Flexural behavior of RC beams strengthened with NSM GFRP strips after exposed to high temperatures

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A B S T R A C T

The present study investigated the flexural behavior after exposure to high temperature of reinforced concrete beams strengthened with glass fiber reinforced polymer (GFRP) strips. To strengthen the beams, the near surface mounted (NSM) method was used to install the GFRP strips inside concrete substrate. Two different adhesive materials of epoxy and mortar were used to bond the GFRP strips inside the concrete substrate. Two strengthened specimens using the mortar and epoxy, respectively, as adhesive materials were first exposed to fire, and then flexural test was performed. The test results showed that after exposure to high temperature, the GFRP strips using epoxy technique could be beneficial to retaining the flexural strength of the concrete beams. In contrast, after exposure to high temperature, the GFRP strips using mortar technique was beneficial to deformability, rather than flexural strength. Finally, analytical study was performed to predict the failure mode, strength, and deformation of the concrete beams after experiencing high temperature, and the analysis results showed good agreement with the test results.

1. Introduction

In the last fifty years, strengthening technologies of existing concrete members have attracted significant attention in civil engineering society. This is because such existing concrete structures might be weakened by concrete carbonation and free-thaw repetition arising from long-term environmental causes. In addition, as time passes, the existing concrete structures could undergo progressive damage (or fatigue) due to repeat loadings. Nowak [1] suggested that over 75 years, a concrete bridge would be subjected to almost 20,000,000 repetitions of truck load. To reduce construction waste and lower construction cost, retrofit of existing structures is preferred to demolition and new construction [2,3]. Thus, cost-effective and easy-to-install retrofit methods of existing structural members have been developed, and have received attention.

External bonding methods using fiber reinforced polymer (FRP) are one of the most popular methods for flexural and shear strengthening of concrete members. The use of FRP as a retrofit material was due to its lightweight, high strength, and convenience in installation. In design and construction practice, various types of epoxy have been used as adhesive material to bond FRP sheets or strips to concrete. To investigate the retrofit effect of FRP materials, many flexural tests were performed using the concrete beams strengthened with FRP plates or sheets (including CFRPs, GFRPs, and hybrid FRPs) [4–8]. The test results showed that the use of FRP plates significantly improved the flexural capacities of the strengthened concrete beams, and increased the initial stiffness and ductility [4,5]. In addition, it was also found that the failure of the retrofitted beams could be brittle, which was attributed to debonding or peeling of the FRP reinforcement. The debonding level of the hybrid FRPs was mainly influenced by the choice of adhesive material, and was more influenced by the thickness of the strengthening material, than by its stiffness [8]. The use of U-shaped FRPs was recommended for construction practice, due to their effectiveness in anchoring, and could thus prevent the debonding failure of the FRP retrofitted beams [7,9].

However, it is unfortunate that the use of the external bonding method for FRP reinforcement could be damaged by environmental conditions, such as fire, temperature, and moisture, or by interactions [10]. Thus, near surface mounted (NSM) reinforcement using FRP reinforcing bars or strips was recently introduced as a new strengthening technique for reinforced concrete members [11–15]. The adhesive materials used were usually epoxy or cementitious grout. In the NSM strengthening method, FRP reinforcement would be bonded to concrete on at least three faces; therefore, higher stress could be transferred between concrete and FRP [11]. Rezaazadeh et al. [17] retrofitted five full-scale beams to investigate the effect of strengthening application on the structural behavior of the beams. Rezaazadeh et al. [16] combined externally bonded CFRP with NSM techniques in the same application,
In this study, to investigate the flexural behaviors of retrofitted concrete beams, four half-scale reinforced concrete beam specimens were constructed, strengthened, and tested. Near-surface-mounted (NSM) GFRP strips were used for retrofit purposes. To bond the GFRP strips with concrete substrate, two different types of adhesive materials of epoxy and mortar were used. In addition, two strengthened beam specimens with epoxy and mortar were exposed to fire, before flexural tests were performed. All specimens were subjected to three-point bending tests until failure. Further, an analytical model was proposed for predicting the flexural capacity of the beams strengthened with NSM GFRPs after exposure to high temperature.

2. Experimental program

2.1. Test specimens

In this study, four reinforced concrete beam specimens having a total length of 2000 mm, and a cross-section \((b \times h)\) of 200 mm \(\times\) 300 mm were constructed and tested. One was considered as a control specimen; meanwhile, the other test specimens were strengthened with glass fiber reinforced polymers (GFRP), using the near surface mounted (NSM) method. Figs. 2 and 3 and Table 1 present the geometries and reinforcement details of the test specimens. Fig. 2 shows the details of the control specimen RB0. The figure shows that the effective depth of specimen RB0 was 240 mm; thus the shear span to depth ratio \((a/d)\) was equal to 2.92. In addition, the bottom reinforcement consisted of two D29 longitudinal re-bars of 29 mm diameter; thus, the correlative longitudinal reinforcement ratio \((\rho_l)\) was 2.75%. The selection of the longitudinal reinforcement ratio of the beams is to ensure that flexural failure could occur during the loading in cases of not only the control specimen, but also the specimens strengthened with NSM GFRPs. In the case of flexural failure, the shear strength \((V_s)\) of the reinforced concrete beam was designed to be greater than the shear demand \((V_d)\) required for flexural failure. In contrast, no longitudinal reinforcement was used at the top of the beam. The transverse reinforcement using steel re-bars D10 having a diameter of 10 mm consisted of double legs, and was designed as open stirrups (see Fig. 2). The arrangement of transverse reinforcement as shown in Fig. 2 was carried out according to KCI 2012 [27], to avoid shear failure of the test specimens.

Fig. 3 shows the details of the specimens RB1, RB2, and RB3. In the application of NSM GFRPs, epoxy was used for adhesive material in RB1 and RB2, while mortar was used in RB3. Fig. 3 shows that these strengthened specimens have the same material and geometrical properties as those of the control specimen RB0, except for the strengthening parts by GFRPs. The GFRP type used was REP-50, having a width of 25 mm and a thickness of 5 mm (see Table 2). However, note that because the length of GFRP strips given by the manufacturers is too short, lengthening of the GFRP strips is necessary by applying the lap splice method with a lap splice length of 400 mm. After strengthening, specimens RB2 and RB3 were fired under high temperature to investigate the effect of high temperature on the performance of beams strengthened with NSM GFRPs (see Test setup for clear explanation).

In this test, to install the GFRP strips inside the reinforced concrete beams, T-shapes. The obtained test results indicated that this strengthening technique significantly increased the stiffness and flexural capacity of the beams, while the maximum strain level in these T-shaped profiles decreased.

In general, previous studies [11–16] have indicated that concrete beams strengthened with NSM FRP reinforcements performed well in normal conditions. Regarding fire conditions or high temperature, the adhesive materials (e.g. epoxy resin) are sensitive to high temperature, and this could thus lead to reduction of the bond strength between NSM FRPs and concrete substrate [17–19]. In addition, high temperature would change the material characteristics of concrete [20–25], which would seriously affect the structural performance of the concrete beams. Fig. 1 shows the strain and strength of concrete corresponding to temperature based on various studies by Change et al. [20], Kodur et al. [21], Khennane and Baker [22], Lie [23], Lie et al. [24], and Jau and Huang [25]. The figure shows that with the increase of temperature, the concrete strength decreases; in contrast, as the temperature increases, the concrete strain at peak strength increases. In the previous studies [20–25], the concrete strain equations were proposed for the test specimens after natural cooling down to room ambient temperature. In addition, Scherfler et al. [26] proposed the concrete strain at high temperature as the summation of mechanical, thermal, creep, and transient strain based on thermo-mechanics.