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Fatigue performance of near-surface mounted CFRP strips embedded in concrete girders using cementitious adhesive made with graphene oxide

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HIGHLIGHTS

- NSM FRP strengthening of beams by cement-based adhesives under fatigue loading has not been studied.
- Cement-based adhesive (IHSSC-CA) is easier to use during NSM CFRP application than epoxy.
- Fatigue load range and frequency were designed to simulate service load conditions.
- Results show better composite action between NSM CFRP and concrete by using IHSSC-CA.
- A damage accumulation model of RC beams under fatigue loading is also proposed.

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ABSTRACT

In this study, the flexural performance and effectiveness of the use of innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA) for the strengthening and repair of reinforced concrete (RC) beams using the near-surface mounted (NSM) carbon fibre reinforced polymer (CFRP) technique under fatigue loading was investigated, with the purpose of improving the serviceability of these RC beams. Cementitious materials with graphene oxide were used to produce the IHSSC-CA. The effect of fatigue loading on the behaviour of all tested beams was assessed by monitoring the deflection, crack widths and strain in concrete, steel reinforcement and CFRP strips during fatigue loading. An analytical model is also proposed to predict the cumulative damage-fatigue life relationship. The test results show that using cement-based adhesive (IHSSC-CA) could represent an excellent alternative to epoxy adhesive, as it improves the serviceability of NSM CFRP-strengthened and repaired RC members. Moreover, the proposed damage accumulation-fatigue life model shows good agreement with the experimental results and can be used in the design of RC members strengthened and repaired with NSM CFRP using IHSSC-CA and epoxy adhesives.

1. Introduction

There are significant numbers of concrete structures worldwide, for example offshore structures, highway and railway bridges and pavements, which are subjected to fatigue loadings. Harsh environmental conditions, deterioration due to ageing and increased applied service loads cause these structures to be at more risk. Therefore, the need for strengthening and repair solutions for these structures, especially bridges, is urgent to extend their service life and guarantee people's safety.

The conventional method of strengthening, rehabilitation or repair of deficient concrete structures that is used in Europe and Australia involves externally-bonding (EB) steel plates to the tension surface of the concrete member. Although this method can increase the strength and stiffness of concrete members and improve their flexural performance, these heavy steel plates are difficult to fix and subject to corrosion. Moreover, they have a tendency for debonding before reaching the required design load, because of the flexural and shear forces that develop at the plate ends [1]. Therefore, to upgrade, strengthen or repair existing ageing concrete structures, fibre reinforced polymer (FRP) has become an accepted option, as it has many advantages over steel plates, because of its properties, such as its lightweight, high strength, outstanding fatigue strength, resistance to corrosion, ease of installation, and reduced maintenance cost [2].

Throughout the past three decades, strengthening using externally-bonded (EB) glass or carbon FRP has attracted substantial

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attention worldwide in the civil construction industry in terms of increased strength capacity and fatigue life [3,4]. The EB FRP technique is consist of bonding FRP, unidirectional or multidirectional, sheets, laminate or fabric to the concrete surface using a suitable adhesive (commonly an epoxy) after preparing the external surface of concrete by using grinding, sandblasting or high pressure water jet to remove the weak concrete surfaces. In spite of the currency of EB FRP method, early debonding of FRP has been found to happen from the concrete surface at low axial strain of FRP. Thus, this method is not utilise the full tensile strength of FRP [5]. For this reason, the EB FRP method have been replaced by the near-surface mounted (NSM) FRP strengthening method. In this NSM FRP method, the FRP strips or rods are bonded into slits cut into the concrete surface using the suitable adhesive (commonly an epoxy).

The NSM FRP system using organic adhesives (epoxy adhesives) shows an increase in the ultimate capacity and fatigue life of strengthened RC structures [6–15]. However, the use of organic adhesive with the FRP strengthening technique has significant issues, owing to the emission of toxic fumes throughout curing, these organic adhesives are highly flammable and needs a minimum temperature for site application (temperatures more than 10 °C) [16]. Moreover, when exposed to temperatures more than 70 °C, organic adhesive loses its properties [17]. Therefore, the need for alternative bonding adhesives to epoxy resins has become necessary for FRP applications. Cement-based adhesives may be suitable alternative adhesive materials, since they have good bonding properties and can withstand high temperatures. They are also non-flammable and there is no emission of toxic fumes [18,19].

In a previous study by Mohammed et al. 2016 [20], the authors established an innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA). The compressive and tensile strengths of this innovative adhesive at 28-day was of 101 MPa and 13.8 MPa, respectively. Graphene oxide (GO) was used to produce the IHSSC-CA. This high strength is believed to be the key-factor in the increase of the bond between NSM FRP-adhesive-concrete substrate in NSM FRP method.

To date, the flexural strengthening or repair of RC beams using NSM FRP techniques with cement-based adhesive under fatigue loading conditions has not been investigated. Therefore, the objective of the present study is to examine the flexural behaviors of RC beams strengthened and repaired with the NSM carbon FRP technique using cement-based (IHSSC-CA) and epoxy adhesives (for comparison purposes) under fatigue loading conditions.

2. Experimental program

2.1. Beam details

Ten RC beams were prepared and tested under monotonic and fatigue loading. Two beams were conventional control beams, and the remaining beams were strengthened and repaired using NSM CFRP method with cement-based (IHSSC-CA) and epoxy adhesives. To simulate a real RC bridge girder with many years of service, four RC beams were pre-cracked before strengthening using the NSM CFRP technique. The monotonic conventional beam was designed along with ACI 318-11 [21] to guarantee that flexural failure happened prior to shear failure. In addition, the monotonic strengthened beam was designed along with ACI 440.2R-08 [22] to attain an increase in load-carrying capacity of about 40% over a monotonic conventional beam through using two 1.4 × 20 mm CFRP strips with epoxy adhesive. For more information about the details of the beams, see Al-Saadi et al. 2017 [23]. Fig. 1 presents the beam details and the test matrix is shown in Table 1. The first letter of the specimen ID “M” means “monotonic test” and “F” means “fatigue test”; the next letter “C” refers to “control beam”, “S” refers to “ strengthened beam” and “R” refers to “ repaired beam”; and the final letter “C” means “cement-based adhesive (IHSSC-CA)” and “E” means “epoxy adhesive”.

2.2. Materials

All concrete beams were casted using ready-mixed concrete. The aggregate size was less than 14 mm. To determine the workability of the concrete mix, slump test was carried out along with ASTM C143-12 [24], giving a slump of 90 mm (medium workable mix). The compressive and splitting tensile strengths of the concrete at the age of testing (8 months after casting) were found along with ASTM C39-14a [25] and ASTM C496-11 [26], respectively, as shown in Table 2. The steel bars properties were obtained from tension tests along with ASTM A615– 15a [27] and ASTM A370 – 15 [28], as shown in Table 2. MBrace CFRP Laminate 210/3300 was used in this work and its properties were found from tension tests along with ASTM D 3039-14 [29], as shown in Table 2. MBrace laminate adhesive was used in this work and its properties, as specified by the manufacturer, are shown in Table 2. Cement-based (IHSSC-CA) bonding agent was also used in this study. The compressive and splitting tensile strengths of the IHSSC-CA at different ages were found along with ASTM C39-14a [25] and ASTM C496-11 [26], respectively, as shown in Table 2. For more information about the IHSSC-CA, see Mohammed et al. 2016 [20].

2.3. Specimen fabrication and preparation

The presence of cross-welded joints appears to reduce the fatigue life of steel reinforcement. Therefore, all the steel reinforcement cages were fabricated without any welding using a long-handled rod tying tool with a 110 mm black rod tie, as shown in Fig. 2. After the steel reinforcement cages were fabricated, six strain gauges were installed on the tensile steel reinforcement bars (Fig. 2). Special formwork consisting of two moulds made of timber with metal fasteners was used in this study (Fig. 2). Before the steel reinforcement cages were placed inside the formwork, appropriate 30 mm plastic spacers were fixed on the bottom reinforcement to provide the cover needed. Additional 15 mm size plastic spacers were also fixed on the side reinforcement, as shown in Fig. 2. Ready- mix concrete was used to cast all the beams. Slump tests were carried out to determine the workability along with ASTM C143-12 [24], as shown in Fig. 2. Next, the concrete was poured into each mould and compacted in four layers. Each layer was compacted using hand vibrators (Fig. 2). For concrete cylinder specimens, plastic cylinder moulds 100 × 200 mm were used. Forty concrete cylinders were cast. The concrete was placed in the moulds in three equal layers and each layer was compacted using a vibrating table until sufficient compaction was achieved (Fig. 2). After casting, the upper surface of the concrete beams was levelled and finished with a steel trowel, and the top surface of each specimen was then covered with MasterKure 100WB curing material to prevent evaporation of water (Fig. 2). The cast beams and cylinders were de-moulded 72 h after casting was completed. The cast specimens were labelled and covered with MasterKure 100WB curing material, as shown in Fig. 2.

After 28-days of curing, the strengthened RC beams were post-strengthened using NSM CFRP, while the repaired RC beams were firstly pre-loaded to about 65% of the ultimate capacity of the conventional control beam (up to service load) and the cracks were recorded on each beam. Then, the beams were unloaded and repaired with NSM CFRP. Two NSM CFRP strips 1.4 mm thick × 20 mm wide were used for strengthening and repair each beam.

Firstly, slits were made in the external tension face of the beams by using a concrete saw (Fig. 3). For the application of IHSSC-CA,