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Modelling of NSM CFRP strips embedded in concrete after exposure to elevated temperature using epoxy adhesives

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ABSTRACT

The repair and strengthening of concrete structures with composite material has become common during the last decade. Based on experimental results of specimens damaged by heating and subsequently repaired using CFRP laminate and epoxy adhesive, finite element analysis (FEA) was conducted to simulate the bond behaviour between NSM CFRP strips and heat-damaged concrete. The theoretical parameters included unheated and heat-damaged concrete and level of heat exposure. The finite element models (FEMs) showed reasonable agreement with the experimental results, and can therefore be used to predict the effects of high temperature on pull-out values after exposure to elevated temperatures.

1. Introduction

Recent years have seen increased emphasis on the repair and refurbishment of all types of structures in preference to demolition and rebuilding. Concrete structures are no exception [1–3]. Since one of the problems facing buildings is exposure to high temperatures, they should be provided with sufficient structural fire resistance to withstand such circumstances, or at least to give the occupants enough time to escape before strength and/ or stability failure ensue [4,5].

In the near-surface mounted (NSM) method, thin grooves are cut in the surface of the concrete member. This system was first used to strengthen bridges in Europe in the early 1950s using steel reinforcement [6]. The benefits of using FRP instead of steel for strengthening are better corrosion resistance and ease of application due to its light weight. The advantages of using near-surface mounted (NSM) compared to externally-bonded (EB) FRP strengthening are that it provides protection from external environmental damage, its application does not require extensive surface preparation work and no delamination between the fibre and the concrete at the ends occurs, particularly in flexural members. Therefore, no anchorage system is required with this technique, as it provides a large bond surface area, which consequently increases the strength. EB systems cannot mobilize the full tensile strength of FRP materials because of premature debonding, and may be negatively affected by freeze/thaw cycles and the strength may decrease significantly when subjected to high and low temperatures [7–9]. The main critical issue which needs to be investigated in the application of the NSM technique is the bond properties between the FRP material used for reinforcement and the concrete surface provided by the adhesive material. Considerable research has recently been conducted into the use of NSM CFRP bars and strips, and investigations have been conducted [10,11] on bond properties, shear and flexure strengthening. The bond strength and load history between CFRP and concrete have been assessed under monotonic loading utilizing NSM FRP [12]. The CFRP was inserted in slits 15 mm deep and 4.8 mm wide. The main aim of the project was to increase the load-carrying capacity of concrete elements, especially in the concrete cover. Studies of the suitability and effectiveness of the CFRP NSM laminate strengthening system to repair concrete after exposure to high temperature have been carried out [13,14]. Many variables were encountered in this investigation, which covered the effect of high temperature on bond strength values using direct pull-out tests (single-lap shear tests) after exposure to temperatures of 200, 400, and 600 °C for exposure periods of one and two hours. FE numerical simulation has been employed by many researchers to predict the peak load and

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failure mechanism in order to provide further understanding of bond behaviour using FRP [15–21]. Therefore, the numerical analysis approach adopted in the present investigation was intended to validate the experimental data with those obtained from FE analysis [22,23]. All material properties and parameters used in this software were taken from the experimental work, and the performance of the developed numerical models was analysed.

2. Material description

2.1. Concrete

A target compressive strength of 35 MPa was specified. The concrete mix was designed according to the American mix design method ACI 211.1-94 [24]. Cylinders of dimensions 100 × 200 mm were used to obtain the concrete compressive strength according to ASTM C39-14a [25]. The average concrete splitting tensile strength was 3.56 MPa using cylinders of 100 × 200 mm dimensions according to ASTM C496-11 [26]. The average modulus of elasticity at 28 days was 27.8 GPa according to ASTM C469 [27]. The top and bottom surfaces of the concrete cylinders were levelled using a grinding machine to provide uniform distribution of stresses on the concrete surfaces. The following proportions by weight were used: 1 (cement); 1.67 (fine aggregate); 2.73 (coarse aggregate). The water/cement ratio was 0.57, giving a slump, according to ASTM C143-12 [28], of about 80 mm. Mixing of concrete was performed according to ASTM C192-13a [29]. After 28 days curing, the prisms were placed in the laboratory for 90 days at ambient temperature (approx. between 19 and 22 °C) and relative humidity (approx. 63%), until they were ready for heating, repair, and then testing. The average compressive strength, modulus of elasticity, and splitting tensile strength of the concrete at the age of pull-out testing were 41.43 Mpa, 29.5 GPa, and 4.3 MPa, respectively.

2.2. CFRP

CFRP laminate with unidirectional carbon fibre with a peel-ply surface was used in this study. The surface texture was rough after removing the protective ply. CFRP laminate with a fibre content of 70% by volume was utilized in this study. The dimensions of the CFRP laminate were 20 × 1.4 mm^2 and the effective bond length was 175 mm, similar to that reported by Al-Bayati and Al-Mahaidi [30]. Three specimens of CFRP laminate were tested according to ASTM D3039-14b [31] for comparison with the data provided by the manufacturer. The results obtained in the laboratory were consistent with the manufacturer's data, as presented in Table 1.

2.3. Epoxy

Epoxy resin adhesive was used for the CFRP laminate system to bond the CFRP strips to the concrete substrate using the NSM method. A two-part epoxy system manufactured by BASF Chemical Company, Australia was used in this study. The typical properties provided by the manufacturer are presented in Table 2.

Table 1
Properties of CFRP laminate.

Properties	Manufacturer's data	Laboratory test
Ultimate tensile strength (MPa)	3300	3122
Modulus of elasticity (GPa)	210	212
Ultimate strain (%)	1.4	1.45

Table 2
Properties of laminate adhesive.

Compressive strength	60 MPa
Flexural strength	30 MPa
Bonding ASTM D 4541	
Concrete	30 MPa (concrete failure)
Steel	5 MPa
Mix ratio	3A: 2B by weight
Colour	Red
Specific gravity@ 23 °C	1.5
Full cure@ 23 °C	7 days
Pot life	
23 °C	40 min
40 °C	20 min

3. Experimental program

Investigations of the bond behaviour between NSM CFRP strips and concrete exposed to elevated temperature using epoxy adhesive, and the effect of elevated temperature on direct tensile strength values using single-lap shear testing after exposure to temperatures of 200, 400, and 600 °C were carried out in the experimental program [13,14]. During the experimental work, the effect of heating on the behaviour of bond strength was based on 12 damaged concrete prisms cast in the laboratory and compared with references not exposed to heat. All prisms were 250 mm in length with a square cross-section of 75 × 75 mm. The concrete prisms were designed to approximate the set-up for single-lap shear testing. The prisms were instrumented with chromel-alumel Type-KK thermocouples. Only one was attached the surface of the concrete prism during the exposure to heating to measure the temperature on the concrete surface. For this purpose, ATENA-GiD was found to be dependent on the temperatures measured during the experimental work, as shown in Fig. 1. At 90 days' age after curing, the concrete prisms were exposed to temperature levels of 200, 400, and 600 °C for two exposure periods of one and two hours in a large furnace. All the concrete prisms were heated under the iSO-834 standard time temperature curve [32]. Fig. 1 shows that the target temperature followed the ISO 834 fire curve reasonably well. In addition, nine cylinders of concrete with

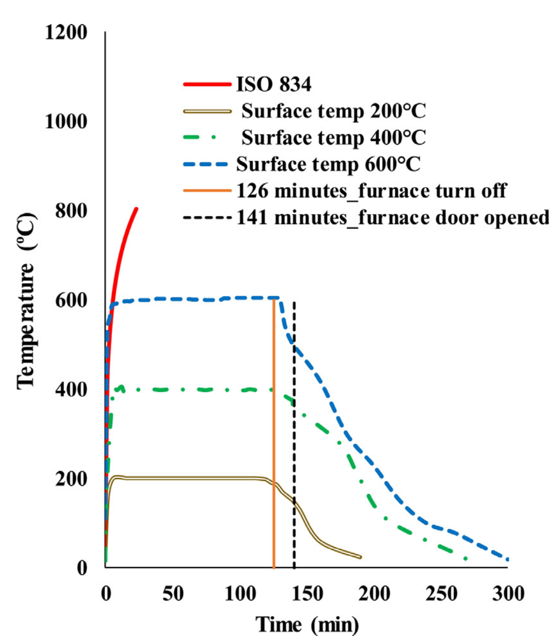

Fig. 1. Temperature-time curves for 200, 400, 600 °C tests.