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Experimental investigation on the seismic performance of steel–polypropylene hybrid fiber reinforced concrete columns

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HIGHLIGHTS

- The effects of steel–polypropylene hybrid fiber on the seismic performance of reinforced concrete columns were investigated.
- Favorable improvements in failure modes, bearing capacity and deformation capacity of HFRC specimens were observed.
- Analytical predictions for evaluating the seismic bearing capacity of HFRC specimens were proposed.

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ABSTRACT

Addition of fibers into cementitious composites has raised concern over decades, which enables considerable improvement in mechanical and dynamic properties of reinforced concrete (RC) members. In this paper, we present an experimental study on the seismic performance of steel–polypropylene hybrid fiber reinforced concrete (HFRC) columns, which is of vital significance to postearthquake serviceability of structures. A total of 24 specimens subjected to combined constant axial load and cyclic lateral force were investigated. The main variables involve fiber type, shear span ratio, axial compression ratio, and reinforcement ratio (longitudinal and transverse). The failure modes, ultimate bearing capacity and deformation capacity were analyzed. The experimental results showed that the presence of hybrid fibers in RC columns had positive influence on improving the seismic bearing capacity. The improvement ratio could reach to 15–20% when a relative high axial compression was applied. Moreover, in comparison to RC columns, HFRC columns exhibited a notable synergetic effect in terms of ductility and energy dissipation capacity, particularly for columns with a higher axial compression ratio. Subsequently, on the basis of principles of equilibrium and compatibility, analytical equations to estimate the seismic bending moment capacity and shearing force capacity were developed, which took into account the synergetic effect of hybrid fibers. The analytical solutions were then validated by the test results, and the correlations were observed in reasonable accuracy.

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1. Introduction

Over the last few decades, numerous postearthquake investigations [1,2] have confirmed that the goal of seismic-resistant design of reinforced concrete (RC) structures was not fully achieved in fact. In those earthquake stricken areas, most of the concrete columns were seriously damaged, and plastic hinges developed widely at ends. This phenomenon was significantly associated with the inherent disadvantages of plain concrete material, i.e. the low tensile strength, toughness and its brittle nature [3,4].

To tackle this problem, the traditional method is to set closely spaced transverse stirrups, which is able to improve the confinement of concrete at those regions where plastic hinges may possibly develop [5,6]. Well confined concrete can significantly restrain the opening and propagation of cracks, reducing the strength degradation that consequently improve the seismic performance of RC columns. However, a relatively large amount of transverse stirrups may result in congestion of reinforcement, as well as increase the difficulties in construction/manufacturing. This method not only raise the cost in both steel reinforcement material and fabrication expense, but also requires additional close quality control thereupon.

To date, advances in concrete technology have led to the development of fiber reinforced concrete (FRC) materials, which is commonly acknowledged as an alternative reinforcement solution. FRC demonstrates excellent tensile strength, toughness,

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energy dissipation capacity, as well as superb resistance to cracking [7]. The randomly distributed fibers in the matrix form a spatial unitary network that can bridge the cracks, carry the tensile stress and dissipate energy. Those attractive properties allow the direct application of FRC in the RC columns to mitigate damage and achieve a strong column.

Considerable efforts have been made to investigate the contributions of various fibers (e.g. steel fiber [8–12], polypropylene fiber [13,14], glass fiber [15], carbon fiber [16], with single steel fiber in particular) in improving the mechanical performance of columns. The experimental results in Stephen et al. [8,9] showed that the introduction of steel fibers into the concrete can arrest the early spalling of the concrete cover and increase the load capacity as well as the ductility of the columns over that of comparable nonfiber reinforced specimens. Similar observations were reported more recently by Lee [10], Joao [11] and Röhm et al. [12]. Meanwhile, investigations from Zhao [13] and Laura et al. [14] indicated that the use of synthetic fiber reinforced concrete also can enhance the ductility and energy dissipation capacity of concrete columns. They claimed that the amount of confinement steel required by design codes can be reduced when synthetic fiber is used, thus resulting in a higher cost-effective value. Notwithstanding those research have convinced us that remarkable improvement in mechanic performance can be achieved by using FRC, however it is worth noting that the failure in concrete is a gradual and multi-scale process, each type of fiber can only be effective in a limited range, an optimal performance cannot been attained when single FRC is used. Therefore, attempts have been made to use fiber combinations with different constitutive responses, dimensions and functions into cementitious composites to optimize the properties of concrete material [17–24], as well as improve the mechanical performance of RC members [25–30]. Of the limited research concerning on the steel–polypropylene hybrid fiber reinforced concrete (HFRC), the seismic performance of HFRC columns has not been well documented to the authors' knowledge.

To this end, the subsequent focus of this paper is to investigate the seismic performance of HFRC columns, aiming to characterize the failure modes, hysteresis loops, skeleton curves, ductility, and energy dissipation capacity. The influences of fiber type, shear span ratio, axial compression ratio and reinforcement ratio on the seismic performances of the columns were addressed. In addition, analytical equations considering the synergetic effect of hybrid fibers to calculate the seismic bearing capacities of HFRC columns were developed, which were then evaluated by the experimental data.

2. Experimental program and setup

2.1. Materials

The mixture design of plain concrete is given in Table 1. Ordinary Portland cement type P.O. 42.5 was used as the binder for the mixtures. Crushed granitic rocks of sizes between 5 and 20 mm were used as the coarse aggregates. Normal river sand including 5% of water (by weight) with fineness modulus of 2.7 was used as the fine aggregates. A highly efficient water reducing agent with a reducing rate of about 15% was used in the mix design. The 28 day compressive strength f_{cu} of the concrete cubes are listed in Table 3.

Table 2 gives the properties of three types of steel reinforcement, where the type Φ8 (plain steel bar) was used as stirrups and the others (ribbed steel bar) were used as longitudinal reinforcement.

Table 1
Designed mix proportions of concrete matrix (kg/m^3).

Cement	Sand	Gravel	Water	Super plasticizer	Water cement ratio
441	794	1097	150	2.3	0.34

Table 2
Properties of steel reinforcement.

	Type	D_N (mm)	D_M (mm)	f_y (MPa)	ε_y ($\mu\varepsilon$)	f_u (MPa)	ε_u ($\mu\varepsilon$)
Transverse	Φ8	8	7.4	320.9	1500	495.6	9000
Longitudinal	Φ12	12	11.6	476.3	2350	636.2	8000
	Φ14	14	12.85	553.9	2500	670.3	6000

Note: D_N, D_M represents the nominal diameter and mean diameter of reinforcement, respectively.

Table 3
Details of the specimens.

No.	Specimen	f_{cu} (MPa)	Section type	λ	n_t	ρ_{sf} (%)	ρ_{pf} (%)
1	C-1-1	53.6	II	4	0.186	–	–
2	C-1-2	55.2	II	4	0.308	–	–
3	C-1-3	52.4	II	4	0.433	–	–
4	PF-1-1	53.1	II	4	0.186	–	0.15
5	PF-1-2	50.5	II	4	0.308	–	0.15
6	PF-1-3	52.1	II	4	0.433	–	0.15
7	SF-1-1	55.1	II	4	0.186	1.5	–
8	SF-1-2	57.3	II	4	0.308	1.5	–
9	SF-1-3	59.4	II	4	0.433	1.5	–
10	HF-1-1	60.2	II	4	0.186	1.5	0.15
11	HF-1-2	56.1	II	4	0.308	1.5	0.15
12	HF-1-3	57.3	II	4	0.433	1.5	0.15
13	HF-1-4	56.5	I	4	0.308	1.5	0.15
14	HF-1-5	57.4	III	4	0.308	1.5	0.15
15	HF-1-6	58.3	IV	4	0.308	1.5	0.15
16	HF-1-7	59.8	V	4	0.308	1.5	0.15
17	HF-1-8	59.3	IV	4	0.433	1.5	0.15
18	HF-1-9	61.2	V	4	0.433	1.5	0.15
19	C-2-1	55.2	II	1.75	0.186	–	–
20	C-2-2	52.3	II	1.75	0.308	–	–
21	C-2-3	51.8	II	1.75	0.433	–	–
22	HF-2-1	57.3	II	1.75	0.186	1.5	0.15
23	HF-2-2	59.0	II	1.75	0.308	1.5	0.15
24	HF-2-3	60.6	II	1.75	0.433	1.5	0.15

Note: the nomenclature of specimen is A–a–b, where 'A' denotes the fiber type (C is none fiber, PF is polypropylene fiber, SF is steel fiber and HF is steel–polypropylene hybrid fiber), 'a' stands for the shear span ratio (1 is $\lambda = 4$ and 2 is $\lambda = 1.75$), and 'b' represents the serial number of specimens of one group.

Corrugated steel fibers, with average aspect ratio $l/d = 29/0.45 = 64.5$, and 500 MPa tensile strength were used. Correspondingly, monofilament polypropylene fibers, with average aspect ratio $l/d = 19/0.048 = 396$, and 400 MPa tensile strength were used (Fig. 1).

As using excessive fibers may introduce unwanted defects, which has a negative effect on concrete strength, steel fiber and polypropylene fiber were used in a volume fraction of 1.5% (117 kg/m^3) and 0.15% (1.37 kg/m^3) respectively (Table 3). These percentages are recommended by our previous work [21–24 that in this level an optimal comprehensive performance can be attained.

2.2. Specimens preparation

Pseudo-static tests of twenty-four specimens were performed. The specimens investigated include six RC columns, three polypropylene fiber reinforced concrete (PFRC) columns, three steel fiber reinforced concrete columns (SFRC) and twelve HFRC columns. Each column was subjected to a combination of constant axial load and cyclic lateral force.

As illustrated in Fig. 2, every specimen consisted of a column with the cross-section of 200 mm × 200 mm and a stub with the dimension of 900 mm × 400 mm × 400 mm. All specimens were grouped into five section types according to the reinforcement ratios. Two shear span ratio λ of 4 and 1.75 were examined, which respectively correspond to the column length of 800 mm and 350 mm. Three different axial compression ratios ($n_t = N/f_{cu}A_0$, where N is the axial load and A_0 is the gross cross area of concrete), i.e. 0.186, 0.308 and 0.433, were considered. In order to prevent potential local failure at the top of the columns, each specimen was strengthened locally by spacing stirrups closer (40 mm apart). All the details above satisfied the requirements of codes GB 50010-2010 [31] and GB 50011-2010 [32].

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