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Experimental study on concrete columns reinforced by hybrid steel-fiber reinforced polymer (FRP) bars under horizontal cyclic loading

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HIGHLIGHTS

- We tested four concrete columns under cyclic loading.
- The reinforcements including steel bars, hybrid steel/FRP bars, and SFCBs.
- The failure modes and hysteretic behaviors were analyzed.

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ABSTRACT

Effective post-yield stiffness of reinforced concrete (RC) columns can significantly contribute to the seismic performance of RC structures. However, because of the elastoplastic properties of steel bars, the post-yield stiffness of an ordinary RC column can be very slight or even negative. Fiber reinforced polymer (FRP) can provide a high degree of ultimate strength, light weight, and protection from corrosion. By combining steel and FRP, a designable post-yield stiffness can be achieved for concrete structures reinforced with steel-FRP composite bars (SFCBs) or hybrid steel/FRP bars. This paper conducted cyclic loading tests on four concrete columns with different reinforcement types, including steel bars, hybrid steel/FRP bars, and SFCBs. The test results showed that (1) the columns reinforced with different bars had similar strain distributions from column base to cap prior to yielding. After yielding, the plastic deformation of the ordinary RC column concentrated at the column base and the loading capacity decreased with the increase of lateral drift because of the P-δ effect. (2) Unlike the negative post-yield stiffness of an ordinary RC column, the post-yield stiffness of a column with hybrid reinforcements was positive. As the post-yield stiffness ratio of the longitudinal reinforcement increased by 27 percent, the post-yield stiffness of the concrete column increased by 7.4 percent. Therefore, the corresponding displacement ductility could reach 11—much greater than that of the RC column (6.28). (3) As a result of the more robust hysteretic curve of the RC column, the equivalent viscous damping coefficients of the RC column were greater than those of the hybrid column, whereas the hybrid reinforced concrete columns could dissipate earthquake energy without a corresponding loss of strength.

1. Introduction

Under the excitation of different near-fault ground motions, the performance of ordinary steel bar reinforced concrete (RC) columns falters after yielding due to the rebar's elastoplastic properties [1], thus leading to poor structural post-earthquake recoverability. Over 250 piers collapsed in the 1995 Kobe earthquake, and approximately 100 piers had to be demolished due to their excessively large residual displacements [2]. Numerous studies had been conducted on the inelastic displacement demand and hysteretic behavior of concrete columns under multi-directional seismic shakings [3]. Numerous statistical analyses have shown that a stable post-yield stiffness of concrete columns (>5%) significantly contributes to lower residual displacements and increased stability of displacement responses compared with cases without stable positive post-yield stiffness [4].

Unfortunately, it is difficult to achieve stable post-yield stiffness for an ordinary RC column because of the elastoplastic properties

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of the steel bar [5]. However, in hybrid reinforcing bars composed of steel and fiber reinforced polymer (FRP), a designable post-yield stiffness can be achieved by adjusting the ratio of FRP to steel [6,7]. Fisher and Li [8] noted that the philosophy of "strong column, weak beam" is easily implemented for frame structures when the columns exhibit high post-yield stiffness. In marine environments, an ordinary RC structure has a short lifespan due to the low anti-corrosion properties of steel [9]. To improve the seismic performance and durability of RC structures, Wu et al. [10] proposed a novel hybrid reinforcement—a steel-FRP composite bar (SFCB)—composed of an inner ribbed steel bar and an outer longitudinal FRP crafted by a pultrusion process. The authors conducted subsequent research with respect to the mechanical properties of the SFCB [11] and the corresponding behaviors of concrete beams/-columns that were strengthened/reinforced by SFCBs [12–14]. Based on this previous research, this paper presents horizontal cyclic loading tests of four concrete columns with different hybrid reinforcement, including steel bars, hybrid steel/FRP bars, and SFCBs. The test results, including hysteretic curves, strain distributions, and the energy dissipation capacity, are analyzed and subsequently followed by application recommendations.

2. Experimental program

2.1. Specimen design and test setup

The post-yield stiffness ratio of an SFCB (r_{sf}) can be defined by Eq. (1). For an ordinary RC column, the reinforcement ratio ρ is defined by the total area of the steel bar over the gross section area. For a hybrid reinforced concrete column, the equivalent longitudinal reinforcement ratio (ρ_{sf}^{e}) with regard to an ordinary steel reinforced concrete column is defined by Eq. (2).

$$r_{sf} = E_f A_f / (E_s A_s + E_f A_f) \tag{1}$$

$$\rho_{sf}^{e} = E_f A_f / r_{sf} E_s A_g \tag{2}$$

where E_s and A_s are the elastic modulus and cross-section area of the inner steel bar, respectively; E_f and A_f are the elastic modulus and cross-section area of the SFCB's outer FRP, respectively; K_1 and K_2 are the stiffness of the concrete column before and after yielding, respectively; A_g is the gross cross-section area of the concrete column. Columns with the same ρ_{sf}^{e} will have the same initial stiffness.

Four concrete columns were designed with a rectangular section of 250 × 250 mm. The specimen numbers and the corresponding mechanical properties of the reinforcements are presented in Table 1. The notation 'C-S12' denotes that column C-S12 is longitudinally reinforced by ordinary steel bars of 12 mm in diameter. The notation 'C-S10B49' denotes that the concrete column is reinforced by 'S10B49,' which is a type of SFCB made of a 10-mm diameter inner steel bar longitudinally compounded with 49 bundles of 2400 tex basalt fibers; 'tex' is the weight (g) of one fiber bundle per kilometer. The case is similar for C-S10B85, only with 85 bundles. The concrete column named 'C-H' is hybrid reinforced by steel bars and basalt FRP (BFRP) bars. The BFRP bar consists of 85 bundles of 2400 tex basalt fibers produced in the same batch as 'S10B85.' The reinforcement ratio of the ordinary RC column C-S12 is 1.09%. The equivalent longitudinal reinforcement ratio (ρ_{sf}^{e}) of the hybrid columns (C-S10B85, C-H) with respect to the elastic modulus of steel is also 1.09%. Compared with C-S10B85, the ρ_{sf}^{e} of C-S10B49 is approximately 89% of that of column C-S10B85 due to a smaller content of BFRP in S10B49.

The detailed dimensions of the columns and the loading patterns are shown in Fig. 1. The shear span ratio is 5, i.e., the distance between the loading point and the column's base (L) is 1250 mm. The vertical load in this test was controlled by an electrohydraulic servo test system to maintain stable axial compression force during horizontal cyclic loading. A spherical hinge was placed at the column top ensure the direction of the vertical load. To minimize the unfavorable effect of the horizontal friction caused by the uniaxial compression at the column cap, tetrafluoroethylene plates and a pulley were set between the vertical loading actuator and the reaction frame. The friction coefficient between the tetrafluoroethylene plates and the reaction frame was approximately 0.03, and the friction coefficient between the pulley and the tetrafluoroethylene plates was less than 0.03. Therefore, it is reasonable to assume that a constant axial load was vertically applied to the cap center of each column during the test. The average tested compressive strength of the concrete cubes (150 × 150 × 150 mm) at 28 days was 36.64 MPa, and the corresponding cylinder compressive strength was 29.31 MPa. The axial load (P) applied to the concrete column was 200 kN and the corresponding axial compression ratio was 0.11.

2.2. Loading program and measurements

The horizontal cyclic loading on the column cap was controlled by lateral force prior to column yielding, with a loading gradient of 10 kN for each step. After yielding, the loading was controlled by yield displacement (7 mm in this paper), with each displacement cycled three times. The test measurements included the following: (1) the column cap force versus lateral displacement curves; (2) the crack formation and development; and (3) the strain distribution of the longitudinal reinforcement, which was measured by seven strain gauges along the longitudinal bar. The surface of the steel bar/FRP bar was rubbed with sandpaper before bonding the strain gauge, and the dimension of each strain gauge was 3 × 5 mm. The strain gauge and the detailed locations are shown in Fig. 2.

3. Test results

3.1. Test phenomena and load displacement curves

As for the hybrid reinforced concrete columns, the concrete cover near the column base initially cracked, followed by yielding of the longitudinal steel bars or the inner steel bars of the SFCBs. Spalling of the concrete cover in the column base subsequently occurred with the rupture or partial rupture of the FRP. The load-lateral displacement curves (V-δ curves) of the columns are shown

Table 1
Specimen numbers and mechanical properties of the longitudinal reinforcements.

Column number		Reinforcement Diameter (mm)	Elasticity modulus (GPa)	Post-yield stiffness ratio	Yield strength (MPa)	Ultimate strength (MPa)	ρ_{sf}^{e}
C-S12		12.00	200	/	400	529.60	1.09%
C-S10B49		16.16	111.3	0.189	208.2	691.42	0.96%
C-S10B85		18.00	94.6	0.266	189.2	544.08	1.09%
C-H	Steel bar	10.00	200	/	450	621.00	1.09%
	BFRP bar	13.00	45.38	/	/	1075.60	