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Characteristics of CFRP–concrete interface subjected to cold region environments including three-dimensional topography

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ABSTRACT

This paper presents an experimental program to examine the interfacial behavior of carbon fiber reinforced polymer (CFRP) composite sheets bonded to concrete substrate when subjected to cold region environments. A total of 53 specimens are exposed to 150 cycles of freezing–wet–dry and wet–dry as well as constant low temperature effects ranging from 0 °C to −30 °C for 2000 h. A novel sensing technology, based on three-dimensional micro-topography, is presented using an instantaneous laser scanner to quantitatively examine the characteristic size of damage-band along the CFRP–concrete interface. Test results show that the effects of freezing–wet–dry are more detrimental than those of wet–dry, in particular noticeable when the temperature is below −20 °C. The low temperature increases the local brittleness of the interface and thus stress-softening is not observed for the specimens subjected to freezing–wet–dry. The specimens in wet–dry, however, exhibited such softening responses. The characteristic size of damage-band along the CFRP–concrete interface is found to be 14.5 mm; however, the size changes when the environmental loads are applied. Damage concentrations are observed in the damage-band with the presence of low temperature effects.

1. Introduction

Structural members in cold regions are subjected to harsh environmental conditions; for example, very low temperatures such as −30 °C and frequent freezing-and-thawing. Kim and Yoon (2010) reported critical factors influencing deterioration of constructed bridges in cold regions, including physical (year-built and daily traffic) and environmental (precipitation and low temperature) attributes. Over 25% of bridges in such environments in the United States are structurally deficient or functionally obsolete (Kim and Yoon, 2010). Structural rehabilitation may be a promising solution to improve the quality of constructed infrastructure, rather than replacement of deteriorated members, taking into account cost–benefit ratios. Fiber reinforced polymer (FRP) composites are a strong candidate to strengthen/repair damaged concrete members. FRP sheets may be bonded to the tensile soffit of a concrete beam to improve structural behavior. Although three types of FRPs are available for such applications (i.e., glass FRP, aramid FRP, and carbon FRP), carbon FRP (CFRP) is dominantly used because of its superior engineering properties such as high strength and modulus, durability, fatigue resistance, and long-term creep behavior (Kim and Heffernan, 2008; Teng et al., 2003). Numerous research results have been reported concerning the durability of CFRP-strengthened concrete members (Green, 2007; Liu and Karbhari, 2007; Ouyang and Wan, 2008). Extant experimental research shows that moisture can affect the behavior of FRP-strengthened concrete members by changing fracture properties and crack propagation rates (Chajes et al., 1995; Ouyang and Wan, 2008; Wan et al., 2006). The effects of freezing-and-thawing are another important factor influencing the behavior of strengthened members (Karbhari et al., 1997). Limited information is available with regard to the behavior of CFRP–concrete interface subjected to cold region environments. Previous research qualitatively examined the effects of freezing-and-thawing on bond of CFRP–concrete interface (Bisby and Green, 2002; Green et al., 2000; Subramaniam et al., 2008), whereas the contribution of various low temperatures when associated with wet environment is not fully understood. No quantitative approaches have been attempted to measure the interfacial characteristics between CFRP and concrete.

The behavior of CFRP–concrete interface is particularly critical for strengthened members. Perfect bond between the CFRP and concrete is assumed when a strengthening design is conducted. The behavior of strengthened members on site, however, may not conform to the design if the CFRP–concrete interface is influenced by environments, such as wet–dry or cold temperature. Despite extensive durability studies concerning moisture and low temperature, there still exists a dearth of understanding the effects of cold region environments on the behavior of CFRP–concrete interface. The present experimental program provides systematic approaches (1) to understand the effects of low temperature on deterioration of CFRP–concrete interface and (2) to quantify the size of CFRP–concrete interface where fracture processes take place when subjected to such environmental conditions.

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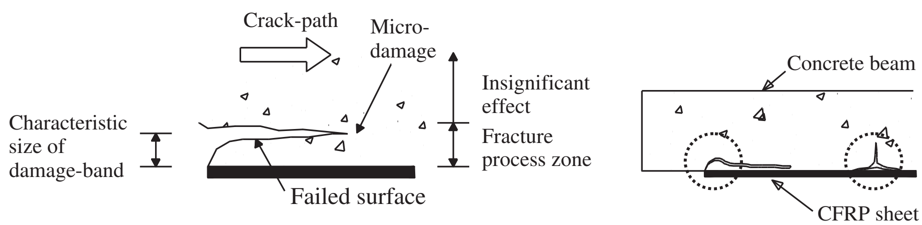

Fig. 1. CFRP–concrete interface and the concept of damage-band.

2. Research significance

The response of a fracture process zone or so-called damage-band along the CFRP–concrete interface of a reinforced concrete beam strengthened with CFRP sheets is an important consideration to understand the failure mechanism of a CFRP-strengthening system, as shown in Fig. 1. Arbitrarily assumed damage-bands are frequently used for numerical analyses because of insufficient understanding of damage-band characteristics. For instance, interface elements that are empirically derived from tests are used to represent the damage-band between CFRP and concrete or a refined mesh is formulated along the CFRP. These approximated modeling approaches may be justified by the fact that interfacial failure occurs beneath the bonded CFRP sheets. Adequate measures of damage-band, however, have not been reported previously. Although such approximated methods reasonably represent the failure of CFRP–concrete interface, the characteristic size of damage-band for CFRP-strengthened members needs to be quantitatively studied. The variation of damage-band properties may be associated with mechanical and environmental loads. Recent numerical research reports that the size of damage-band along CFRP–concrete interface can be affected by boundary conditions (Coronado and Lopez, 2007). This observation indicates the need for refined research with regard to the variation of damage-band in various loading configurations. Limited experimental observations are currently available to clarify the characteristic size of damage-band of CFRP-strengthened concrete members. Ouyang and Wan (2008) attempted to measure the local surface of failed CFRP–concrete interface using a digital-coordinate-measuring machine, whereas the accuracy and applicable ranges need significant improvement to measure the size of damage-band. The effects of environments (e.g., cold region conditions) on the behavior of damage-band have not been discussed previously. Harsh environments may influence the interfacial characteristics of CFRP-strengthened members; nevertheless, limited experimental data are available, in particular rare for cold region applications. This paper experiments a hypothesis: the size of damage-band along CFRP–concrete interface is affected by harsh environmental effects, based on an experimental program that evaluates the performance of CFRP–concrete interface subjected to typical cold region conditions. A novel experimental technique using an instantaneous laser scanner is employed to measure the micro-topography of failed CFRP–concrete interface. The proposed sensing technology has great potential to examine the surface characteristics of failed FRP composites and strengthened concrete members.

3. Experimental program

The experimental program included 53 concrete blocks bonded with CFRP sheets to examine the bond characteristics and size of damage-band along the CFRP–concrete interface when subjected to cold region environments. Note that the test method described here (i.e., single lap shear test) is well understood in the research community (Coronado

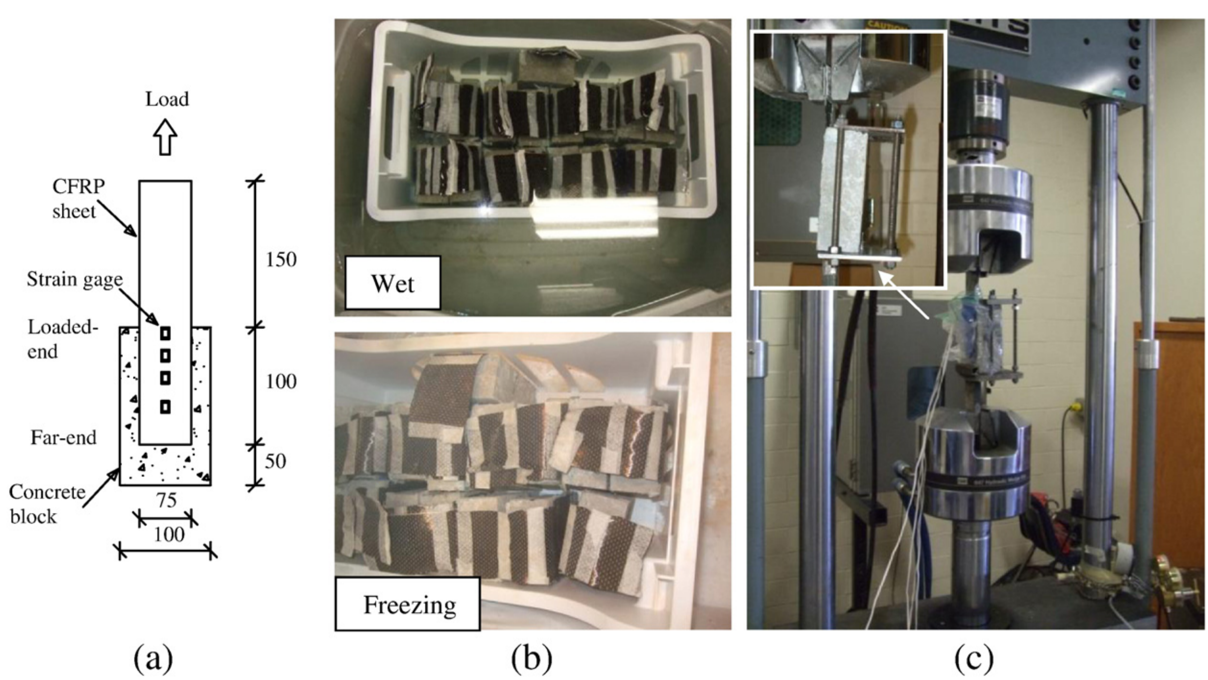

Fig. 2. Single lap test: (a) specimen detail; (b) environmental cycling; and (c) tension test.