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The effects of accelerated Freeze-Thaw conditioning on CFRP strengthened concrete with pre-existing bond defects

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HIGHLIGHTS

- Performance of conditioned specimens with defects compare to specimens without.
- Defects size standards are conservative even for freeze-thaw conditioned specimens.
- Pulse phase thermography is successful for non-destructive evaluation of bond.
- Bond degradation is exacerbated by certain sizes and locations of bond defects.

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ABSTRACT

Despite demonstrated success in both the laboratory and in the field, significant questions remain unanswered regarding the durability of Carbon Fiber Reinforced Polymer (CFRP) for strengthened concrete members. Little is known about the impact of pre-existing bond defects when subjected to harsh environmental conditions. The results from a study observing the performance of 18 small-scale CFRP-to-concrete pull test specimens is presented herein. Half of the sample set was stored in ambient laboratory conditions while the remaining sample set was subjected to 50 freeze–thaw cycles. Repeated for each condition were 3 specimens prepared without any intentional bond defects and 3 specimens containing 645 mm^2 Teflon inserts, for comparison purposes. It was found that, not only did the freeze–thaw conditioning reduce the debonding capacity of the externally bonded CFRP, but that the presence of defects resulted in a greater reduction in debonding capacity following the environmental conditioning, when compared to specimens exposed to ambient conditions only. Nondestructive evaluation of the bonded interface was also performed by using Pulse Phase Thermography (PPT).

1. Introduction

1.1. Durability of FRP strengthened concrete

A sizable body of knowledge exists on the durability of externally bonded fiber-reinforced polymer (FRP) strengthened concrete. For consistency in the manner in which specimens are experimentally conditioned in laboratory environments, there has been effort to put forth standard procedures and guidelines for conducting accelerated conditioning protocols for durability assessment. In 2007, ICC Evaluation Service, LLC. established an acceptance criterion for concrete and masonry using externally bonded FRP, known as the AC125 [1]. This criterion has been applied to several commercially available FRP composite products and has served as a useful reference for many years. However, for research purposes it offered limited description of each test with much interpretation left up to the individual investigator.

More recently, the American Concrete Institute (ACI) Committee 440 published a detailed guide for conducting accelerated conditioning protocols for durability assessment of internal and external FRP reinforcement [2]. This document describes the environment and stress to which a specimen should be exposed for each test, and the duration for which to expose them. It even specifies the ambient laboratory conditions in which control specimens are to be stored.

With only a few conditioning protocols specified therein, the authors of [2] acknowledged the need to establish procedures that examine additional environmental exposures. The necessity of

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these documents rest on the fact that there is general agreement that the strength of members repaired by FRP is compromised by extended exposure to harsh environments [3]. A wide range of these environments, and their synergistic effects [4] have been simulated in several research laboratories over the years however, without a consistent approach it is difficult to perform a comparative analysis across studies.

1.2. Freeze-Thaw durability studies

Freeze-Thaw, for instance, is a type of specimen conditioning aimed at mimicking real-world fluctuations in temperature, and humidity (i.e. moisture), but variations have been seen in the application and results of this conditioning method. Yen and Wu examined the shear behavior of bond interface of concrete strengthened with Carbon FRP (CFRP) [5]. In their study, 17, 33, 50, or 67 cycles from 4 °C to −18 °C at 4 h per cycle was applied to specimens placed in either salt water (4% NaCl) or tap water and the CFRP facing downward, while approximately 6 mm of concrete was submerged. This was determined to cause a reduction in not only bond strength, but bond stiffness, interfacial fracture energy and maximum slip. The effects also became more pronounced with increase in the number of freeze-thaw cycles.

Similar degradation has been observed in constituent materials as well. In 2011, Shi et al. concrete was seen to retain up to 80% of its original strength at 100 and 200 freeze-thaw cycles, but only retained 50% after 300 cycles. Epoxy resin coupon specimens retained approximately 75% and 70%, respectively, of their ultimate tensile strength and ultimate strain after 300 cycles [6]. Basalt FRP was the main focus in this study, as their coupon specimens were found to only lose an average of approximately 5% of its strain capacity after 300 cycles. This reduction indicated a higher relative resistance than similar experiments with CFRP [7] and Glass FRP [8] that produced greater reductions in capacity after fewer freeze-thaw cycles; 200 and 100 respectively.

In a recent review published by Zeng-Zhu Zhu et al., entitled "Progress in Durability Study of FRP Materials", the authors compared and analyzed several durability studies of FRP, including freeze–thaw cycles along with humidity, high temperature, wet–dry cycles, ultraviolet radiation exposure, and other natural exposures [9]. While the intent of this publication was to confirm the superior corrosion resistance of FRP material, there was also notable conflict in conclusions made regarding the extent of degradation expected as details of the applied conditioning protocols varied from study to study.

1.3. FRP strengthened concrete with bond defects

While standard accelerated conditioning methods are of concern, it is upon the presence of defects, and the determination of their criticality, that inspectors have based the quality assurance of strengthening systems in the field. Debonded regions, caused either by environmental exposure or manufactured error, of themselves have been widely shown to reduce capacity with presence with a certain size and location [10–12].

To establish an acceptance criterion, published guides for the design of externally bond FRP have set forth threshold limits for defect sizes that are allowed to go unrepaired in an FRP strengthening system. ACI 440 states that "Defects less than 2 in^2 (1290 mm^2) each are permissible as long as the defected area is less than 5% of the total area and there are no more than 10 such defects per 10 ft^2 (0.93 m^2)" [13]. In more conservative measures, the National Cooperative Highway Research Program (NCHRP) Report 514 declares small entrapped voids or surface discontinuities no larger than 6.4 mm (¼ in.) in diameter shall not be considered defects and require no corrective action unless they occur next to edges or when there are more than five such defects in an area of 0.9 m^2 (10 ft^2)" [14]. This document went on to definitively state "*significant research is needed to determine critical defects… and the effect of such defects on the long-term performance of FRP repair systems.*"

1.4. Durability of FRP strengthened concrete with bond defects

While past experiments have shown defects of the allowable size to have very little, if any, impact on the performance of bonded FRP systems, what remains unexamined is their impact on performance when coupled with experiencing harsh environments. In most durability studies, conditioning is carried out with the implied assumption that the bond interface is properly prepared, absent of any known debonded areas. This differs from how existing FRP strengthened concrete members likely experience such environments in the field.

The durability of externally bonded FRP strengthened concrete with preexisting defects is of interest because of the possibility that bond defects, of allowable sizes, grow and exacerbate nominal degradation. Since CFRP is the most common material used in FRP strengthening of concrete, it is the primary focus of this study. However, what is novel herein is examination of bond defects, before and after freeze-thaw conditioning, using special nondestructive (NDE) evaluation to assess the subsurface defect areas [15]. This assessment was also followed by the mechanical single-lap shear testing to measure change in capacity due to freeze–thaw degradation.

2. Experimental program

For the experimental program, 24 concrete prisms (150 mm × 150 mm × 250 mm) were cast along with standard companion cylinders (100 mm diameter × 200 mm height) using a concrete mix with target design strength of 34.5 MPa. Various defect sizes and CFRP strengthening schemes were considered in effort to optimize use of the number of available specimens. The rationale for the selected configurations was such that the area of debonding should be comparable to thresholds permitted by ACI 440.2 [4]. Also, there was a necessity to keep the width of the CFRP (2 in) within the size restraints of the testing apparatus. Furthermore, the chosen bond length was necessary to achieve maximum debonding resistance, as determined by Chen and Teng [16]. The resulting test matrix can be seen in Table 1. The items found under the heading "Reference Notation" references the defect size (e.g. "ND" meaning no defect, "1D" meaning 645 mm^2 (1 in^2) defect, and "2D" meaning 1290 mm^2 (2 in^2) defect), defect location (, and environmental conditioning prior to pull testing.

Fig. 1 shows a schematic of the specimen designed for this study which includes the concrete, CFRP and a manufactured defect. Concrete curing took place for 28 days (consistent with common traditional curing time), and cylinders were tested in compression to provide a baseline with which to determine any strength changes dues to future conditioning. The samples yielded an average compressive strength of f'_c = 35.2 MPa. Compression tests were also done at the time of CFRP strengthened concrete pull testing to compare with those conditioned in the freeze-thaw environment. These results can be seen in Table 2.

A thorough roughening of the concrete surface was required during fabrication to achieve the best substrate for adhesion of the FRP; per manufacturer's recommendations. To achieve such, two methods were used to prepare the 150 mm × 250 mm side of each block designated for strengthening. First, a masonry grinder was used to remove surface paste and small pieces of exposed aggregate. Secondly a pneumatic needle gun was used to provide additional roughness. What resulted was a surface well condi-