Construction and Building Materials 154 (2017) 632–643

Contents lists available at ScienceDirect

Construction and Building Materials

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

Recovering flexural performance of thermally damaged concrete beams using NSM CFRP strips

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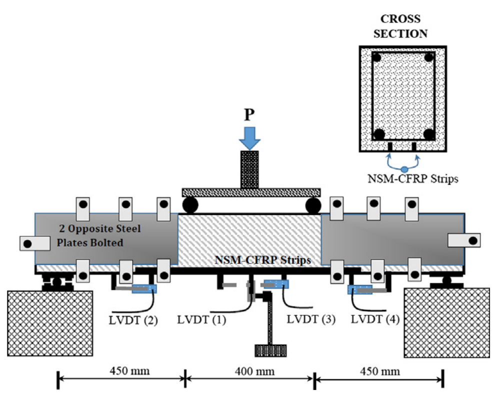
HIGHLIGHTS

- Exposure of beams to 600 °C for 2 h degraded their mechanical properties.
- Flexural behavior of post-heated beams with NSM CFRP strips was recovered.
- Ductility was recovered for heat-damaged beams with NSM CFRP strips.
- Heat-damaged had significantly reduced bond strength between concrete and NSM CFRP.
- End-concrete cover peeling off was the dominant failure mode for repaired and strengthened beams.

GRAPHICAL ABSTRACT

The potential of recovering flexural performance of thermally damaged concrete beams using near surface mounted (NSM) carbon fiber reinforced polymer (CFRP) strips was satisfactory when enough development lengths beyond critical stress region were provided. Intact/strengthened and heat-damaged/repaired beams showed improved load capacity and toughness, yet experienced reductions in ductility and toughness as compared to control ones.



ARTICLE INFO

Article history:
Received 29 April 2017
Received in revised form 11 July 2017
Accepted 29 July 2017
Available online 8 August 2017

Keywords:
Strengthening
NSMCFRP strips
Configuration
Peeling off
Analytical prediction

ABSTRACT

The potential of recovering the flexural performance of thermally damaged concrete beams using near surface mounted (NSM) carbon fiber reinforced polymer (CFRP) strips was experimentally investigated. Twenty reinforced concrete beams (150 × 250 × 1400 mm) were cast then cured for 28 days in moist burlap. A set of ten beams were heated at 600 °C for 2 h using an electrical furnace whereas those of the second set were left in laboratory air. Four pairs of beams from each set were repaired/strengthened at their tension side using similar configurations of NSM CFRP strips. Duplicate beams of each set were tested as controls. The mechanical performance of different beams was evaluated under four-point loading test setup including measurement of strain in NSM CFRP strips and slippage between NSM CFRP strips and concrete. Moreover, cracking and failure modes were monitored and characterized. Intact/strengthened and heat-damaged/repaired beams showed improved load capacity and toughness, yet experienced reductions in ductility and toughness as compared to control ones. Different performance indicators revealed good potential of repairing heat-damaged beams using NSM CFRP strips. End-cover separation failure mode was observed for both strengthened as well as repaired beams. Analytical predictions of ultimate load capacity for different beams confirmed experimentally obtained results.

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.211

1. Introduction

Reinforced concrete (RC) structural members are designed to have sufficient strength to resist all types of loads. In an event of fire, however, these structures are exposed to very high temperatures that affects negatively their mechanical and physiochemical properties; causing the structural elements to deface and displace and possibly spall under certain circumstances. As exposure temperatures exceeds 400 °C, evaporable water is forced out from concrete's capillary, gel and interlayer pores, in sequences, with calcium hydroxide decomposed at about 400 °C and C-S-H broken down and combined water lost in the temperature range of 500–800 °C [1,2].

Usually reinforced concrete (RC) structures withstand low to moderate fire exposure conditions because of their high thermal capacity, and low thermal conductivity. However, upon exposure to an accidental fire for periods exceeding 2 h, concrete structures would show noticeable degradation, sever reductions in concrete's strength and stiffness, loss in steel reinforcements yield strength, and degradation in bond between concrete and steel [3–6]. The level of degradation in these structural elements is dependent upon the type of structural element and extent and rate of fire, type of load and support conditions. Documented fire accidents showed that few concrete structures had collapsed as a result of fire and that the majority of these structures are repairable. Accordingly, the potential of repairing heat-damaged concrete members had received a lot of interest; especially over the past 30 years or so [7–13].

The present database showed that reinforced concrete beams are the most repaired structural elements, owning to their high susceptibility to fire, which impacts tangibly their load resistance mechanism. Until about 20 years ago, steel plates and elements or reinforced concrete jacketing (RCJ) were mainly used in repair/strengthening of beams; both of which had its disadvantages [9,10]. Possessing better physical, chemical and mechanical properties than steel plates and RCJ, Fiber Reinforced Polymer (FRP) plates and sheets have been used to strengthen/repair various concrete structural elements. The outcome of approximately twenty years of research indicated many advantages of FRP materials over conventional repair techniques; including higher repair efficiency, and easier application within a relatively short period of time [11–13]. However, the tendency of FRP composites in the forms of conventional plates and sheets to detach from concrete at relatively low loads undermined the benefit of their use in repair works.

To overcome the shortcomings associated with the use of conventional FRP plates in repair, a new form of FRP composite is currently emerging, near surface mounted (NSM) Carbon FRP (CFRP) strips. Those are inserted in man-created groove that is filled with a strong adhesive. Compared to externally bonded FRP plates or sheets, NSM CFRP strips are protected against accidental mechanical damage, sun and moisture hence would be very attractive to promote negative moment capacity in areas exposed to mechanical damage or environmental attacks. Furthermore, NSM CFRP strips are less prone to de-bonding from concrete substrate and their application introduces no aesthetic changes to repaired structural elements [14–29]. Consequently, various studies were recently undertaken to investigate the mechanical performance and failure modes of beams repaired for shear and flexure using NSM CFRP strips. The major findings indicated: (a) higher contribution of NSM CFRP strips to improving structural performance as compared to externally attached strips of similar sectional area and strength properties; (b) grove's thickness and spacing to have a significant impact on the efficiency of repair; and (c) premature concrete cover delamination as a major disadvantage. Most studies reported soffit cover delamination as the dominant failure mode in shear strengthened beams; especially when relatively close strip spacing is used [14–29].

2. Problem statement and objectives

Premature detachment of conventional Carbon FRP (CFRP) plates in strengthened concrete beams before compression concrete develops its ultimate strain capacity had limited the benefit of using such materials in repair works. Recently, NSM CFRP strips had been manufactured and used for repair of concrete flexural elements because their insertion in grooved concrete contributes to an improved bond with concrete in addition to other benefits, discussed earlier. In an event of exposure of fire, reinforced concrete elements may crack and loses its load capacity partially or fully and hence the potential of regaining their structural capacity using NSM CFRP strips becomes questionable. This work tends to investigate the contribution of NSM CFRP strips to recovering the original load capacity of heat-damaged and repaired beams.

3. Methodology of study

To achieve the objectives of the study, twenty reinforced concrete beams (150 × 250 × 1400 mm) were designed according to ACI committee 318 as under reinforced, then prepared, and moist-cured for 28 days [30]. The first set of ten beams were left at laboratory air whereas the second set, represented the other half, were subjected to an elevated temperature of 600 °C in an electric furnace for a period of 2 h. Duplicate beams from each set were either kept as controls or strengthened/repaired using CFRP strips at different numbers and embedment lengths. The testing program is summarized in Table 1 with strengthening/repair configurations illustrated schematically in Fig. 1. Letter-number designations were used to designate beams' status (intact, heat-damaged) and strengthening/repair configuration with regard to number of NSM CFRP strips, and their extension and spacing.

All beams were tested under the effect of four-point loading with applied load, mid-span deflection, strain in NSM CFRP and slippage between NSM CFRP strips and concrete acquired using a data acquisition system. The data were processed for load-deflection and load-slip diagrams and their characteristics to establish the significance of repairing heat-damaged beams using the proposed techniques.

4. Experimental program

Material properties, mix design, concrete mixing and casting, detailing of test beams and reinforcement, heat treatment protocol, procedure of repair applications and testing setup and procedure are presented in this section in details.

4.1. Concrete ingredients and proportions

Type I ordinary Portland cement, tap water, coarse limestone aggregate with 19 mm maximum aggregate size, and a mixture of fine limestone aggregate and silica sand at 70% and 30%, respectively, were used in casting the concrete mixture used in this work. A commercial superplasticizer was added to the mixture to achieve the target workability. The coarse aggregate gradation meets the requirements of the ASTM method C33 [31]. The physical properties for the different aggregate particles were carried out according to ASTM specifications with results listed in Table 2, [31].

The proportions of concrete's ingredients were determined according to the mix-design method ACI-211.1 [32] such that a cylinder compressive strength of 35 MPa is achieved at 28 days