Construction and Building Materials 70 (2014) 399–409

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Bond strength of different strengthening systems – Concrete elements under freeze–thaw cycles and salt water immersion exposure

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HIGHLIGHTS

- We study the effect of environmental exposure for different CFRP strengthening systems.
- A total of thirty-six specimens were prepared.
- Results showed a decrease in ultimate bond strength for sheets with salt water.
- A decrease in bond strength for sheet and plate with freeze–thaw cycles was recorded.
- No change in bond strength for NSM FRP rod strengthened specimens after exposure.

ARTICLE INFO

Article history:
Received 7 November 2013
Received in revised form 5 July 2014
Accepted 16 July 2014
Available online 24 August 2014

Keywords:
Durability
Strengthening
FRP
Bond
Freeze–thaw
Immersion

ABSTRACT

The long-term durability of fibre reinforced polymer (FRP) composites is often stated as being the main reason for the use of these materials. Indeed, structures externally or Near Surface Mounted (NSM) reinforced with Carbon Fibre Reinforcement Polymer CFRP are often in contact with temperature cycles and salt water immersion and other environmental conditions that reduce the expected durability of the system. Bond degradation is a frequent cause of premature failure of structural elements and environmental conditions are known to relate to such failures. The purpose of this study is to investigate the effect of environmental exposure on the bond for different CFRP strengthening systems. Bending tests were conducted to evaluate the bond with and without environmental exposure. The specimens were strengthened with CFRP sheets, CFRP plates and NSM CFRP rods embedded in two filling materials: epoxy resin and mortar. Then, they were exposed to up to 300 freeze–thaw cycles. One freeze–thaw cycle consisted of four stages according to ASTM or immersed in 3.5% salted tap water. A total of thirty-six specimens were prepared for this purpose. Results showed a decrease in ultimate bond strength for specimens strengthened by CFRP sheets that were immersed in salt water for 120 days, while a reduction was shown for CFRP sheet and plate bonded specimens that were subjected to 300 freeze–thaw cycles. Exposing NSM CFRP rod strengthened specimens, embedded in resin or mortar, to freeze–thaw cycles or to immersion in salt water does not affect the bond strength.

1. Introduction

The need to strengthen civil engineering structures is becoming a serious problem for facilities owners. Composite materials offer interesting possibilities due to their high tensile strength for a low density, their absence of sensitivity to corrosion and their long fatigue life. Under-performing structures are usually strengthened by bonding FRP sheets or plates onto the external concrete surface of the structural members. But, sometimes, this type of strengthening may be difficult or impossible to set up. For example, cantilever tension components of structural members supporting hot bituminous mix are subjected to high temperatures which can affect the adhesive layer and so damage the bond between the concrete and the FRP sheet. In the presence of longitudinal concrete cracks due to steel reinforcement corrosion, the external concrete surface is no longer suitable for the bonding of FRP sheets. For these particular cases, the Near-Surface Mounted reinforcement (NSM) technique, where a composite rod is bonded in a pre-sawn groove in the concrete cover, can be used. This technique has attracted extensive research in recent years [1–6].

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http://dx.doi.org/10.1016/j.conbuildmat.2014.07.039
0950-0618/

The long-term durability of fibre reinforced polymer (FRP) composites is often stated as being the main reason for the use of these materials. However, their durability depends on the choice of constituent materials, method and conditions of processing, and surrounding environmental conditions throughout their service lives. Although previous studies have demonstrated the merits of using FRP composites for strengthening concrete beams, a number of issues related to the lack of a clear understanding of the long-term performance of FRP-based repairs are hampering their widespread implementation. One of the primary concerns for the application of FRP to civil infrastructure repair is the long-term behavior of the bond between the FRP composite and the existing structure under harsh environmental conditions such as freeze–thaw cycles or salt water immersion.

Although the freeze–thaw durability of NSM strengthened concrete has yet to be studied, several studies have examined the performance of externally bonded FRP strengthened reinforced concrete members after exposure to environmental (freeze–thaw) cycling.

Results from tests on pull-off specimens conducted by Green [7] have suggested that freeze–thaw cycling does not reduce the ultimate bond strength of the joint between concrete and CFRP plates. It was noted, however, that the failure mode shifted from failure in the concrete in specimens without environmental cycling, to failure in the adhesive and even into the CFRP plate in some cases, suggesting the adhesive is slightly affected by freeze–thaw action. Colombi et al [8] investigated the effects of different reinforcing lengths (100 mm and 400 mm) and types (strips and wraps) and of 100 and 200 freeze–thaw cycles from −18 to +4 °C for a duration of about 5 h each on the concrete strength and on the bonding between FRP and concrete. They concluded that freeze–thaw cycles did not seem to noticeably affect the value of the debonding force in conditioned specimens compared to the unconditioned ones.

Studies conducted by Silva and Biscaia [9] with pull-out and bending tests showed the effects of cycles of salt fog, temperature and moisture as well as immersion in salt water on the bending response of beams externally reinforced with GFRP or CFRP, especially on bonds between FRP reinforcement and concrete. Temperature cycles (−10–10 °C) and moisture cycles were associated with failure in the concrete substrate, while failure associated with salt fog cycles originated at the concrete–adhesive interface. Results showed that, immersion in salt water and salt fog caused considerable degradation of bonds between the GFRP strips and concrete. However, immersion did not lower the load carrying capacity of beams, unlike temperature cycles that caused considerable loss. Specimens subjected to freeze–thaw cycles showed a reduction in the load carrying capacity of beams while failure was found in the concrete substrate. Toutanji and Ortiz [10] tested concrete beams (50 mm × 50 mm × 300 mm), in wet–dry environments, which were strengthened with GFRP and CFRP plates bonded using different types of epoxy. A wet–dry cycle involved immersion of the samples in a 3.5% salt solution for 4 h followed by 2 h of drying at 35 °C and 90% relative humidity (RH). When tested in flexure after 300 wet–dry cycles, all the beams failed due to debonding of the FRP plates within 3–33% of the unexposed strength. However, the load and deflection for CFRP strengthened beams were higher than the GFRP strengthened beams. It was also reported in the study that the type of epoxy could be a critical factor concerning the long-term durability of the strengthened beams. Toutanji and El-Korchi [11] presented the results of an experimental study on the tensile performance of cement-based specimens wrapped with FRP sheets subjected to 300 freeze–thaw cycles. Ultimate strength and load–extension behavior were obtained and then compared to the performance of unconditioned samples; specimens wrapped with CFRPs experienced no significant reduction in strength due to exposure. Qiao and Xu [12] used notched, three-point bending tests to characterize temperature effects on the Mode-I fracture interfaces in concrete beams strengthened using CFRPs. Specimens were frozen for several hours and the surface near the bonded interface was enclosed in an aluminium insulating foil to maintain the temperature during testing. Chajes et al. [13] investigated RC beams (38 mm wide, 28.6 mm high, and 330 mm long) in both wet–dry and freeze–thaw environments with AFRP, GFRP and CFRP sheets bonded to the tension face of the beams. The strength losses after 100 freeze–thaw cycles were observed to be 9%, 27% and 21% for the AFRP, GFRP and CFRP strengthened beams, respectively. This study indicates that the long-term performance of CFRP strengthened beams is better than AFRP and GFRP strengthened specimens. It also indicates that a wet–dry environment yielded more degradation in the strength of beams than a freeze–thaw environment. Kootsookos et al. [14] studied CFRP and GFRP, with polyester and vinylester matrices, immersed in sea water at a temperature of 30 °C and showed that the carbon composites displayed better durability. The moisture absorbed by CFRP composites is lower compared with GFRP, the flexural properties of the glass composites declining slowly over long periods in seawater. Chajes et al. [15] showed a 36% decrease in ultimate strength for GFRP retrofitted specimens that were subjected to 100 wet/dry cycles, while a 19% reduction was shown for CFRP bonded specimens. Toutanji and Gomez [16] observed a strength reduction of up to 33% on specimens made of different epoxies and subjected to 300 wet/dry cycles in salt water. Failure was reported as a debonding mode that generally took place near the FRP/concrete interface. Karbhari and Zhao [17] investigated the short-term effects of four environment exposure conditions on the structural response of concrete beams strengthened by using FRPs, focusing on the concrete cover below the level of the reinforcing steel, i.e., the weakest link of the system. Specimens subject to the freeze–thaw exposure between −23 °C and 15.5 °C every 24 h failed in a more brittle mode and with lower failure levels. A 40% reduction in bending capacity was noticed after 120 days of moisture exposure.

Although many research studies have been conducted on externally bonded FRP specimens to investigate there durability, as previously described, the experimental results cannot be generalized on all externally bonded FRP structures. Different researchers used different size beams in experiments while relying on the observed ultimate load capacity rather than the fracture parameters. This might be one of the possible causes for discrepancies in observations reported in the literature on the influence of freeze–thaw cycling [18].

Although the durability of externally bonded FRP structures against potential damage caused by freeze–thaw cycling or salt water immersion has been largely studied, near surface mounted FRP has yet to be examined in this context. Research into the specific issue of freeze–thaw durability for NSM strengthening applications is thus warranted. The purpose of this study is to investigate the effect of environmental exposure on the bond for different CFRP strengthening systems. Bending tests were conducted to evaluate the bond with and without environmental exposure. The specimens were strengthened with CFRP sheets, CFRP plates and NSM CFRP rods embedded in two filling materials: epoxy resin and mortar. Then, they were exposed to up to 300 freeze–thaw cycles. One freeze–thaw cycle consisted of four stages according to ASTM or immersed in 3.5% salted tap water. A total of thirty-six specimens were prepared for this purpose.

2. Experimental program

2.1. Materials

For the NSM technique, one type of FRP rod was used: carbon-epoxy pultruded FRP with a diameter of 10 mm. The modulus of elasticity and tensile strength of the CFRP rods were determined by laboratory testing. They were 146 GPa and