the lowered adhesive strength and enhanced concrete strength due to moisture.

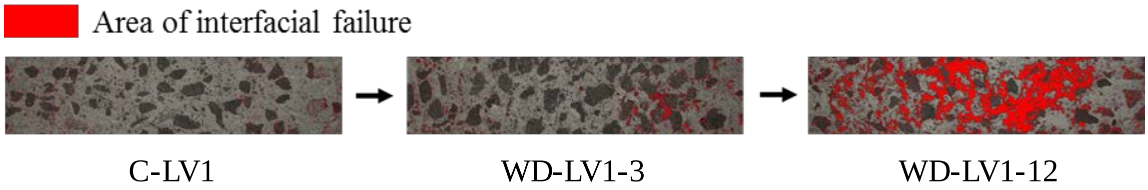

Figure 1: Typical change of interfacial failure area at different exposure durations (C-control, WD- wet-dry condition)

Global load-slip behaviour (P-Δ curves)

The global load-slip (P-Δ) behaviour is an essential experimental output, as it is used to extract the local bond stress versus slip properties. From the load-slip curve, two key points exist, namely, the maximum force (P_{max}) and the corresponding loaded end slip (S_{max}). Importantly, it should be noted that the reported P_{max} does not always correlate directly to the commencement of global debonding, that is, the initial debonding load (P_{ini}). Based on the measured P-Δ curves, it was observed that under ambient temperature conditions no change in behaviour was observed after 12 months. On the contrary, the influence of the environmental conditions, especially the wet-dry conditions under water and 5% salt solution, exert significant influence on the concrete prisms in terms of the debonding initiation capacity and initial stiffness of the composite systems. The maximum increase in P_{ini} in wet-dry in potable water and 5% salt solution was approximately 25% for the HV series. However, all the samples under thermal conditioning experienced a detrimental effect on $P_{ini.}$ The most severe degradation was found on the HV series which was reduced to approximately 85% of its original Pini due to the presence of adhesive debonding from FRP plate. Figure 2 presents the load versus slip results for control samples compared to cyclic wet-dry in water for the 3 types of FRP adhesive combinations.

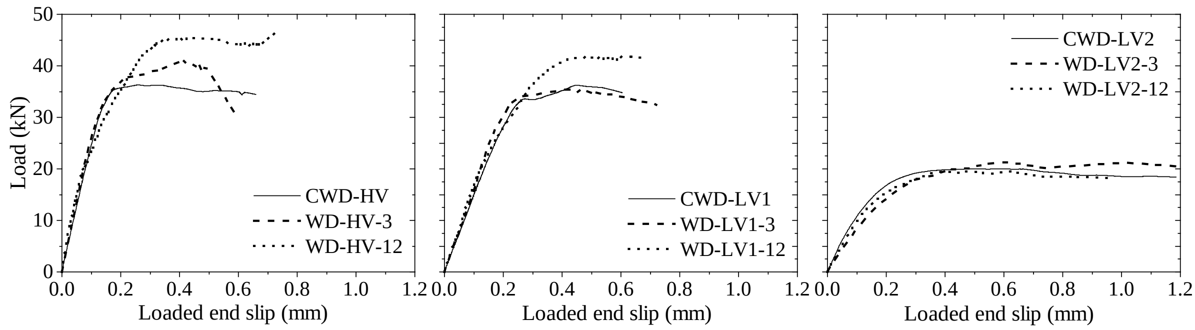

Figure: 2 Average global load versus displacement curves of control samples compared to cyclic wet-dry in water.

Bond stress-slip model

An inverse analysis technique is used to extract the local bond slip (τ-δ) properties from the measured P-Δ response. A specific shape of the bond slip relationship is first assumed – in this case the tri-linear relationship which is defined by the peak bond stress τ_{max} and corresponding slip δ_1 and the frictional stress τ_f and slip at the commencement of the frictional branch $\delta_{ini.}$. Figure 3 depicts an example of the variation of the bond stress-slip relationship after exposure for cyclic temperature, (d-f) cyclic wet-dry in water. The analysis of results revealed two main features: 1) the overall maximum bond stress deteriorates after the exposure regardless of the type of condition and sample series, and 2) the corresponding slip (δ_{ini}) at debonding initiation point increased after the exposures.

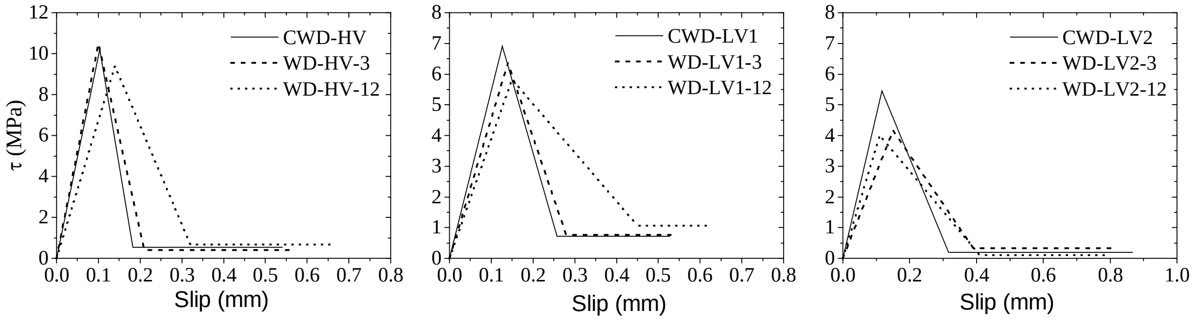

Figure 3 Variation of the bond stress-slip relationship after exposure to cyclic wet-dry in water

Conclusions

In this paper the global load slip response and extracted local bond stress versus slip parameters are analysed and failure modes are discussed. The results show that the failure mode of specimens under all environmental conditions transitioned from cohesive failure towards interfacial failure regardless of the conditioning regimes. However, it was found that for the cyclic thermal condition the transition from cohesive failure to interfacial failure is due the reduction of the adhesive strength, whereas for cyclic wet-dry the change in failure mode is due to the combination of the lowered adhesive strength and enhanced concrete strength due to moisture.

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