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Behavior of RC columns confined with CFRP using CSB method under cyclic axial compression

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HIGHLIGHTS

- Eleven strengthened RC columns were tested under cyclic axial compression loading.
- Three techniques IW, CSW and CSB were used for confining of columns.
- Two different strengthening methods EBROG and EBR were employed for longitudinal strengthening of columns.
- The best performance in ductility and load capacity was observed in combination of CSB and EBROG techniques.

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ABSTRACT

It is the aim of this study to investigate the influences of the recently developed corner strip-batten (CSB) technique on reinforced concrete (RC) columns strengthened with carbon fiber reinforced polymer (CFRP) under cyclic axial loading. In CSB technique, CFRP battens do not undergo any curvature in transverse strengthening the specimen but are stretched as flat sheets. For the purposes of this study, 11 one-third scale RC columns were subjected to cyclic axial loading. The columns were strengthened with transverse FRP sheets using the three confining techniques of FRP composites employed as wraps, corner strip-wrap (CSW), and CSB. Furthermore, the two different strengthening procedures of externally bonded reinforcement on grooves (EBROG) and externally bonded reinforcement (EBR) were employed for bonding longitudinal composite strips. Results revealed that the columns confined using the CSB method exhibited improved load carrying capacity, ductility, equivalent damping ratio, energy dissipation, and secant stiffness under cyclic axial compression loading by 41.9%, 102.5%, 47.6%, 31.0%, and 25.9%, respectively, when compared with the reference column. Moreover, EBROG was discovered to have a significantly greater contribution to delaying the buckling of longitudinal CFRP composites and to improving column performance than did the conventional EBR technique. Finally, based on the compressive stresses of the carbon fibers in CFRP, the EBROG technique led to higher values of compressive strength of FRP sheets.

1. Introduction

It is inevitable to strengthen and/or retrofit concrete structural elements in order to prevent their potential vulnerability. One common procedure is confining such elements with CFRP wraps, which completely limit the lateral expansion of concrete and delay concrete cover peeling and longitudinal bars buckling. The general influence is clearly an increase in the peak loads of the specimens. Most studies in this area have been focused on column behavior under concentric and eccentric loads [1–14], while only a few have been assigned to the behavior of columns under cyclic axial compressive loads [15–20].

It has been demonstrated that FRP jackets in columns thus strengthened exhibit their best performance when they are applied to circular rather than square or rectangular columns. The declining effectiveness of the wrapping technique has been mainly attributed to the presence of sharp corners in noncircular columns [21–26]. As a remedy, creating round corners in columns with square or rectangular cross-sections prior to the application of FRP wraps has been found very effective in reducing stress concentration [27–29]. On the other hand, research has exhibited that the rupture strain in the FRP wraps in the square columns is considerably lower than the tensile strain of the flat coupons [30]. An alternative method to make better the efficiency of CFRP in confining

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rectilinear columns to avoid premature collapse due to local stress concentration is to apply FRP sheets locally at the edges under the transverse FRP sheets around the column [30,31]. The so-called "corner strip-batten" (CSB) technique is a novel alternative introduced for confining square columns that yields a more uniform confining stresses around the specimen circumference and achieve the ultimate rupture strain in the FRP battens nearby the tensile strain of the flat coupon. In this technique, CFRP sheets are employed at column edges while CFRP battens are mounted at its sides, which are then adhered onto the corner strips at both ends [30,32,33].

Limited studies have investigated the performance of wrapped columns under cyclic compression loading [15–20]. Rousakis [16] carried out an investigation on circular columns with the concrete strength rate of 33–104 MPa and confined with 1–5 layers of FRP subjected to cyclic loading. Ozbakkaloglu and Akin [17] studied the cyclic response of high strength and normal strength circular specimens confined by FRP wraps and concluded that the grade of the concrete and the level of the confinement have slight efficiency on the plastic strain. Abbasnia et al. [29] carried out a study on the efficiency of corner radius, concrete grade, aspect ratio, and confinement level on the behavior of concrete specimens wrapped by CFRP under cyclic axial compression loading. The results showed that the plastic strain is dependent on the grade of concrete.

While CFRP sheets with fibers aligned in the transverse direction have been most commonly used for strengthening RC columns, those strengthened with longitudinal fibers can also be effectively employed [34,35]. To achieve enhanced FRP effectiveness, recent studies have developed such strengthening methods as grooving method (GM) as a replacement of the traditional ones. A more recent development is a method called "externally bonded reinforcement on grooves" (EBROG) that has been shown to achieve higher enhancements in the peak loads of strengthened beams than that achieved by the EBR technique. Moreover, the EBROG has exhibited the capacity to modify the failure modes of the columns from debonding to CFRP strip rupturing [36–39]. While there is a relatively large body of the database on column specimens longitudinally strengthened utilizing the EBR procedure subjected to monotonic loads, the database is scant on columns strengthened with longitudinal FRP composites utilizing the EBROG technique and subjected to monotonic compressive loading. This is while no study has been reported, to the best of the present authors' knowledge, on the behavior of columns retrofitted with longitudinal FRP straps through the EBROG technique and subjected to cyclic compressive loads.

The research represents the results of experimental research on RC square column specimens confined with CFRP composites through the four different techniques of a full wrap, intermittent wrap, corner strip-wrap (CSW), and CSB while they are longitudinally strengthened through the two EBROG or EBR methods and subjected to cyclic compressive loading. The research specially aims to:

- Compare the ductility, peak load, equivalent damping ratio, energy dissipation, and secant stiffness under cyclic axial compressive loading in un-strengthened (reference) RC columns and those identical in every aspect except that they are confined with CFRP sheets through such different techniques as CSW and CSB.
- Investigate the effects of surface preparation techniques (that are, EBROG and EBR) on columns strengthened with longitudinal FRP under cyclic compressive loads.
- Investigate the behavior of specimens strengthened with CFRP composites applied in longitudinal and transverse configurations under cyclic axial compressive loads.
- Compare the compressive strength of longitudinal CFRP straps according to the compressive stresses of the fibers when the EBROG or the EBR method is used.

2. Experimental program

2.1. Columns details

The specimens employed in the current research consisted of 11 one-third scale square columns, each with a cross-section of 150 × 150 mm and a height of 900 mm. The scale of the specimens was selected based on the limitation of the maximum loading capacity and the maximum available clearance between the top and bottom plates of the loading apparatus. The specimens were reinforced with four longitudinal bars Φ12-mm and ten transverse rebars Φ8-mm as ties. The center-to-center space of ties and clear concrete cover on steel bars were 90 mm and 20 mm, respectively. It is noteworthy that the longitudinal bars in the specimens provided a steel ratio of 2%, which passes the minimum reinforcement required by ACI 318 [40] and is, in fact, a practical steel ratio in many projects. Moreover, the transverse ties were implemented in order to provide very low confinement but with an appropriate array with respect to the specimen's height. The dimensions of the columns and the details of the internal reinforcement used are presented in Fig. 1.

2.2. Material specifications

The yield strengths of the 8-mm and 12-mm bars were measured through ancillary tests as 470 and 447 MPa, respectively. The ultimate tensile strengths for the same rebars were respectively 627 and 698 MPa. The FRP composite employed consisted of unidirectional carbon fibers (SikaWrap-300C) and a two-component epoxy resin (Sikadur-330). The mechanical specifications of the SikaWrap-300C and the Sikadur-330 as reported by Sika [41] are repeated in Table 1. Moreover, the ancillary tests on provided coupons exhibited an average ultimate strength of 2620 MPa for the fibers saturated by Sikadure-330 utilizing wet lay-up procedure [42]. It is while the ultimate load of the CFRP composites (with 1.0 mm thickness) reported by the manufacturer is 430 kN/m. As a result, the effective ultimate strength of 2510 MPa can be calculated based on the net thickness of the fibers [41]. The concrete utilized in the specimens had a compressive strength of 28 MPa. The concrete mix was strictly controlled to a cement: water: coarse aggregate (5–10 mm): fine aggregate (0–5 mm) proportion of 1.0: 0.36: 2.52: 3.4.

2.3. Classification of the specimens

The RC columns were categorized into three groups named by S1 to S3 as reported in Table 2. The following symbols were employed to specify the columns: a) R, standing for reference column or un-strengthened column; b) FW for full wrap, IW for intermittent wrap, CSW, or CSB as the strengthening techniques employed for bonding the transverse FRP straps; and c) either EBROG or EBR, illustrating the strengthening technique employed for bonding longitudinal FRP straps.

In the FW technique, the specimen was confined with one layer of CFRP strip 700 mm long and 900 mm wide wrapped around the specimen. In the IW method, each confined column was strengthened with nine FRP straps 700 mm long and 50 mm wide wrapped around the specimen with 100 mm of overlap left for each wrap. In the CSW method, each confined column was strengthened using 36 FRP corner strips, 100 mm long and 50 mm wide, and also nine FRP wraps of 700 × 50 mm. In the CSB method, each confined column was strengthened using 36 FRP corner strips, 100 mm long and 50 mm wide, and also 36 FRP battens, with a dimension of