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Experimental and theoretical analysis of severely damaged concrete beams strengthened with CFRP

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HIGHLIGHTS

- Repairing of severely damaged reinforced concrete beams with CFRP.
- Beams fabricated from concrete with fly ash, waste rubber and polypropylene fibres.
- Theoretical verification of experimental results adopting shear friction model.
- Reasonable accuracy of theoretical results compared to the experimental results.

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ABSTRACT

In recent years, carbon fibre reinforced polymer (CFRP) has gained its popularity for repairing reinforced concrete structures. At the same time, numerous research have been conducted on the use of different admixtures in the concrete to enhance its various physical properties. This study investigates the repairing techniques of three concrete beams which contain fly ash, waste rubber and polypropylene fibre in the concrete mix. The control beams were loaded up to its ultimate strength (severely damaged) and then repaired using CFRP, externally bonded to the beam soffit and anchored with complete CFRP wraps. The repaired beams were tested under four-point bending set-up to investigate its failure modes and improvement in strength, stiffness and ductility. In terms of strength and stiffness, two of the repaired beams (with fly ash and waste rubber) exceeded the capacity of the control beams, whereas the beam with polypropylene fibre gained around half of the strength and stiffness compared to its control counterpart. While the ductility of the repaired beams was found to be less than the control ones, the repaired beams exhibit pseudo ductile behaviour. In addition, an analytical study is conducted considering the effect of transverse CFRP anchorage wraps on the flexural capacity of repaired beams using shear friction model which can predict the strength of repaired beam to great accuracy.

1. Introduction

Local failure of structural members under an extreme event, such as earthquake or blast loading may require retrofitting of severely damaged members to maintain partial functionality of the structure. A typical example may be where a bridge girder is subjected to localised failure due to an extreme event, however, required to be functional immediately/temporarily to allow for partial traffic flow. Lately, the use of fibre reinforced polymer (FRP) composites for the rehabilitation of concrete structures has become a popular choice due to its advantageous properties – high strength to weight ratio, high resistance to corrosion and ease in application. It is more practical and common to repair structural elements, e.g., reinforced concrete beams within the service loading regime and FRP composites already proved its performance in such repairing. However, an extreme load event can exceed the serviceable limit resulting in excessive cracking and large plastic deformation in reinforced concrete beams and therefore investigating the suitability of FRP composites to repair such severely damaged beams can be an important investigation. The theoretical analysis of these severely damaged beams retrofitted using CFRP can also be different compared to the retrofitted beams under

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service load due to the fact that the latter scheme experienced tensile cracking of concrete only, whereas the former one was subjected to high degree of permanent deformation. As a result, incorporation of permanent deformation is required to consider in a theoretical model for predicting the strength of the repaired beams.

Limited research studies have been conducted on the strengthening of damaged reinforced concrete beams using FRP. Arduini and Nanni [1] investigated the behaviour of pre-cracked reinforced concrete (RC) beams strengthened with carbon FRP (CFRP) sheets where pre-cracking was induced by service load. Siad et al. [2] conducted experiments on the performance of two different CFRP-repair schemes on beams damaged by combination of pre-crack and corrosion of steel reinforcement. Pre-cracking was induced by 60% of ultimate load followed by different degrees of corrosion. The beams were repaired by using (a) CFRP sheet on the tension side and (b) CFRP sheet on the tension side, plus U-wrap covering the complete length of the CFRP sheet. Although both methods improved the strength and stiffness of beams, the second method outperformed the first one and added to the ductility unlike the first technique. Benjeddou et al. [3] conducted experimental studies on damaged reinforced concrete beams repaired by externally bonded CFRP laminates on the tensile face of the beam. In this study, four different degrees of damage: 0% (without pre-cracking), 80% (the beam was in elastic range without cracks), 90% (the beam reached plastic stage with two cracks on each side of mid-span in a four-bending test) and 100% (more cracks appeared: the beam was loaded to the full capacity of control beam) were applied before repairing, and the effect of the cross-sectional area of CFRP and concrete strength classes on the effectiveness of the repaired beams were also investigated. The load carrying capacity and the rigidity of the repaired beams of all degree of damages were found to be significantly higher than those of the control beams. However, this study did not apply any anchorage wrap to prevent/delay FRP delamination or concrete cover separation, and the focus of the study was experimental investigation only. Although aforementioned studies considered repairing of pre-cracked and/or corroded beams, retrofitting of beams damaged completely due to concrete crushing and/or complete loss of steel reinforcement capacity were not investigated.

Apart from the retrofitting of conventional concrete beams, the concrete as a material has undergone various changes in terms of its mix design. Different admixtures, such as, supplementary cementitious materials, fibres and waste materials are often used in concrete to improve the performance of various properties which includes, but are not limited to, durability, toughness and ductility. The effect of tyre-rubber chips to replace mineral aggregates in concrete was reported in literature and found to be effective to improve toughness [4] and ductility [5] of concrete. Sharifi [6] replaced coarse aggregates with Styrene Butadiene Rubber (SBR) to improve the damping properties of concrete. Currently, various forms of metallic and synthetic fibres are used to enhance the concrete performance. Song et al. [7] added nylon and polypropylene fibres in concrete which can improve impact resistance and reduce cracking potential due to enhancement in restrained shrinkage property and improved split tensile strength. Since fibres are found to be effective to bridge cracks in concrete, the application of fibres to reduce the crack width due to restrained shrinkage is becoming increasingly popular. Banthia and Gupta [8] reported the effectiveness of polypropylene fibres in controlling the plastic shrinkage cracking of mortar matrix. The influence of recycled macro polypropylene fibres in concrete was investigated and found to be effective in terms of enhancing the post-cracking behaviour of concrete [9,10]. The use of mineral admixtures, such as fly ash and silica fume reduces the porosity of cement matrix [11] and acts as supplementary cementitious materials. Since the use of different admixtures in concrete and addition of fibrous materials are becoming common nowadays, investigating the repair and strengthening techniques of concrete beams, made from the aforementioned materials, using CFRP can be valuable.

To theoretically predict the ultimate flexural capacity of a repaired concrete beam using FRP, the governing failure mode should be taken into consideration [12–14]. In addition to concrete crushing, steel reinforcement yielding and CFRP fracture, delamination of CFRP and concrete cover separation are found to be the common modes of failure which are sudden and catastrophic [15–17] and thus undesirable, especially in the earthquake prone zone. Consequently, research have been performed to delay the debonding and to improve the ductility by providing end plate anchorage. Different anchorage schemes were investigated and proposed in the literature [18–21]. Since these schemes delay the debonding process, it contributes to the flexural capacity of the composite beam [22,23]. Accordingly, theoretical analysis should include the effect of anchorage in the model to predict the ultimate moment capacity of a section. Based on the results of extensive research, ACI committee 440 [24] provided design guidelines for strengthening of concrete beams for flexure and shear. However, the guidelines did not consider the effect of end anchorages on the longitudinal shear stress capacity of tensile FRP reinforcement externally bonded to concrete. FIB-CEB Task Group 9.3 [13] accounts for the capacity of the beam at the end anchorage by considering the required bond length. Even though the equation proposed by FIB-CEB yield satisfactory results [15], the shear friction model proposed in [25] consider the properties and area of the transverse CFRP, used for the anchorage, on the flexural capacity of the beam. Therefore, the shear friction model is expected to reflect the actual behaviour of CFRP-concrete composite beams with end anchorage.

The present study proposes the retrofitting techniques of severely damaged concrete beams of three different mix designs, containing fly ash, waste rubber and polypropylene fibre. The surface preparation technique for the damaged beams is different than the conventional concrete beams subjected to service load and discussed in this paper. Following the surface preparation, the damaged beams are repaired for flexure using CFRP longitudinal reinforcement anchored at both ends and mid-span and tested under four-point bending. The experimental outcomes are examined in terms of ultimate strength, flexural stiffness and ductility and compared against the control ones to observe the effectiveness of the proposed schemes. In addition, theoretical investigation based on shear friction model is conducted considering the effect of anchorage and the permanent deformation of the damaged beam to predict the ultimate moment capacity of the repaired beams.

2. Experimental program

2.1. Fabrication of beams

Three reinforced concrete beams with identical geometry and steel reinforcements were fabricated as part of separate research studies by Ghosni [26], Haddad [27] and Sharifi [6] from three different concrete mixes. These beams are considered as the control beams for this study. Control Beam 1 (CB1) was fabricated by substituting 30% cement content (shrinkage limited Portland cement) with Fly Ash (FA) [Class F]. The fabrication of Control Beam 2 (CB2) was carried out by partially replacing coarse aggregates with 6% –12 to 15 mm Styrene Butadiene Rubber (SBR) by mass. Similar to CB1, cement was also replaced in CB2 by FA with an amount of 30% by mass. For Control Beam 3 (CB3), 1% –19 mm Fibrillated Polypropylene (PP) fibre with specific gravity of 0.91 and nominal