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Strength of circular HSC columns reinforced internally with carbon-fiber-reinforced polymer bars under axial and eccentric loads

Abdeldayem Hadhood, Hamdy M. Mohamed, Brahim Benmokrane *

Department of Civil Engineering, University of Sherbrooke, Quebec, Canada

HIGHLIGHTS

- Behavior and failure mechanisms of circular HSC columns reinforced with CFRP bars and spirals under eccentric loads are presented.
- The performance of CFRP bars in compression is assessed.
- A detailed sectional analysis for predicting the axial force and bending moment at different load eccentricity is introduced.
- *The P-M* interaction diagrams encompassing different parameters are developed.

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ABSTRACT

So far, limited research has been conducted on high-strength concrete (HSC) columns reinforced with fiber-reinforced polymer (FRP) bars under axial and eccentric compressive loads. The behavior and failure modes of steel-reinforced HSC (steel-RHSC) columns are well known: they fail in compression by concrete crushing and/or in tension (steel yielding). The strength and failure mechanisms of HSC columns reinforced with carbon-FRP (CFRP) bars and spirals has not, however, been investigated yet. This paper presents test results from an experimental program conducted to study the failure mechanism and axial–moment capacity of 10 circular HSC columns reinforced with either CFRP or steel bars and tested under different levels of eccentricity. All the specimens measured 305 mm in diameter and 1500 mm in height. The test variables included different eccentricity-to-diameter ratios and two types of reinforcement (CFRP and steel). Laboratory recorded load–axial displacement, load displacement, failure mode, and reinforcement strain responses of the CFRP-RHSC columns were compared to the steel-RHSC columns. A further analytical study was then conducted based on the test results and plane section theory. Based on this study, the axial and flexural capacity of CFRP-RHSC columns can be accurately predicted using plane sectional analysis. Furthermore, a comprehensive parametric investigation was conducted to generate numerous axial force–flexural moment (*P-M*) interaction diagrams.

1. Introduction

Nowadays, fiber-reinforced-polymer (FRP) bars have been winning the trust and acceptance of public agencies and regulatory authorities in North America. At the same time, numerous investigations have been conducted to provide experimental and analytical data on different reinforced-concrete (RC) members with various types of FRP bars [1–11]. Whereas steel is isotropic, susceptible to electrochemical corrosion, and yields, FRP is anisotropic with a high tensile strength–to–weight ratio, is non-corroding material, and has linear elastic behavior up to failure [10]. Getting the most out of the advantages of FRP bars in design requires a rational understanding of the material's characteristics. Therefore, the performance of FRP bars in concrete structures has been in the spotlight of civil-engineering research [12,13].

Carbon-FRP (CFRP) bars are sound substitutes for steel bars, due to the little difference between their elastic moduli (the steel modulus is higher by approximately 40%). Based on past studies on various types of FRPs, CFRP was thought to be the least susceptible to creep and fatigue rupture [14,15]. Other studies have also demonstrated the effectiveness of CFRP as the main reinforcement in different structural elements [16–18]. To date, few studies have been conducted to investigate the behavior of CFRP-RC columns [17,19–21].

* Corresponding author at: Department of Civil Engineering, University of Sherbrooke, 2500 Université Blvd., Sherbrooke, Quebec J1K 2R1, Canada.

E-mail addresses: Ahmed.Abdeldayem@Usherbrooke.ca (A. Hadhood), Hamdy.Mohamed@Usherbrooke.ca (H.M. Mohamed), Brahim.Benmokrane@usherbrooke.ca (B. Benmokrane).

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High-strength concrete (HSC)—that is, 55 MPa or greater—has been used primarily in high-rise buildings, long-span bridges, and offshore structures [22]. In general, increasing concrete strength increases member capacity, leading to a probably considerable reduction in member size. HSC is generally produced by increasing the amount of cement and adding mineral admixtures to the concrete mixture, which reduces the heat generated. Such mixtures have exhibited increased durability characteristics due to compactness and reduced permeability. It must be remembered that the use of HSC in columns is of great importance, particularly when high compressive forces and small bending moments are expected. Steel-reinforced HSC (Steel-RHSC) columns fail in compression due to concrete crushing and/or tension-controlled yielding of the steel. The failure of such columns under eccentric loading always initiates by the yielding of steel bars on the compression and/or tension sides, followed by concrete crushing, provided that the reinforcement ratio does not exceed 8% (the maximum reinforcement ratio in columns limited by North America's codes [23,24]). Due to a lack of experimental data, FRP bars have not been recommended to resist compression stresses as longitudinal reinforcement in columns or compression reinforcement in flexural elements [12]. Moreover, the Canadian Standard [25] neglects the contribution of the compressive resistance of FRP longitudinal reinforcement in the compression zone in flexural and compressive concrete members.

CFRP bars do not yield: they function up to failure. The failure of columns reinforced with CFRP bars has yet to be defined. Nevertheless, due to the significant difference in maximum strain between the concrete and CFRP bars, it is expected that the failure could be controlled by concrete. The compressive strength of CFRP bars, however, is also questionable. Past research has indicated that the strength and modulus of FRP bars are lower in compression than in tension [26,27]. When the concrete strength in such columns is increased, CFRP-RC is expected to exhibit a reasonable increase in axial and flexural strength. A few studies have investigated the behavior of CFRP-RC columns under eccentric loading. Sharbatdar [19] tested 5 full-scale square columns reinforced with CFRP bars under monotonic eccentric loading (eccentricity-to-width ratio, e/b, = 26% and 33%). It has been reported that the longitudinal CFRP bars were able to develop the high tensile strains required to maintain the section in equilibrium under increased bending as the concrete on the compression side was gradually crushed. None of the columns tested failed due to rupture of CFRP bars in tension [19]. A recent study [21] revealed that CFRP reinforcement could be used as an internal reinforcement in eccentric columns, provided that the maximum compression strength could be limited to 40% of the reinforcement's ultimate tensile strength. The CFRP bars developed up to 0.41 and 0.48% compressive and tensile strains, respectively, at peak, confirming that CFRP bars were effective in resisting compressive and tensile stresses [21].

2. Research significance

A targeted experimental program is under way at the University of Sherbrooke (Quebec, Canada) to study the performance of concrete columns reinforced with FRP under different load combinations (static and dynamic). This program aims to enrich the research of FRP-RC columns and hence builds a data bank for a reliable discussions and results. This work is a part of a comprehensive research program concerned with the performance of circular columns reinforced with glass- and carbon-FRP bars made with normal- and high-strength concrete under eccentric loading and conducted in Tier-1 Canada research chair in Advanced Composite Materials for Civil Structures in the Department of Civil Engineering at the University of Sherbrooke.

3. Experimental program

In this study, 10 full-scale circular HSC columns reinforced with either carbon-FRP or steel bars/spirals were prepared and tested under monotonically increasing concentric and eccentric loading. Eight specimens were tested under eccentric loading; two were tested under concentric loading. All the specimens measured 305 mm in diameter and 1500 mm in height, and were totally reinforced with CFRP or steel.

3.1. Materials

Sand-coated CFRP bars and spirals manufactured by a Canadian company (Pultrall Inc., Thetford Mines, Quebec) [28] were used. The CFRP longitudinal bars and spirals were made of continuous carbon fibers impregnated with a thermosetting vinyl-ester resin, additives, and fillers. No. 5 CFRP bars were used as longitudinal reinforcement and No. 3 CFRP spirals were used as transverse reinforcement. Fig. 1 shows bar and spiral samples for the CFRP reinforcement employed in this study. The tensile properties of the CFRP reinforcement were determined according to ASTM D7205 [29]. Also, M15 steel bars and No. 3 steel spirals were employed for the control steel-RHSC columns. Table 1 provides the mechanical properties of the reinforcement used in this study.

All specimens were vertically cast on the same day from a single truckload of ready-mixed HSC. A concrete pump was used to pour the concrete into the column formwork. The maximum aggregate size was 14 mm. The slump was around 80 mm (before adding the superplasticizer). The concrete strength was determined in accordance with ASTM C39/C39M [30] by testing 150 × 300 mm cylinders that were cured adjacent to the member specimens under similar conditions. The actual compressive strength was

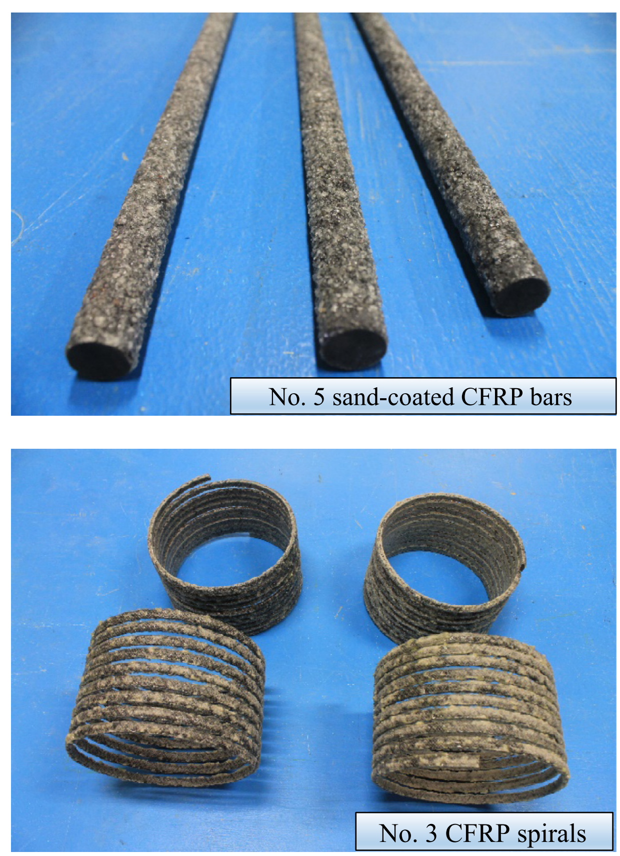

Fig. 1. CFRP reinforcement (bars and spirals).