Construction and Building Materials 122 (2016) 525–536

Contents lists available at ScienceDirect

Construction and Building Materials

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

Comparison of laboratory and field environmental conditioning on FRP-concrete bond durability

Jovan Tatar *, H.R. Hamilton

University of Florida, Department of Civil and Coastal Engineering, 365 Weil Hall, Gainesville, FL 32611, USA

HIGHLIGHTS

- CFRP-concrete bond was evaluated following field and accelerated conditioning (AC).
- Direct tension pull-off and notched three-point bending tests were utilized to test the bond.
- AC resulted in degradation of bond properties.
- Some field conditioned samples experienced slight degradation between 6 and 18 months.
- ACP at 60 °C may result in a pessimistic estimate of bond durability for short service life.

ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form 3 June 2016
Accepted 14 June 2016

Keywords:
FRP
Concrete
Adhesive
Epoxy
Bond
Durability
Field
Accelerated conditioning
Degradation
Bridge engineering

ABSTRACT

Assessment of bonded FRP durability by means of accelerated conditioning is sometimes thought to be too harsh compared to ambient environmental conditions; consequently, this may result in underestimate of the actual durability. To assess the efficacy of utilizing accelerated conditioning protocols (ACP) for FRP-concrete bond durability testing, results from laboratory and field conditions (Sunshine Skyway Bridge in Tampa, FL) were compared. Direct tension pull-off test patches were applied to the approach span girders and notched beam three-point bending test specimens were placed on the dolphins adjacent to the bridge. These results were compared to notched beam specimens exposed to ACP. Testing indicated that characteristics of the FRP-concrete bond failure modes changed in some of the field samples within 6 months of field exposure, which may be an indication of durability problems. Moreover, ACP under elevated temperatures (60 °C) of notched three-point bending test resulted in a 36% loss of strength compared to no strength degradation after 18 months of field conditioning.

1. Introduction

FRP composites have been used extensively in the past 20 years to retrofit bridges in need of repair or strengthening. The severity of the environmental conditions experienced by externally bonded FRP reinforcement in such applications can affect the durability of the adhesive joint between FRP and concrete. Accelerated conditioning protocols (ACP) are commonly used to assess the durability by accelerating the aging process of the bimaterial system in a laboratory setting; the applicability and relationship of ACP to in-situ, real-time environmental conditions, however, is not fully understood.

This paper presents a study that compares the effect of ACP to that of real-time exposure on the FRP bond properties. The bond properties were tested using notched three-point bending and direct tension pull-off test methods. Field conditioning was conducted on the Sunshine Skyway Bridge in Tampa, FL, which had recently been repaired with a commercially available wet layup bonded FRP composite system. This same system was applied to small beam specimens, which were then placed on the bridge dolphins. Companion beam specimens were also subjected to accelerated conditioning protocols (ACP) for comparison.

2. Literature review

Multiple authors have reported results of durability tests on FRP-concrete bond, concentrating primarily on the effects of dry

* Corresponding author.
E-mail addresses: jtatar@ufl.edu (J. Tatar), hrh@ce.ufl.edu (H.R. Hamilton).

http://dx.doi.org/10.1016/j.conbuildmat.2016.06.074
0950-0618/

heat [17], moisture [9], salt and moisture [18], freeze-thaw cycles [13], and alkaline environments [23], among others. The agreement is mutual, however, that the most critical environment for FRP-concrete bonded joints is moisture. Choice of conditioning temperature in hygrothermal environments is the most challenging aspect of selecting an appropriate accelerated conditioning protocol; accelerating degradation by using temperatures higher than the glass transition temperature (T_g) of the epoxy adhesive used to form the composite and/or the bond between composite and concrete substrate can introduce degradation mechanisms that may not accurately represent those occurring in the field under real time.

AASHTO [4], International Code Council Evaluation Service (ICC-ES) [16], and ACI [7], however, recommend multiple conditioning protocols that specify a temperature of 60 °C. While this temperature can exceed the T_g of the composite-saturating resin or adhesive, conditioning at temperatures slightly higher than T_g is thought to be beneficial to establishing a lower bound estimate of residual strength. On the other hand, ACI [8] prescribes a conditioning temperature of 50 °C (slightly lower than the T_g of most commercial epoxies) to avoid introducing the glass transition during the conditioning. While convenient, it is not clear whether testing at temperatures higher than T_g is justified. The research reported in this paper compares the field durability data to those obtained in the laboratory and draws conclusions based on the findings.

3. Experimental procedures

Field exposure and ACP were compared by measuring the bond strength retention using the direct tension pull-off test method, and the notched beam three-point bending test method, which are detailed in the following sections.

3.1. Three-point bending test method

The design and test procedures followed for three-point bending test were implemented from Gartner et al. [12]. Concrete specimens had a square cross section measuring 10 cm by 10 cm and were 35 cm long (Fig. 1). The amount of FRP reinforcement was chosen to allow for a debonding failure mode. Higher reinforcement ratios usually result in flexure-shear failure of the test specimen, which does not provide an assessment of the bond durability; FRP strips measuring 2.5 cm in width and 20 cm in length achieved the desired failure mode. To better represent the cracked concrete, a 5 cm deep notch was introduced at the specimen midspan. The notch also eliminated the need for a constant moment region (debonding path is predefined), allowing for use of three-point bending instead of four-point bending loading condition.

The concrete mixture used to produce the concrete beam specimens had a target compressive design strength of 69.9 MPa, which was accomplished by using a low water to cementitious material ratio (w/cm) of 0.353. The cement used was Type I/II (ASTM C150 [1]), and the ratio of cement:sand:coarse aggregate was 1:1.74:2.22 by volume. The coarse aggregate with maximum size of 9 mm and the gradation conforming to #89 was used (ASTM C33 [2]). The mix had a slump of 64 mm and air content of 3.5%. The actual 28-day compressive strength was 78.7 MPa.

Test specimens were loaded at a constant displacement rate of 0.04 mm/min. until the ultimate failure. All specimens experienced a debonding failure mode (Fig. 2). The loading rate was selected to induce an increase in average FRP bond stress between 0.4 and 0.8 MPa/min [15], which generally resulted in total time to failure of less than three minutes; this loading rate is believed to minimize the effects of creep of the epoxy adhesive and is in conformance with ACI 440.9R-15 guidelines.

Test results from the three-point bending test are presented as bond strength retention (R_b):

$$R_b = \frac{ACP\ strength}{SLC\ strength} \quad (1)$$

where "ACP strength" is the mean ultimate strength of beams exposed to the selected (ACP) and "SLC strength" is the mean ultimate strength of beams exposed to standard laboratory conditions (SLC), as defined in ACI 440.9R-15 (temperature of 23 ± 3 °C, and relative humidity of 50 ± 10%).

3.2. Pull-off test method for FRP-concrete bond

Direct tension pull-off test (Fig. 3) is specified under ASTM D7522 [3]. The test is most commonly utilized as a part of quality control in newly installed repairs with externally bonded FRP. In this study, direct pull-off testing was conducted to assess the durability of FRP-concrete adhesive bond in-situ and in the laboratory setting. One side of the three-point bending test specimen had a FRP patch for the purpose of pull-off bond testing (Fig. 2). Results are presented in terms of R_b, in a similar manner as the notched beam three-point bending test.

4. Composite system

Durability of bond of one wet-layup CFRP composite system was evaluated (Composite A). Composite A system consists of a low-viscosity polyamine epoxy primer, paste epoxy putty, and dry carbon fiber fabric that, when soaked with the saturant, forms

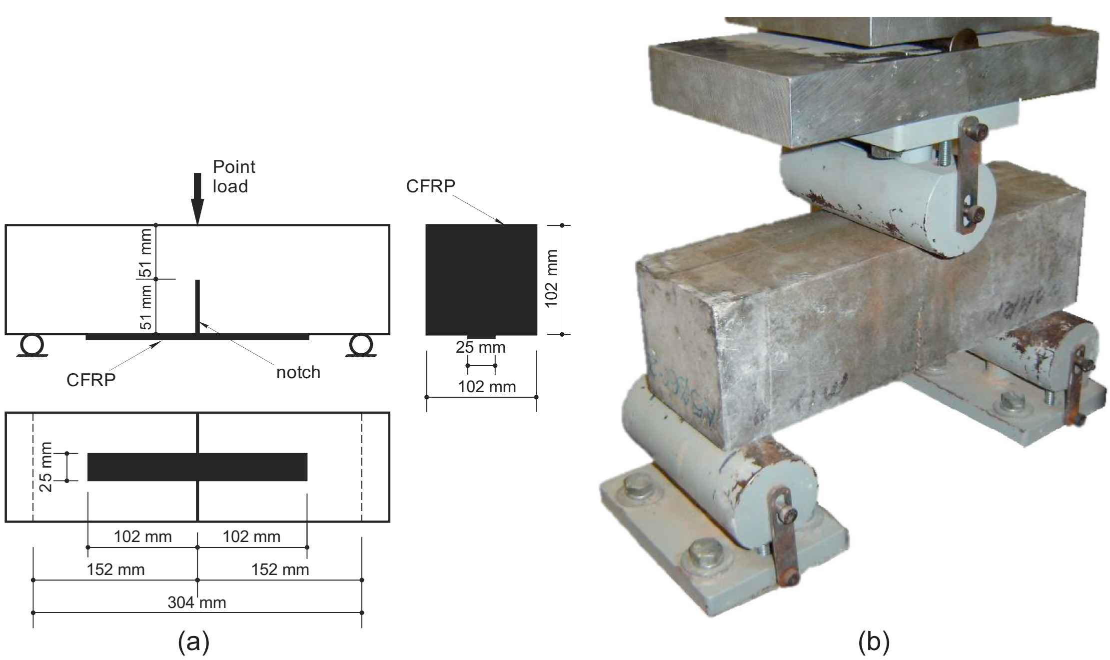

Fig. 1. (a) Notched three-point bending test schematic; and (b) test setup.