Investigation on long-term durability of FRP-concrete bond interfaces under moisture conditions

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Introduction

The civil infrastructures around the world are deteriorating faster due to various external environmental exposures over the period of their service lives. In addition, increase in traffic loads, change in design codes and service requirements etc. have felt great necessity to strengthen or rehabilitate these structures to ensure safety and durability. Fiber reinforced polymer (FRP) composites have become a good option to strengthen or rehabilitate such civil infrastructures for past few decades due to various advantages such as high-strength and stiffness, light weight, high durability, ease for construction etc. Further, wide applications of these materials in strengthening of structural members; beams, slabs, bridge deck, column have resulted in extensive studies and thus development of numerous design codes and guidelines/recommendations. Despite all of these efforts, environmental degradation has been neglected or not properly addressed in these standards. The environmental deterioration factor currently being proposed by few of the guidelines does not extensively cover deteriorations in bond properties due to various environmental conditions under long-term due to insufficient research in the field. Therefore, the predicted performances of these structures does not match with their behavior in the real scenario. Realizing the importance of durability issues in the FRP composites, recently ACI committee has been developing a guide to accelerated conditioning protocols for durability assessment of internal and external fiber reinforced polymer (FRP) reinforcement for concrete [9]. However, there are still necessities to identify all the severe environmental conditions which can potentially affect the FRP composites and its bond action, determine the deterioration mechanisms, evaluate the long-term durability of the material and bond properties by developing standardized durability testing methods and predict the service life of the structures strengthened or rehabilitated with FRPs.

During the service life of the structures, some of the common severe environments which can affect the durability of the FRP bonded concrete structures are moisture, high temperature, freeze-thaw cycles, wet-dry cycles, UV radiation etc. and their synergies. In order to study the above mentioned durability related issues for the FRP bonded concrete structures, researchers around the world have been using accelerated laboratory ageing method with wide variety of testing methods, materials and exposure durations. Due to lack of guidelines to perform such tests and diversity in availability of materials used, there is no uniformity in the results and the degree of its effect. Therefore, understanding the bond mechanism and effects of all of those factors in the bond performance is essential to enhance the interfacial behavior to ensure safe, economic and durable design of the structures.

Research Objectives

In the present study an attempt has been made to address the influence of one of the major durability issues that a structure may face in moist condition such as marine environment.

The main objective of the research is to address and clarify one of the key environmental related deterioration mechanisms in the FRP strengthened concrete structures. The more specific objectives are listed as follows:

- To evaluate the long-term influence of continuous water immersion on the mechanical and thermal properties of the epoxy resins used in FRP composite systems.
- To clarify the moisture related deterioration mechanism at the FRP-concrete bond interfaces as a result of continuous water immersion.
- To compare the durability performances of several different commercial FRP systems produced by well-known manufactures around the world to demonstrate the importance of material selection in governing the degree of environmental effects due to moisture.
- To investigate the influence of several key parameters such as primer, concrete strength, surface roughness, exposure duration, testing conditions etc. in order to clarify their roles on durability of FRP and concrete bonds.
- To identify relationship between environmental effects on the mechanical properties of the materials and their bond behavior along with their failure modes to explain the mechanisms of deteriorations at the interfaces.
- To propose bond deterioration factor applicable in the moisture condition along with the simplified bond-slip models for the FRP-concrete interfaces incorporating the moisture effects.
Dissertation Overview

This dissertation is organized into six chapters and an appendix which are described briefly as follows.

Chapter one gives brief idea on the research background, research framework, objectives, and the organization of the dissertation.

Chapter two presents comprehensive literature reviews on the relevant topics of FRP composites and its adhesion mechanisms with concrete. This chapter also focuses on previous studies conducted on environmental related degradations of FRP materials and its bond behavior with concrete.

Chapter three presents comparison of shear and tension bond performances of 6 commercial FRP systems subjected to water immersion for the maximum period of 18 months. This chapter tries to explain the moisture deterioration mechanism based on the comparison of the bond strengths and analysis of the failure modes. The variation of durability outcomes based on the selection of the materials for investigation is also included.

Chapter four tries to explain the necessity of proper surface preparation method and its relationship with the durability of the FRP-concrete bond interfaces under moisture conditions. The chapter mainly focuses on different effect of moisture in high-strength concrete substrate with sufficient and insufficient surface roughness profiles.

Chapter five gives overall formulation of a simple analytical bond stress-slip relationship in moisture conditions based on the strain results obtained from single-lap shear bond tests. The information obtained from the experimental results is used to propose analytical constitutive models taking the effects of moisture conditions.

Chapter six summarizes all the conclusions obtained from my work along with some recommendation for future work.

Appendix includes some of the initial experimentation results on the durability of FRP-concrete bonds under elevated temperature condition.

Brief discussion of the results

This research includes results of extensive experimentation performed to understand the behavior of moisture environmental conditions on material and bond properties between FRP and concrete.

The material properties and its durability characteristics under moisture conditions are determined in 8 epoxy resins and concrete for the maximum period of 18 months at 20°C. The results of immersion in water revealed that the mechanical properties of most of the epoxy resins degraded after exposure indicating some harmful effects of water. The average reduction in the tensile strength of the resins was in the range of 11% to 38% after exposure. These degradations are usually associated with the quantity of the absorbed water by epoxy resins but, no such relationship was found between them in the study. The absorption by the resin specimens varied from 0.71% to 2.65% after 18 months of immersion, in which, the higher water absorption did not necessarily yield greater deterioration. In fact, highest reduction in the tensile strength occurred in the cases when the water absorption was the least, whereas no changes occurred in some cases despite over 2% of water absorption. This concludes that the quantity of water absorption cannot solely explain the degradation mechanism of the epoxy resins but more depended on the type of epoxy resins. Nonetheless, in contrast to the behavior of the epoxy resins, the concrete compressive strength remained unaffected throughout the exposure durations.

After confirming the material behavior, the effect of water was evaluated by the assessment of the shear and tensile bond interfaces under moisture conditions using 6 commonly used commercial FRP systems in various parts of the world. In laboratory water immersion test for the maximum period of 18 months, two of systems showed 25% and 16% reductions in average shear bond strengths, while the remaining systems showed either improvement or insignificant effect. Two of the most affected systems consistently showed bond failures at the adhesion interface between resin and concrete, while in other cases, the failures were either concrete cohesion or mixed failure of concrete cohesion and resin-concrete interface failure. Observation of the failure modes suggests that, the durability against water related deteriorations are worst in cases when the adhesion bonds between concrete and resin interface are weaker than the cohesive bonds of the adjacent layers. This indicates the importance of strong adhesion bond necessary at the interface that can be achieved by proper surface roughness of substrate concrete and selection of the suitable resins with good adhesion strength with the concrete. Unlike shear bond behavior, failures were governed by the concrete cohesion strength in almost all the cases when the bond interfaces were investigated by the direct pull-off test. Despite the large scatter in the data, average tensile bond strength after exposure was significantly reduced about 19% to 41% depending on the FRP systems. As the properties of the concrete remained unchanged throughout the exposure duration, it can be concluded that loss in tensile bond strength after the immersion is due to adverse effects of water on the bond properties. However, mechanism of deterioration in the tensile bond behavior remains unknown due to limited information generated through the test method itself.

The unique relationship observed between the deterioration in the shear bond strength and the adhesion failure modes due to moisture condition was further confirmed in the high-strength substrate case. With the main purpose of generating both sufficient and insufficient concrete surface roughness profiles, disk-grinding and sand-blasting methods were adopted while preparing the shear bond specimens. The average arithmetic roughness was determined as 0.11 mm and 0.54 mm respectively in disk-grinded and sand-blasting method. The comparison of the results after water immersion test at 20 °C for 12 months duration confirms that the average bond strength reduction was around 30% for disk-grinded case whereas, the average bond strength reduction was only about 7% in case of sand-blasted specimens. As expected, failure mode changed to adhesion from mixed after exposure in case of insufficient roughness due to disk-grinded case but the mixed failure mode was retained in case of sand-blasted case when the surface roughness was sufficient. The results were further compared in case on normal-strength substrate with concrete surface roughness profile similar to high-strength disk-grinded case. The bond strength reduction...
was below 7% and the failure modes were mostly mixed modes. Despite the use of same FRP materials, such significant differences in the overall performances show that surface roughness plays a key role in the overall durability of the FRP-concrete bond interfaces. The bond mechanism at the interface between the FRP and concrete is governed by mechanical and chemical bonds. The chemical bonds are the result of interaction between concrete and resin whereas, the mechanical bond is due to the friction and interlocking action due to concrete surface roughness. The water mainly deteriorates the chemical bonds at the interface, but presence of strong mechanical bonds as a result of proper surface preparation could prevent greater loss in bond strength. The study also confirms that the level of sufficient surface roughness requirement varies based on the strength of the concrete.

Finally, for the prediction of service life of the structure strengthened with FRPs in moisture conditions, the interfacial bond-slip models are proposed. Dai’s simple method of determining the bond-slip models which is applicable only for the ambient condition was modified to incorporate the moisture conditions. The two key parameters in the model which are interfacial fracture energy (Gf) and ductility index (B) were determined from the experimental results of single lap shear test conducted using six different FRP systems until the maximum exposure period of 18 months. Based on the responses to moisture, the six FRP systems investigated were grouped in to two categories as wet-layup and pre-impregnated systems. Wet-layup systems showed some adverse effects of moisture whereas the pre-impregnated systems showed positive effect. The interfacial fracture energy (Gf) and ductility index (B) were related separately with the exposure duration to incorporate the moisture related effects. The predicted ultimate loads compared with the experimental loads at different exposure duration show fairly good agreement.

Conclusions

The research findings have recognized moisture conditions as one of the most important factors which needs to be considered for the environmental durability design of the structures. However, it was also confirmed that the degree of such effect varies mainly with the selection of the FRP strengthening materials. From the current set of systems, the wet-layup systems performed poorly than the factory impregnated systems. In response to moisture exposure, the shear bond behavior either showed no effect, positive effect or significant reductions in the bond strength depending on the FRP systems. As an effect of water immersion, transition of failure modes occurred from concrete cohesion to mixed mode or interface failure but significant reductions in bond strength were observed only in cases of complete interface failures. The study also identified the role of surface preparation in governing the failure modes and its importance in determining the environmental durability. The degree of roughness greatly affects the durability of bond between high-strength concrete and FRP. There was significant loss in bond strength after the exposure for the disk-grinded cases whereas, such losses were much lower in sand-blasted cases. Presence of good mechanical bonds due to sufficient surface roughness could retain the bond strength despite some destruction of chemical bonds at the interface by water. Transition of failure modes to adhesion at the interface after exposure seems to have greater effect on the bond strength than other failure modes. By increasing the surface roughness, adverse effects of the moisture conditions can be minimized at the bond interfaces. Finally, the study also proposes the bond-slip models with the consideration of the moist environmental exposure and its duration.