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Axial behavior of circular CFFT long columns internally reinforced with steel or carbon and glass FRP longitudinal bars

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ABSTRACT

This paper presents the test results of an experimental study aimed at investigating the behavior of concrete-filled fiber-reinforced-polymer (FRP) tube (CFFT) long columns internally reinforced with longitudinal steel or carbon and glass FRP bars tested under axial compression loading. A total of ten reinforced concrete (RC) and CFFT columns measuring 1900-mm in height and 213-mm in diameter were constructed and tested until failure. The test parameters were: (1) internal reinforcement type and amount; (2) GFRP tube thicknesses; and (3) nature of axial loading (i.e. monotonic and cyclic). The experimental results showed that the GFRP-reinforced CFFT columns had comparable ultimate axial strength and strain capacities compare to their counterparts reinforced with steel bars. As expected, an increase in the FRP tube thickness (or stiffness) resulted in an increase in the strength and strain enhancement ratios. The results also indicated that the residual plastic strain of FRP-reinforced CFFT columns is linearly related to the envelope unloading strain, and this relationship is not influenced significantly by the FRP confinement level but strongly influenced by the internal reinforcement amount and type, particularly when the envelope unloading strain (> 0.0035). The presented study showed the applicability of exclusively reinforcing the CFFT columns with FRP bars and subjected to axial compression load. However, further experimental investigations on the axial cyclic behavior of CFFT columns internally reinforced with FRP bars are required to establish such key relationships.

1. Introduction

The construction industry is expressing great demand for innovative and durable structural members. Fiber-reinforced-polymers (FRPs) have recently gained wide acceptance as a viable construction material for repair, rehabilitation, or new construction of the aging infrastructures particularly those exposed to harsh environment conditions. Some of the most important applications of FRP composites in civil engineering are as a confining material for concrete, both in the seismic retrofit of existing reinforced concrete (RC) columns and in the construction of concrete-filled FRP tubes (CFFTs) as earthquake-resistant columns in new construction [27], or as an internal reinforcing bars for concrete members.

The CFFT technique has been successfully used in different concrete structure elements such as pier column and girder for bridges and also as fender piles in marine structures [12]. The FRP tube acts as a stay-in-place structural formwork, a noncorrosive reinforcement for the concrete in flexure and shear using the multidirectional fiber orientation, provides confinement to the concrete in compression, and protects the concrete core from intrusion of moisture with corrosive agents (ACI 440. R-07 2007). Few studies reported on the seismic behavior of CFFT columns have demonstrated the ability of CFFTs to develop very high inelastic deformation capacities, making them an attractive alternative for construction of new high-performance columns [26,30,14]. The majority of existing studies have been focused on the monotonic axial stress–strain behavior of FRP-confined unreinforced concrete, which have led to the development of over 80 stress–strain models (e.g. [32,38,11,18,10,37]. Meanwhile, there is a distinct lack of research on the axial cyclic stress–strain behavior of full-scale CFFT columns with internal reinforcement bars. It is worth mentioning that the existing stress–strain models of FRP-confined concrete were developed almost exclusively based on results of specimens with height-to-diameter ratio ($H/D = 2$) [28]. It is, therefore, important to examine the stress–strain behavior of full-scale CFFT columns reinforced with and without

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Table 1
Tensile properties of the GFRP, CFRP, and steel bars.

Reinforcement type	Nominal diameter (mm)	Nominal area (mm^2)	Modulus of elasticity (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Yield strain (%)	Ultimate strain (%)
GFRP	9.5	71	45.4	–	856	–	1.89
	15.9	199	48.2	–	751	–	1.60
CFRP	9.5	71	128	–	1431	–	1.20
Wire (mild steel)	3.4	9	200	675	850	0.30	0.43
15 M (deformed)	16	200	200	419	686	0.21	0.34

internal bars with high (*H*/*D*) ratios and develop new analytical models to describe this behavior under axial cyclic compression loading.

Lam et al. [19] performed an experimental study on the behavior of FRP-confined concrete cylinders under axial cyclic compression. The test results indicated that unloading/reloading cycles had little effect on the envelope curve of stress–strain responses of FRP-confined concrete, except for a small enhancement of the FRP hoop rupture strain. Also, the plastic strain of FRP-confined concrete was linearly related to the envelope unloading strain, but was independent of the amount of FRP-confinement. This observation was then supported by that of [27], which were based on an experimental investigation of CFRP-confined NSC square prisms and cylinders. It should be noted that the authors have been reached the above conclusions on the basis of tests conducted on small-scale specimens (i.e. standard cylinders). Size effects may exist and such effects should be examined using full-scale specimens in the future [19]. Meanwhile, the slenderness ratio of such columns might be a critical factor that controls the mode of failure. Few studies observed that instability of CFFT columns might occur at a lower slenderness ratio than that of ordinary RC columns (without FRP tubes); however, the ultimate capacity of the former might be higher than that of the latter. This attributed to the bilinear stress–strain behavior of the CFFT columns in which the buckling mode of failure initiated at the plastic branch of the curve, which was characterized by a lower Young's modulus. Therefore, [40] recommended that the current slenderness limit of 22 for steel RC columns bent in single curvature be reduced to 11 for CFFT columns.

Nowadays, FRP bars as an alternative to steel bars have emerged as a realistic and cost-effective solution to overcome the corrosion problems. FRP bars offer many advantages over conventional steel bars, including a density of one-quarter to one-fifth that of steel, greater tensile strength than steel, and no corrosion even in harsh chemical environments [29,9,6]. Previous experimental studies indicated that the compression behavior of concrete columns reinforced with glass-FRP (GFRP) reinforcements has been similar to that with steel, but with less contribution of FRP longitudinal bars to strength capacity [34,8,35,3,25]. These studies also showed the applicability of exclusively reinforcing the columns with FRP bars and subjected to concentric load. Using FRP bars, therefore, instead of conventional steel bars in the CFFT columns can provide a step forward to develop a promising totally corrosion-free new structural system. Nonetheless, the axial behavior of FRP bars as longitudinal reinforcement in compression members has been quite limited, especially for the CFFT columns. To the best knowledge of the authors, no study in the literature to date addressing the behavior of FRP-reinforced full-scale CFFT columns under axial cyclic compression loading. This paper reports on an experimental investigation that was undertaken to address this important research gap. The main objective of this study is to introduce a preliminary investigation on the behavior and strength of FRP-reinforced CFFT columns under axial cyclic compression. This paper presents the test results of ten full-scale RC and CFFT columns reinforced longitudinally with steel or GFRP and CFRP bars tested under monotonic and cyclic axial compression loads. All columns had 1900-mm in height and 213-mm in diameter with ($H/D = 8.9$). The effect of internal reinforcement type and amount, GFRP tube thicknesses, and natural of axial loading (i.e. monotonic and cyclic) are addressed.

2. Experimental program

2.1. Material properties

2.1.1. Concrete

All columns were cast on the same day with a ready-mixed normal-strength concrete. The concrete strength was determined using six standard concrete cylinders measuring 150 × 300 mm. The average concrete compressive strengths after 28-days were measured between 42.1 and 46.0 MPa. Hence, the design concrete resistance (f'_c) was taken as 44 MPa for all columns.

2.1.2. Steel bars

In this study, steel and FRP bars were used to reinforce the CFFT and control specimens. Two types of steel bars (Grade 60) were used: deformed steel bars 15 M (16 mm-in diameter) as longitudinal reinforcement and 3.4 mm-in diameter mild steel bars as spiral reinforcement. The mechanical properties of steel bars were determined from the standard test according to the ASTM [5] based on five representative specimens. The average yield tensile strengths (f_y) were 419 and 675 MPa and ultimate tensile strengths (f_{su}) were 686 and 850 MPa for steel bars 15 M and 3.4 mm diameters, respectively.

2.1.3. FRP bars

Two types of sand-coated FRP bars were used as longitudinal reinforcement: Glass-FRP (GFRP) bars No. 3 and No. 5 (9.5 mm and 15.9 mm in-diameter, respectively) and Carbon-FRP (CFRP) bars No. 3 (9.5 mm-in diameter). The ultimate tensile strength and modulus of elasticity were 856 and 751 MPa and 45.4 and 48.2 GPa for the GFRP bars No. 3 and No. 5 and 1431 MPa and 128 GPa for the CFRP bars No.3, respectively. Table 1 reports the mechanical properties for steel and FRP bars, as determined from testing.

2.1.4. FRP tubes

Two types of GFRP tubes; namely Type A and B; were used in this investigation as structural stay-in-place formwork for the CFFT columns. The GFRP tubes type A and B were standard products with the same internal diameter of 213 mm and different wall thicknesses of 2.9 and 6.4 mm. Tubes type A and B were consisted of six and twelve FRP layers with stacking sequences of [60/90/90/90/90/60] and [60/60/90/90/60/60/90/90/90/90/90/90], respectively. The GFRP tubes were fabricated using filament-winding technique; E-glass fiber and Epoxy resin with different fiber angles respect to the longitudinal axis of the tubes. The fiber orientations of the tubes were mainly in the hoop direction and no fibers in the longitudinal direction. Coupon tensile tests were performed according to ASTM D638-14 [4] standard on five specimens from each tube to determine the mechanical properties in the axial direction. The ultimate tensile strengths, Young's modulus, and ultimate tensile strains in the axial direction were 55.2 and 59.2 MPa, 8865 and 7897 MPa, and 0.0062 and 0.0075 (microstrains) for FRP tubes type A and B, respectively. While the mechanical properties in hoop direction were determined theoretically using the classical laminate theory through Laminator software. Table 2 reports the mechanical properties for each tube in the hoop and axial directions. More details regarding the standard tests of these tubes can be found