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Durability of CFRP–concrete joints under freeze–thaw cycling

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ABSTRACT

The long-term durability of fiber reinforced polymer (FRP) strengthening systems under freeze–thaw cycling is crucial to the safety of structures in cold climates. The durability of the FRP–concrete bond interface under freeze–thaw cycling was investigated in the study reported here, with exposure condition, concrete grade, and number of freeze–thaw cycles as the parameters considered. The behavior of the carbon FRP (CFRP)–concrete bond interface was investigated with single-face shear tests. The results indicate that the bond strength, bond stiffness, interfacial fracture energy, and maximum slip of the joints decrease with increases in the number of freeze–thaw cycles, and they are also affected by the exposure environment. The depth of cracking and effective bond length increase with increases in cycle number, thus affecting bond stiffness and strength. The deterioration of bond strength can be attributed to the damage caused to the concrete by the freeze–thaw cycling.

1. Introduction

The research community has made great progress in determining how to retrofit, strengthen, and repair reinforced concrete (RC) structures using fiber reinforced polymer (FRP) materials. However, most attention has been paid to the short-term mechanical properties of such retrofitted structures (Smith and Teng, 2001; Teng et al., 2002; Nakaba et al., 2001). Another very important aspect that needs to be carefully investigated to ensure the safety of this technology is the evaluation of the long-term durability of adhesively bonded joints. To date, the bond characteristics of FRP–concrete joints under freeze–thaw cycling has received insufficient attention (Pavel, 2006; Karbhari et al., 1997, 2003; Bonacci and Maalej, 2000).

A large number of RC structures in need of retrofitting are located in regions that regularly experience freeze–thaw cycling. Freeze–thaw cycling can cause differential thermal expansion between the FRP laminate and the substrate concrete, leading to bond deterioration and thus premature debonding of the FRP reinforcement from the concrete. Many of these structures may also be exposed to deicing salts or seawater. Chajes et al. (1995) found that the combined action of freeze–thaw cycling and chlorides is more damaging. Hence, the long-term durability of FRP strengthening systems under freeze–thaw cycling, particularly under salt water, is crucial to the safety of structures in cold climate regions.

Chajes et al. (1995) studied the flexural strengthening of small concrete beams with externally bonded FRP under two different freeze–thaw conditions (50 and 100 cycles). A small decrease in ultimate strength with the increase in cycle number was observed. Kolluru et al. (2008) investigated the impact of freeze–thaw action on FRP–concrete bond behavior using a direct shear test. Their result showed that the fracture energy decreased from 0.65 to 0.42 N/mm (a 35% drop) after 300 freeze–thaw cycles, and that the corresponding drop in the ultimate load was 17%. The most pronounced degradation of bond properties was recorded by Davalos et al. (2005): at the end of 100, 200 and 300 freeze–thaw cycles, the corresponding reductions in fracture energy for normal, non air entrained concrete were 38.5%, 50.5%, and 59%, respectively. Air entrainment is the intentional creation of tiny air bubbles in concrete. The bubbles are introduced into the concrete by the addition of an air entraining agent into the mix. Entrained air can improve the resistance to salt scaling (removal of small chips or flakes of binder) of concrete in cold region by two ways: 1) entrained air reduces bleeding; and 2) ice in the air voids sucks pore fluid from the surrounding matrix, which compresses the porous body (John and George, 2007). Karbhari and Engineer (1996) also found that significant degradation in strength occurred in FRP strengthened beams under freeze–thaw cycling accompanied by an increase in flexural stiffness; and both changes were more pronounced in GFRP strengthened beams.

In contrast, Green's group (Green et al., 1997, 2000; Bisby and Green, 2002) reported an increase or preservation in bond strength under freeze–thaw cycling that employed a dry-freeze/water-thaw procedure and a relatively small number of freeze–thaw cycles. Pavel (2006) also showed that freeze–thaw cycling in water did not produce any significant damage to the bond strength; rather, the bond strength increased in most specimens. Mukhopadhyaya et al. (1998) pointed out that the ultimate bond strength between FRP and

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concrete was not affected after freeze–thaw exposure. However the differential movement between FRP and concrete was increased and the failure mode changed from concrete shear failure to adhesive failure.

From the foregoing review, it is clear that information on the durability of the bond between FRP and concrete under freeze–thaw cycling is limited. Given the numerous differences and even contradictory conclusions among these studies, it is difficult to draw general conclusions from them. However, the studies did identify the parameters that significantly affect the durability of the bond: exposure condition, concrete grade, and the number of freeze–thaw cycles. To the best of our knowledge, no study had extensively investigated a combination of these parameters. Hence, the authors set out to investigate the combined effect of these parameters on the bond strength, bond stiffness, interfacial fracture energy, maximum slip, and the effective bond length of FRP–concrete bonded joints.

2. Experimental program

The variables investigated in the study included freeze–thaw solutions, number of freeze–thaw cycles, and the concrete grade of the specimens. Details of the test program are given as follows.

2.1. Freeze–thaw cycling

As there is no existing standard for testing the FRP–concrete interface under freeze–thaw conditions, the following two standards for concrete were referred to: ASTMC672/C672M (2003) and ASTM C666 (2003). These two standards have been used by others to design freeze–thaw test methods for FRP–concrete joints. The former is suitable for tests in salt water, and the latter is used for tests in tap water.

ASTM C672 specifies the freeze–thaw condition of specimens being constantly submerged in 6 mm of 4% NaCl solution in a specially built testing chamber. This type of exposure simulates applications subjected to deicing chemicals or seawater. The characteristics of salt scaling were studied over the past 50 years through hundreds of laboratory and field investigations. It has been found that a maximum amount of damage to concrete is achieved with a solute concentration of 3–4% by weight (John and George, 2007; Sellevold and Farstad, 1991; Marchand et al., 1999). For tap water, the chlorate content is about 0.002%. Even with impurities in tap water, it hardly causes scaling of concrete within 100 freeze–thaw cycles (John and George, 2007). Therefore, normal tap water was used for the tests without measuring the impurities.

In this study, the specimens were subjected to an accelerated freeze–thaw cycling in an environmental chamber. The carbon FRP (CFRP)–concrete joint was placed in salt water (4% NaCl) or tap water with the CFRP facing downward and approximately 6 mm of concrete being submerged, as shown in Fig. 1a. A complete freeze–thaw cycle was as follows: starting at +4 °C, the temperature decreased to −18 °C in 110 min and was held constant for 10 min; it was then increased to +4 °C in 115 min and held for 5 min. The temperature of the specimens was monitored using a calibrated digital thermometer throughout the freeze–thaw process, as shown in Fig. 1. The specimens were subjected to 17, 33, 50, or 67 cycles in different groups. Reference specimens without freeze–thaw cycling were stored at a room temperature of 23 °C and an ambient humidity of about 75%. The specimens were submerged in water for no less than 24 h before freeze–thaw cycling.

2.2. Material properties

A high tensile strength carbon fiber fabric named TORAYCA Cloth with a nominal thickness of 0.167 mm was utilized in the program as the reinforcement. Two types of saturant resin (Sikadur-30 and Sikadur-300) were used as adhesive. Flat coupon tensile tests in accordance with ASTM D3039 (1995) were conducted to determine the material properties of the CFRP composite. The flat coupons contained a single-ply CFRP that was 50 mm in width. The mechanical properties of the CFRP laminate that were obtained from the coupon tests, and those provided by the manufacturer are listed in Table 1. The manufacturer-specified properties of the SIKA adhesives are given in Table 2.

Two concrete grades (normal concrete without air entrainment) with design cube strengths ($100\times100\times100$ mm^3) of 30 MPa and 45 MPa were tested in the program. Details of the concrete mixes are given in Table 3. Previous studies (Green et al., 1997; Bisby and Green, 2002; Green et al., 2000) have noted that concrete strength increases during the freeze–thaw process when the age of the concrete increases. To avoid variation in concrete strength during the process of freeze–thaw cycling, all the specimens were left in the laboratory for more than 500 days. The C30 and C45 concrete had average 500-day cube strengths ($100\times100\times100$ mm^3) of 36.9 MPa and 48.6 MPa, respectively.

2.3. Test specimens and preparation

The conventional single shear pull-off test was used for the bond tests. The concrete specimens (blocks) had dimensions of 340 (length) × 150 (depth) × 150 (width) mm^3. The blocks were removed from the forms 24 h after casting and were wet cured for 28 days.

The FRP bond area was 300×50 mm^2, as shown in Fig. 2a. To avoid a possible edge effect, a 20 mm zone from the edge of the concrete block was left unbonded at the loaded end; see Fig. 2a. The bond area was prepared using a Hilti electrical roughening machine (TE-Y-SKHM Bushing Tool) to provide a rough bond surface. Following the mechanical abrasion, the surface was vacuum cleaned. Before adhesive bonding, a coat of primer (Sikadur-300) was applied to the concrete surface, followed by a thin coat of putty (Sikadur-30) before

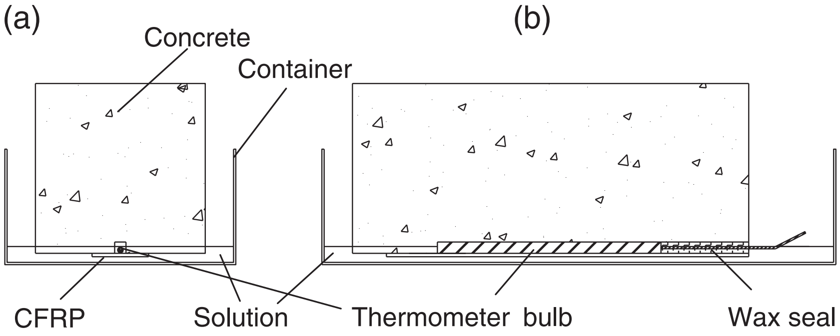

Fig. 1. Freeze–thaw test setup.