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Grooving methods in square RC columns strengthened with longitudinal CFRP under cyclic axial compression

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ABSTRACT

The current research investigates the application of carbon-fiber reinforced polymer (CFRP) composites with longitudinally aligned fibers for enhancing the compressive strength and ductility of square reinforced concrete (RC) columns under cyclic axial compression. Global buckling of the composite described may result in the debonding of CFRP off the specimen surface, which hinders proper enhancement in the ductility and compressive strength of the strengthened specimens. To postpone the buckling of the longitudinal CFRP sheets under compression, the recently developed grooving method (GM) was employed in the current research and compared with the externally bonded reinforcement (EBR) technique using the conventional surface preparation technique. For this objective, 8 square RC columns were subjected to cyclic axial compression. The experimental parameters consisted technique employed for longitudinal strengthening of the columns and the presence (absence) of intermittent confining wraps. Two grooving techniques, the externally bonded reinforcement on grooves (EBROG) and the externally bonded reinforcement in grooves (EBRIG), were used. Experimental results indicated the considerably higher contribution of the grooving method, relative to that of the conventional EBR, to limiting the buckling of CFRP sheets and to enhancing the ductility and compressive strength of the columns. It was observed that when the GM is employed, the compressive strength of FRP is enhanced based on the exploitation of the compressive capacity of the carbon fibers in the longitudinal sheets. The results illustrated that in the specimens longitudinally strengthened using the EBROG or EBRIG techniques, fiber compressive capacity in the composite reached 43.9% and 69.3% of ultimate tensile strength of fibers in flat coupons; this amount was only 9.6% for the columns strengthened through the EBR technique.

1. Introduction

Earthquakes worldwide have proven the vulnerability of reinforced concrete (RC) constructions to seismic loading. Poorly detailed columns are the most critical structural members, which may fail due to concrete crushing, longitudinal reinforcing bar buckling. The employ of fiber reinforced polymer (FRP) composites has been identified as an efficient method for the strengthening and repair of columns. Many experimental and numerical researches have been guided to investigate the contribution of FRP jackets to the compressive strength of RC columns. In one stream of these studies, the behavior of CFRP strengthened columns has been investigated using composite fibers laid in the hoop direction. In the majority of these studies, strengthening of concentrically or eccentrically loaded concrete columns has been practiced using transverse FRP strips in which fibers are aligned in the hoop direction to provide confinement by resisting hoop tensile stresses. This configuration has reportedly led to considerable improvements in the behavior of confined columns, including both their ductility and load carrying capacity [1–6]. Moreover, a number of studies have been conducted in recent decade focusing on the presence of axial load on the column during strengthening and also interaction between internal steel reinforcement and external CFRP strengthening [7,8].

While transverse FRP strips contribute to the compressive strength of column specimens due to enhanced compressive strength of concrete resulted from confinement, longitudinal FRP composites contribute to enhancing their direct compression strength [9–14]. Most researchers and construction codes state that although CFRP sheets are capable to resisting compressive stress, their compressive strength is lower than their tensile strength. A major cause of this issue might be the buckling of CFRP under compressive stress. Furthermore, typical externally bonded reinforcement (EBR) configurations exhibit a low flexural rigidity so that buckling can happen at a small stress. Longitudinal sheets should not be, therefore, employed as compression strengthening, or if used, provisions such as lateral supports should be made to fix

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longitudinal FRP sheets against buckling [15–20].

Confining longitudinal CFRP sheets by transverse CFRP sheets is a technique that provides lateral support for longitudinal strips to prevent their buckling [11,14,21,22]. In an experimental research, Tan [14] evaluated the load carrying capacity of concrete specimens strengthened with unidirectional, mainly in the longitudinal and transverse directions, CFRP strips. The experimental results showed that the longitudinal CFRP strips led to the maximum load of the specimen if suitably restrained from local buckling by transverse CFRP strips. Issa et al. [11] evaluated the behavior of specimens through different configurations of transverse and longitudinal FRP sheets under monotonic axial loading to conclude that the compressive strength of specimens could be considerably increased by longitudinal CFRP sheets if they were transversely strengthened by CFRP strips.

While there is no shortage of published reports on simultaneous application of longitudinal and transverse FRP composites, few, if any, studies have been reported in the literature on the behavior of column specimens strengthened only using longitudinal CFRP sheets. As already mentioned, confining longitudinal CFRP strips with transverse CFRP wraps help prevent global buckling. The present study uses the newly developed grooving method (GM) for strengthening RC specimens to determine whether this method is able to postpone the buckling of longitudinal CFRP composites and their debonding off the column surface. The method was first introduced as a substitute for the conventional EBR technique to either prevent or postpone the debonding of CFRP strips off the column surface in beams strengthened with FRP on their tension face [23,24]. Experimental results showed that GM, later renamed to ‘externally bonded reinforcement on grooves’ (EBROG), enhanced the load carrying capacity of strengthened beams, when compared with the EBR technique, and changed the failure mode of the beams from one of debonding to one of FRP sheet rupture [23]. More recently, a different version of GM named the ‘externally bonded reinforcement in grooves’ (EBRIG), has been developed in which CFRP composites attached in direct contact with the inside of the grooves' surfaces. The authors concluded that the EBRIG method yielded greater load bearing capacities in the strengthened columns, particularly when more FRP layers were applied [24].

Despite the rather large body of literature and different databases available on columns strengthened longitudinally through the EBR technique under monotonic compressive loading, the literature on RC columns longitudinally strengthened using the EBROG method under monotonic compressive loading is relatively small. According to these studies, columns strengthened through GM exhibit considerable enhancements in their compressive load carrying capacity, while those strengthened through the EBR method and those tested only with the epoxy in grooves without using any longitudinal fibers show no considerable enhancements in their compressive capacity [12,13].

Apart from these, there is almost no research reported on the behavior of RC columns longitudinally strengthened through GM method under cyclic compressive loading. This is motivated by the observation that RC elements such as port structures impacted by the sea waves and bridge columns subjected to traffic loading are typically subjected to axial cyclic compression loadings. Present research was, thus, designed to investigate the effects of longitudinal strengthening techniques and confinement on the ductility and compressive strength of RC columns longitudinally strengthened using the EBROG and EBRIG techniques under cyclic compressive loading. The average compressive stress of the composite fibers was calculated for the longitudinally strengthened specimens and the test results obtained were compared with the fibers' tensile strength of flat coupons.

2. Experimental program

2.1. Specifications of specimens

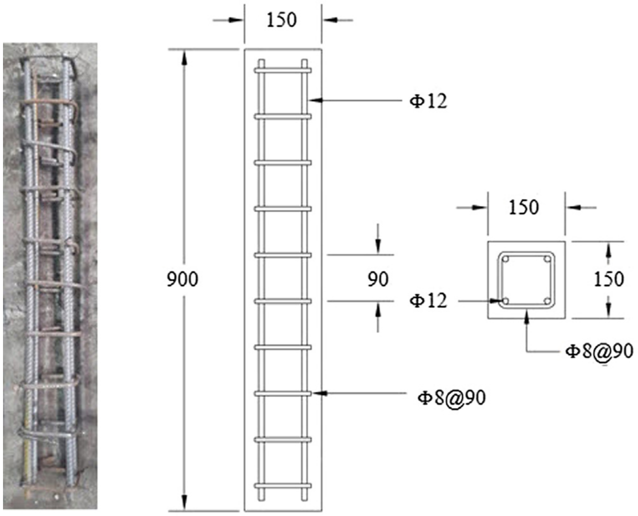

Fig. 1. Reinforcement details of column specimens (dimensions in mm).

Eight square RC columns, with cross sections of 150 × 150 mm^2 and 900 mm height, were used for the purposes of this study. All column specimens were longitudinally reinforced with 4 steel rebars, each 12 mm in diameter, to provide a longitudinal steel ratio of 2.0% which is higher than the minimum value required by ACI-318 [25] and is a practical steel ratio in many projects. The transverse reinforcement used as ties included ten steel rebars, 8 mm in diameter with a concrete cover of 20 mm and spaced at 90 mm. Details of the reinforcement employed in the columns are illustrated in Fig. 1.

2.2. Material characteristics

Concrete with a practical compressive strength of 30 MPa was employed. The materials employed included 5–10 mm coarse aggregate, 0–5 mm sand, and type I Portland cement with concrete mixture proportions (cement: sand: coarse aggregate: water-cement ratio by weight) of 1:3.4:2.52:0.36. All the columns were cured in a water pool at ambient temperature for 28 days under standard condition. The ultimate and yield stress of the 8 mm rebars were measured as 627 and 470 MPa, respectively. The values for the same stresses in the case of the 12 mm rebars were 698 and 447 MPa, respectively.

The fibers employed in current research were unidirectional carbon fibers with a nominal design thickness of 0.17 mm (SikaWrap-300C). The epoxy resin Sikadur-330 was employed as the matrix phase of the CFRP composites. Based on the ambient temperature (25 °C) and according to the producer's catalog, the resin of the strengthened specimens was cured for 7 days before testing. The properties of the resin and the fibers as provided by the producer are presented in Table 1 [26].

2.3. External strengthening

Three different strengthening methods were employed for adhering the longitudinal CFRP; i.e., EBR, EBROG, and EBRIG. Detailed

Table 1
Mechanical properties of CFRP materials [26].

Material	Type	Thickness (mm)	Ultimate tensile strength (MPa)	Elastic modulus (GPa)	Ultimate tensile strain (%)
Fibers	SikaWrap-300C	0.17	3900	230	1.50
Resin	Sikadur-330	–	30	4.5	1.50