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Bond behavior of near surface mounted CFRP rods under temperature cycling

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ABSTRACT

A near surface mounted (NSM) strengthening technique using CFRP rods has been developed to increase the load-carrying capacity of deteriorating concrete structures compared to that possible with traditional external bonding techniques. This paper investigates the bonding behavior between the CFRP rod and the concrete under temperature cycling when the near surface mounted (NSM) strengthening technique is applied. A total of 27 pullout specimens were fabricated and tested to investigate the effects upon filling materials of applying various numbers of temperature cycles from −15 to 55 °C. The test results included failure load, average bond stress, strains in CFRP bar, and failure mode.

1. Introduction

Most rods used in prestressed concrete (PSC) structures are made of steel, and many concrete structures in shore areas are exposed to inclement environments. Serious problems have occurred in these structures owing to the loss of load capacity arising from the corrosion of the steel reinforcements. Recently, carbon fiber reinforced polymer (CFRP) has gained growing interest as an alternative material to replace steel reinforcements, prestressing tendons, and tensile elements owing to its immunity to corrosion, high strength, and light weight. Strengthening methods commonly adopted for strengthening deteriorated concrete bridges are bonding of steel sheets, external prestressing of steel rods, and bonding of fiber reinforced polymer (FRP). FRP strengthening has been known to fail due to debonding between the concrete and the FRP before the FRP material's capacity is reached; thus, the full capacity of the FRP is not used. This disadvantage of early debonding can be overcome by employing a near surface mounted (NSM) strengthening technique. In this technique, grooves are cut into the cover of a concrete member; FRP rods are then placed in the grooves, which are then filled with epoxy adhesive or mortar grout. FRP reinforcement is then bonded to the concrete, which ensures higher stress transfers between concrete and FRP than the external bonding technique.

Externally bonded (EB) CFRP strengthening techniques involve attachment to only one side. Therefore, full efficiency of EB techniques has not been achieved because of the bond failure at the interface between the CFRP rods and the concrete. NSM strengthening techniques have been developed to minimize these problems and increase the efficiency of CFRP strengthening techniques. The NSM technique has three key advantages over the EB technique. First, the NSM technique reduces debonding from the concrete because the technique employs attachment to three sides of the base concrete structure. In addition, prestressing can be more effectively introduced in the NSM strengthening method than in the EB strengthening method. Furthermore, the CFRP rods are protected from damage by the concrete cover in the NSM strengthening technique.

A number of studies [1–16] have used the pullout test to examine the fundamental bond behavior of the FRP strengthening method without considering the effects of temperature. Benmokrane et al. [17] examined the pullout behavior of AFRP and CFRP rods in a sleeve. Their experimental evaluation considered the types of rods, cement grouts, and anchorage tubes used. Shraky et al. [18] experimentally investigated the effects of adhesive properties, rod type, rod size, and FRP properties upon bond behavior.

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They discussed the bond behavior including failure load, average bond stress, end slip, and transverse strains upon adhesive and concrete, as well as the failure mode of the tested joints.

Few previous studies have addressed the behavior of FRP rods with respect to temperature. At high temperature, above the glass transition temperature (Tg), the polymer loses its mechanical properties, depending on the number of connections and grade of crystallization [19]. Recently, several researchers have investigated bond behavior under temperature variation. In FRP, however, the inorganic fibers support the load in the longitudinal direction

The properties in this direction depend mainly on the properties of the fibers, which exhibit better thermal properties than the resin. Silva et al. [20] performed pullout test and RC beam test after temperature variation (from −15 °C to 60 °C). Experiment result represented that bond strength of epoxy filler higher than bond strength of mortar filler after temperature variation. NSM strengthening system has to be studied considering the change in external environment. Recently, NSM strengthening system needs more studies about resistance to external environment and long-term bond behavior of filler. Katz and Beramn [21] studied the effect of high temperature upon the bond between FRP reinforcing bars and concrete. The bond strength was severely reduced, by 80–90%, at temperatures up to 200 °C, which was accompanied by changes in the pullout load-slip behavior. A semi-empirical model was developed to describe the reduction in bond strength with increasing temperature. Leone et al. [22] discussed the behavior of FRP/concrete interfaces at elevated service temperatures. Their experimental results showed the influence of temperature upon bond performance in terms of the interfacial failure mode, effective bond length, and bond strength. Palmieri et al. [23] experimentally analyzed the performance of NSM FRP-strengthened concrete beams under fire conditions, showing that these beams can achieve a fire endurance of at least 2 h when insulated. The structural evaluation of the fire-tested beams to failure at room temperature showed that well-insulated members can retain their original strengthened flexural capacity. Yu et al. [24] experimentally studied the effect of temperature upon the bond strength of NSM FRP-strengthened concrete. Thirty-six NSM FRP specimens, which were fabricated by using various types of epoxy adhesive and FRP reinforcements, were tested to evaluate bond strength over the 20–400 °C temperature range. Results from these tests indicated that the bond strength of NSM reinforcements significantly decreases during heating in the 20–200 °C temperature range, retaining only 20–30% of the original strength at 200 °C. Data from these tests were utilized to propose empirical relations regarding the variation of bond strength and modulus of the NSM FRP strengthening system versus temperature. Yu and Kodur [25] experimentally investigated the effect of temperature upon tensile strength and elastic modulus of two types of NSM CFRP reinforcement using epoxy mortar filler in the 20–600 °C temperature range. Results from these tests indicated that both the CFRP strip and CFRP rod retain most of their initial tensile strength and elastic modulus properties up to 200 °C. However, these properties degrade significantly when the CFRP is heated above 300 °C because the FRP resin decomposes. Firmo et al. [26] performed an experimental study of bond behavior at high temperatures (from 20 to 150 °C, measured in the adhesive) between concrete and CFRP strips installed according to the NSM technique. Double lap shear tests were performed upon concrete blocks strengthened with CFRP strips installed into slits and bonded by using either an epoxy adhesive or a mixed grout composed of epoxy and cement binders.

Even though NSM CFRP shows adequate bonding performance under static temperature conditions, the bond behavior between NSM CFRP and concrete under repeated temperature cycles is still not understood well because of uncertainty regarding the sensitivity of filler to temperature variation. Regardless of whether the NSM strengthening technique is used, the bond behavior of CFRP strengthening systems under temperature cycling should be further investigated to better understand the durability, particularly of these systems because the glass transition temperatures of epoxy adhesives can be reached in specific applications.

The present study had three main objectives. The first was to determine an appropriate NSM groove filling material that would best endure temperature cycling. Three filler materials were considered for this purpose: nonshrinking mortar (NM), epoxy putty (EP), and epoxy mortar (EM). Epoxy putty is the typical material currently used for maintenance of concrete bridges in Korea. The second objective was to experimentally investigate the bond characteristics of NSM CFRP strengthening techniques after various numbers of temperature cycles from −15 to 55 °C. The upper bound of temperature variation was set higher than the glass transition temperature (50 °C) of the EP, while the lower bound of temperature variation was set at −15 °C based on the lowest temperature condition in Korea. The considered range of temperature cycles was from 3 to 100 cycles. Three cycles were chosen to analyze the bond deterioration right after the temperature change, while 100 cycles were studied to study the effects of a relatively large number of temperature variations under laboratory conditions. Lastly, the third objective was to examine the workability and durability of the filling material in terms of the sensitivity of the filling material to temperature variations.

2. Experimental program

Pullout tests are commonly used to evaluate the bonding performance of FRP rods in concrete. The experimental evaluation consisted of pullout tests of 27 NSM CFRP specimens subjected to three different temperature cycles; Table 1 lists the test parameters used. To improve the reliability of the results, the bond strengths were taken as the averages from triplicate pullout tests. In this study, C-shaped specimens were used in the modified pullout test; the C-shaped concrete blocks were fabricated in the external dimensions of 300 mm × 300 mm in external dimensions and the height of 300 mm to avoid eccentricity during the loading process. An anchorage system bonded to the loaded ends of the CFRP rods was used to tie them to the universal testing machine (UTM), as shown in Fig. 1.

The CFRP rods used in the tests were prepared for use by covering them with an oxide coating (Fig. 2); this coating was anticipated to increase the bond capacity by increasing the frictional force between the CFRP rod and the filler material in the NSM groove. The tensile stress applied to the CFRP rod was 3433 MPa based on a preceding tensile failure test. The specimens were cast by using ready-mixed concrete. The average compressive strength of the concrete according to standard cylinder (150 × 300 mm) tests was 40.2 MPa. As mentioned earlier, the experimental evaluation comprised pullout tests of concrete blocks and CFRP rods installed according to the NSM technique and bonded by using three types of fillers: NM, conventional EP, and EM. The compressive strength and tensile strength of EP were 107 MPa and 13.4 MPa, respectively. The thermal properties of the EP were examined using differential scanning calorimetry (DSC) in order to determine the glass transition temperature (*Tg*). Tests were carried out according to ASTM D3418. The glass transition temperature of EP and EP primer was 65 °C and 50 °C, respectively.

First, NM was applied to the specimens as the filler. The strength of the NM was 70 MPa and its water content was 14.5%. The NM specimens were cured for approximately 14 days. The next considered filling material was EP. First, a layer of fluid "primer" was applied to ensure good bonding between the epoxy and the