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Effects of applied environmental conditions on the pull-out strengths of CFRP-concrete bond

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HIGHLIGHTS

- Studied CFRP-concrete bond exposed to three exposure conditions.
- Maximum normal stress at CFRP, strain distributions and failure modes are presented.
- Conducted comparison of the results of exposed specimens to unexposed specimens.
- The highest strength degradation due to outdoor environment is shown.

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ABSTRACT

This paper presents observation and results of an experimental study undertaken to investigate the time dependant behaviour of bond between external Carbon Fibre Reinforced Polymer (CFRP) reinforcement and concrete subjected to temperature cycles, wet-dry cycles and outdoor environment separately. Single shear tests (pull-out test) were conducted to investigate bond strengths (pull-out strengths) of control (unexposed) and exposed specimens. Based on the results, the most significant degradation of bond strength was observed in specimens exposed to outdoor environment, whereas no significant deterioration due to temperature cycles was found probably due to the nature of applied cyclic temperature where the temperature was below the glass transition temperature of epoxy resin and the difference between the upper and lower boundary of the temperature envelope was small.

1. Introduction

Fibre Reinforced Polymer (FRP) composites possesses advantageous properties such as high strength to weight ratio, high corrosion resistance and easy application process. These properties have made it a popular choice for rehabilitation of reinforced concrete structures lately. Due to debonding being a premature mode of failure of rehabilitated RC structures, extensive research on the FRP-concrete bond system under short term loads can be found in literature. However, limited studies can be noticed on the long term performance of FRP-concrete bond subjected to environmental conditions.

Different approaches of research can be observed where some research dealt with durability of concrete beams strengthened with FRP, aiming at observations related to change in ultimate beam strength and stiffness after various environmental exposures. Other research studied the changing nature of bond strength under aggressive environment. Chajes et al. [1], Toutanji and Gómez [2], Myers et al. [3] and Li et al. [4] exposed FRP strengthened concrete beams to various environmental conditions such as freeze-thaw cycles, wet-dry cycles, combined environmental cycles, boiling water and UV radiation and studied the degradation of ultimate strength and stiffness of beams. Homam et al. [5], Dai et al. [6], Benzarti et al. [7] and Yun and Wu [8] investigated FRP-concrete bond degradation under freeze-thaw cycles, temperature cycles, alkali solutions, moisture ingression, hydrothermal ageing. They used various test set-ups such as pull-off, bend tests and single-lap-joint shear tests for their investigation. Tuakta and

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Büyüköztürk [9] applied peel and shear fracture tests to investigate the effect of moisture on FRP-concrete bond system by tri-layer fracture mechanics. As a variety of test methods and environmental conditions were applied in the research, comparison of the findings of these research studies is difficult. In regard to the suitable test set-up, Benzarti et al. [7] showed more sensitivity of single shear test (pull-out test) to environmental conditions in terms of changes in failure modes and bond strength, and suggested to use the set-up for the study of adhesive bonded joint. In addition, this test set-up simulates the intermediate flexural crack-induced debonding which is an important failure mode [10] of RC beams strengthened with FRP for flexure. Therefore, more research with similar test set-ups can be conducive to create a large database of FRP-concrete bond behaviour under various environmental conditions.

Studies by Litherland et al. [11], Phani and Bose [12], Dejke and Tepfers [13] and Chen et al. [14] mainly focused on durability of FRP and FRP in simulated concrete environment and proposed long term prediction models based on the acceleration of degradation rate applying high temperature. Regarding the use of high temperature as an accelerating factor, Robert et al. [15] stated that high temperature may cause amplification of the reduction of properties, leading to conservative prediction of long-term properties. The conservativeness involved in the application of very high temperature for acceleration requires further investigation separating high temperature from an intended degradation mechanism.

The lack in research findings of natural ageing of FRP-concrete bond is another aspect in the available literature. In the research by Nishizaki and Kato [16] the durability of CFRP-concrete bond exposed to outdoor environment of Tsukuba Japan (moderate climate) was studied for 14 years since 1992 by means of pull-off and peel tests. Although insignificant reduction of pull-off strength was observed after 14 years of exposure, the peel test showed much reduction of strength due to natural ageing. However, the results of peel tests were not conclusive since the unexposed specimens of this series were fabricated much later (in 2006) and not from exactly the same materials used in 1992. Al-Tamimi et al. [17] investigated the effect of dry exposure to sun as well as saline water coupled with sun exposure on CFRP bonded concrete specimens for more than 150 days. In addition, they applied sustained loads of 15% and 25% for both conditions. Summer environment of United Arab Emirates (UAE) was chosen for outdoor exposure (temperature stays within the range between 38 and 55 °C at least for three months). Single shear tests revealed that aggressive environment increased the bond strengths and the reason was attributed to greater polymer cross-linking due to elevated temperature. The interesting findings of the available two studies clearly impose the need for further research on natural ageing of FRP-concrete bond in different climate zones.

The purpose of this research was to investigate effects of three separate exposure conditions, namely, temperature cycles, wet-dry cycles and outdoor environment on FRP-concrete bond (both CFRP and GFRP) using single shear test (pull-out test) for up to 18 months. In addition, the effect of environmental conditions on the material properties of CFRP and concrete was another objective of this investigation [18].This paper only presents the experimental results of CFRP bonded specimens. The characterisation of concrete compressive strength under same environmental conditions is also discussed to understand the effect of material properties on the pull-out strength of CFRP-concrete bond.

2. Experimental program

Long term performance of CFRP-concrete bond was studied by exposing CFRP-concrete bond specimens to three different environmental conditions (temperature cycles, wet-dry cycles and outdoor environment) for durations up to 18 months and testing them using single shear test (referred to as pull-out test herein). In addition to the FRP-concrete bond specimens, FRP coupons and concrete cylinders were also exposed to the same environmental conditions and the material properties of FRP and concrete were identified on the day of each pull-out test; the details of the material testing can be found in the thesis by Kabir [18].

2.1. Pull-out test of CFRP-concrete bond specimens

2.1.1. Specimen geometry

Each pull-out specimen consisted of a concrete prism with dimensions of 300 mm × 200 mm × 150 mm and two layers of 40 mm wide CFRP strip bonded to the top of concrete prism. The total length of FRP was 400 mm, of which, only 150 mm was bonded to concrete (Fig. 1). The bond length chosen in this study was longer than the effective bond length calculated using Chen and Teng [19] model. A gap of 50 mm was provided between the loaded edge of adhesive bonded joint and concrete edge to prevent the boundary effect and to avoid failure in concrete prism with triangular or wedge shaped section [7,20,21]. Mazzotti et al. [20], stated that if FRP is bonded very close to the concrete edge, high tensile stress occurs in the edge of concrete leading to an early concrete splitting with triangular sections on both sides of FRP. The inclusion of a gap can reduce this stress and may prevent this type of failure. The FRP strip was extended to 200 mm beyond the concrete prism. This overhanging part was needed to facilitate gripping with the jaws of the testing machine in order to exert tensile stress on the bonded FRP.

2.1.2. Fabrication of pull-out specimens and material properties

Concrete prisms were fabricated from two batches of concrete. After concrete prisms were moist cured for one week and air cured for three weeks, concrete surfaces were prepared by exposing the aggregates with the help of a needle-gun followed by blowing off dust particles with an air blow gun. Two plies of CFRP strip were externally bonded with two part epoxy impregnation resin to the concrete prism by wet lay-up method. The FRP bonded specimens are referred to as pull-out specimens from here onwards. Apart from the pull-out specimens, CFRP coupons with 250 mm length (150 mm gauge length) and 15 mm width were prepared as per ASTM D3039/D3039M [22] to investigate the tensile properties of CFRP in exposed and unexposed environments. All the pull-out specimens and CFRP coupons were kept under lab condition (22–23 °C temperature and 61–63% relative humidity) for curing of CFRP. Moreover, concrete cylinders with diameters of 100 mm and 150 mm were cast to determine compressive strength and modulus of elasticity of unexposed and exposed cylinders according to Australian Standards [23,24].The properties of concrete from two batches are shown in Table 1, whereas Table 2 provides the properties of CFRP and epoxy resin.

2.1.3. Exposure conditions

2.1.3.1. Control specimens. Five specimens were used as control specimens (CControl-1 to 5; where C refers to Carbon and numbers from 1 to 5 refer to the specimen number). Control specimens were kept in lab environment before being tested under pull-out load.

2.1.3.2. Exposed specimens. The remaining specimens were subjected to three types of exposure conditions – (i) temperature cycles (ii) wet-dry cycles and (iii) outdoor environment.

The temperature cycles used in this study was targeted to generate the usual highest temperature (about 40 °C) in Sydney environment. In addition, the highest temperature was intentionally kept below the glass transition temperature of epoxy (T_g = 47 °C) to avoid any over-degradation of FRP or FRP-concrete bond. The minimum temperature in the cycles was kept at 30 °C due to the limitation of the drying oven (Fig. 2(a)) used. Typical temperature cycle consisted of very sharp rise to 40 °C from 30 °C within three minutes, constant 40 °C for four hours and 57 min and a gradual decrease to 30 °C and two cycles per day were maintained (Fig. 2(b)). The reason for using the cyclic temperature instead of constant temperature was to simulate the effect of natural fluctuation in temperature. The sharp increase in temperature was applied mainly to simulate the effect of sudden temperature increase and the gradual decrease in oven temperature for seven hours was chosen to allow the cooling of the specimens. Total of nine specimens were used for this cyclic temperature series and specimens were exposed to 70 cycles (35 days), referred to as CT2 series, 180 cycles (90 days), referred to as CT3 and 730 cycles (one year), referred to as CT4 series.

The wet-dry cycles consisted of 1 week wetting followed by 1 week drying and at least 95% RH was maintained for wetting. Although constant immersion in water was observed to be used in a number of previous studies, wet-dry cycles were chosen for this current study to simulate the condition of cyclic moisture absorption and desorption of FRP-concrete bond, which is closer to reality. The one week time for both wetting and drying process was selected to allow the specimens to gain and loose sufficient amount of moisture. Wet environment was created using a humidifier in a small closed chamber. Fig. 3(a) shows the photo of the humidity chamber. Although the main aim was to maintain constant temperature during wet and dry cycles, steam generated from humidifier raised the temperature to about 30–32 °C. The humidifier was operated twice in a week for 10 h each time and the peak of the temperature plot in Fig. 3(b) represents the high temperature