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Assessment of effectiveness of CFRP repaired RC beams under different damage levels based on flexural stiffness

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HIGHLIGHTS

▶ This paper investigates the CFRP repair effectiveness of RC beams.
▶ Flexural stiffness is useful indicator to monitor the CFRP repair effectiveness.
▶ Repair with CFRP recovers the stiffness and increase it more than undamaged stiffness.
▶ Repair with CFRP increased the load capacity regardless of the pre-repair damage level.
▶ Failure modes are governed by pre-repair flexural cracks which cause CFRP debonding.

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ABSTRACT

This paper presents a study to determine the effectiveness of Carbon Fiber Reinforced Polymer (CFRP) sheets as a flexural repair system for Reinforced Concrete (RC) beams. The effectiveness of these sheets is ascertained by monitoring the flexural stiffness recovery. Experimental work is conducted on scaled beams where four beams are used as the datum. The first beam is without CFRP sheets, the second is a repaired beam after pre-damaged under design load limit, whilst the third is a repaired beam after pre-damaged under steel yield load limit, and the fourth is a repaired beam after pre-damaged under ultimate load. Comparisons are made based on the flexural stiffness recovery, crack patterns, load capacity, and failure modes of the beams. The study validates the ability of the flexural stiffness change in order to monitor the effect of the damage as well as the effectiveness of the repair on stiffness recovery. The results prove the effectiveness of the CFRP sheets as a repair technique which increases the flexural stiffness and the ultimate load capacity whatever the pre-repair damage levels. In addition, this study indicates the ability of re-repairing the beams in the case of CFRP debonding. The failure modes are controlled by the pre-repair damage flexural crack wherein it causes the CFRP debonding.

1. Introduction

Repairing of RC structures has become increasingly important, especially in the last decade. Many RC structures are damaged mostly due to various forms of deterioration, such as cracks or large deflections. These are affected by different factors, like earthquakes, vibrations, corrosion of reinforced bars, and environmental changes. Externally Carbon Fiber Reinforced Polymer (CFRP) is one of the new materials used to strengthen or repair RC structures. Research on use of FRP began in Europe in the 1960s [1], and the first investigation on the use of FRP plate bonding was at the Swiss Federal Laboratory for Materials Testing and Research (EMPA) in 1984 [2]. FRP materials have the advantage of high tensile strength fibers and excellent corrosion resistance, fatigue resistance, good performance at elevated temperatures, low density, and high specific stiffness and strength [3,4]. Most of the research on using FRP plate bonding for flexural strengthening has been carried out over the last decade [5–7]. Indeed, there has been a tremendous growth in recent years as result of worldwide need for structural performance improvement and retrofitting works. The use of the bonded prefabricated FRP plate has been found to ensure the highest degree of material uniformity and quality control [6,8,9]. An increase in the ultimate capacity is observed after adding the externally bonded CFRP sheets [10], and the ultimate capacity of strengthened beams increases by up to 230%. Even for the preloaded beam before strengthening, the ultimate capacity is significantly increased which indicates good performance for repair application [11]. Strengthening of corroded RC beams with externally bonded CFRP plates was found to increase the ultimate capacity by 37–87% [12]. CFRP laminate for strengthening of RC beams shows the ability for doubling the load capacity with deflection close to that of

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the un-strengthened beams [13,14]. Roy and Chakraborty [15] found that the hybrid laminate of Kevlar/epoxy–graphite/epoxy is more flexible than the graphite/epoxy one. Repairing of corroded RC beams with bonded CFRP sheets restores the undamaged state stiffness and reduces the ultimate deflection in comparison to the un-strengthened beams [16]. Bouchikhi et al. [17] concluded that the interfacial shear stress is affected by the FRP plate thickness and the adhesive layer, where the interfacial stress obviously increases with the increase in the FRP thickness. Experimental work carried out by El-Maaddawy et al. [18] proved the effect of the CFRP cross-sectional shape and the loading conditions on the repaired RC members. Using CFRP sheets with U-shape anchorage can increase the capacity of the strengthened RC beam by up to 10–24% depending on the number of the U-shape anchors along the beam length [18]. Repairing of damaged thin steel structures with FRP was found to improve its behavior to the stage of undamaged [19]. Repairing of damaged steel beams with CFRP sheets increases the ultimate capacity up to 22.5%, and the pre-repair levels do not affect the strain development in the CFRP sheets while they do affect the debonding progression of the sheet [20]. Based on early studies conducted over the last decade on the use of the bonded FRP plates to beam soffit as flexural system, a number of failure modes have been observed. These modes can generally be classified as (1) flexural failure by FRP rupture, (2) flexural failure by crushing of concrete at compression, (3) shear failure, (4) concrete cover separation, (5) plate end interfacial debonding, (6) intermediate flexural crack induced interfacial debonding and (7) intermediate flexural shear crack induced interfacial debonding [5–7,9,21–25]. Using U-shape CFRP anchors for the CFRP repair system of corroded RC structures, alters the failure mode from CFRP debonding to CFRP rupture [16]. Using CFRP sheets with U-shape anchorage results in CFRP rupture failure mode, while increasing the number of the U-shape anchorage can transfer the failure mode to combine with the flexural–shear mode [26]. Stress concentration at the damage region prior to repair of steel beams with CFRP sheets results in local debonding failure [20]. Strengthening of RC beam with an externally bonded CFRP plate was found to fail as Intermediate Crack (IC) debonding, and strengthening with CFRP fabric found to fail as IC adhesive failure at CFRP/concrete interface while strengthening with GFRP fabric found to fail as GFRP rupture [27]. Fiber direction of the CFRP sheets has a significant effect on the shear capacity of strengthened deep RC beams [28]. Using U-wrap CFRP strips increases the shear capacity of the RC beams up to 25%, while using the CFRP sheets increases it by up to 50% [29]. Using close-wrap CFRP strips increases the shear capacity to 75%, while using the CFRP sheets increases it by up to 114% [29]. Strengthening of RC beams with FRP sheets increases the shear strength by 26%, and using of mechanical anchorage showed up to 48% higher shear capacity than beams without mechanical anchorage [30].

The present study aims to investigate the effect of different pre-repair damage load levels on repair effectiveness using externally bonded CFRP sheets. This objective is addressed by monitoring the effect of CFRP repair on the flexural stiffness change which is calculated based on the secant modulus of the load against deflection curves. Following this, the study presents the effect of different pre-repair damage levels on the recovery of the flexural stiffness change as well as on the increase of the load capacity. Moreover, the paper also presents the observed failure modes.

2. Experimental work

In order to investigate and to validate the effect of the pre-damage level on the effectiveness of CFRP sheets as repair system and its influence on the stiffness recovery, four RC beams are prepared for the tests and the clear span length for each beam is 2.2 m, with a beam cross section of 150 mm and a width of 250 mm. Beams are designed according to ACI 318-08 [31], whereby it is reinforced with a two 12 mm diameter deformed steel bars. Figs. 1 and 2 show the beams' detail and test setup, whilst Table 1 shows the RC beams properties. RC beams are tested under point load located at mid-span, where the load is applied gradually with a loading rate of 4 kN/min. One of the beams is used as the datum (DB) where it is tested under cyclic loading of 10 kN for each cycle up to failure. Other beams are initially damaged under design load limit (RBD), steel yield load limit (RBY) and ultimate load limit (RBU).

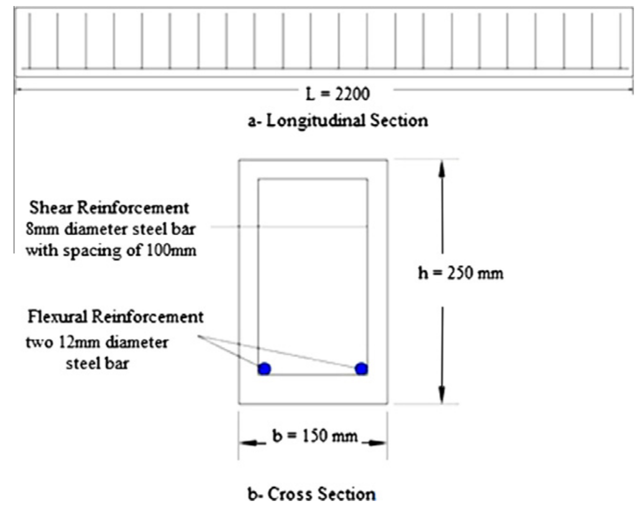

Fig. 1. Beam dimensions and details.

For the purpose of repairing, beams are turned over and roughness equipment was used on the tension face to get a roughened surface finish and to have as much friction as possible with the CFRP sheet. Fig. 3 shows the beam surface after roughening and fixing of the CFRP sheets. The surface is cleaned by using air gun to avoid any dust on the surface, where the substrates must be sound, dry, clean and free from laitance, standing water, grease, oils, old surface treatments or coatings and all loosely adhering particles. The concrete is cleaned and prepared to achieve a laitance and contaminant free, open textured surface. When the concrete surface is prepared, the CFRP sheet is fixed by using adhesive material, and then it is left for one month to harden. Repairing with CFRP sheet is in accordance to ACI 440.2R [32] Code requirements where a CFRP sheet with 100 mm width and 1.2 mm thickness is used, and the length is along the clear span of the beam. The CFRP properties are shown in Table 2. Static load is applied again on the repaired beams and gradually with an increase rate of 4 kN/min up to failure. During the test, load against deflection, steel strain, and CFRP strain is carried out. Crack pattern and failure modes are highlighted. The repaired beams are left for 18 days after the fixing of the externally bonded plate in order to give the adhesive material sufficient time to harden, as suggested by Fayyadh and Abdul Razak [33].

3. Flexural stiffness change

For flexural damage scenarios, the flexural rigidity or the flexural stiffness is an change for the state of the structure under different damage levels. Since the data obtained from the static test load versus deflection, the relationship of the stiffness will be based on the theoretical equation of the deflection calculation in the case of flexural stiffness. For a simply supported beam with a concentrated load at the mid-span, the deflection can be calculated as in the following equation:

$$\delta = \frac{PL^3}{48\mathrm{EI}} \tag{1}$$

The flexural stiffness (EI) can be calculated as in the following equation:

$$\mathrm{EI} = \frac{P}{\delta} \cdot \frac{L^3}{48} \tag{2}$$

In order to calculate the flexural stiffness, the secant modulus (Ks) of the load against deflection curve will be used to find $\frac{P}{\delta}$. The flexural stiffness for any RC beam will be affected by the applied load level, and with a load higher than the first crack load