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Behavior of high-performance fiber-reinforced cement composite columns subjected to horizontal biaxial and axial loads

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HIGHLIGHTS

- The strength and ductility of HPFRCC specimens were remarkable improved.
- The capacity of the FC and SF columns adding PVA showed very little difference.
- The ductility and energy dissipation are inversely proportional to axial load.

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ABSTRACT

Current design in the ACI building code for reinforced concrete columns under seismic load combinations requires reinforced detailing which causes reinforcement congestion and construction difficulties. As an alternative solution, the use of high-performance fiber-reinforced cement composites (HPFRCC) with an economical type of Poly Vinyl Alcohol (PVA) fibers in column elements was investigated in this paper. Six column specimens with 2/3 scale including three standard reinforced columns and three columns using PVA fibers were tested. In the research work herein presented, biaxial cyclic lateral loads were applied to specimens subjected to either 10% or 30% constant axial loads. The experimental results are presented and the global behaviors of the tested columns are discussed, particularly focusing on stiffness and strength degradations due to increasing cyclic demand. Test results indicated superior damage tolerance and stable inelastic load–displacement responses up to 5% or 9% drift for the HPFRCC columns, even though they suffered severe shear cracks. Specimens without PVA all showed very limited ductility and low strengths.

1. Introduction

One of the most fundamental observations in research projects on past earthquakes is that biaxial bending moment damage caused to reinforced concrete (RC) elements by earthquake loading in two directions is much greater than that caused by earthquake loading in one direction. This is because the application of biaxial bending-moment cyclic demands to RC columns tends to reduce their capacity and stiffness and strength degradation occurs during successive load reversals. These factors indicate the importance of investigating the inelastic response of structural elements when subjected to biaxial or bidirectional cyclic loading. While previous studies have been mostly focused on the structural performance of members under constant axial loading, very few investigations are available on their structural behavior under multi-dimensional earthquake conditions.

Among those very limited researches, Qiu et al. [8] tested seven specimens of RC column subjected to biaxial loading with different load paths and concluded that the interactions of biaxial deformation, under biaxial loads, were found to weaken biaxial strength and hysteretic energy dissipation capacity. Tsuno and Park [9] performed cyclic bi-directional tests on two RC columns with rectangular cross-section and Bechtoula et al. [10] tested eight large-scale and eight small-scale RC columns under various vertical and horizontal loading patterns. From the test observations, bi-directional loading had a significant influence on the envelope curves as well as on damage progress. It is therefore important to implement additional studies on structural behavior under multi-dimensional loading, and apply the results to improve the seismic capacity of columns.

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Researchers have recently looked at the applications of high-performance fiber-reinforced cement composites (HPFRCC), such as coupling beams Afshin Canbolat et al. [11], low-rise walls Kim and Parra-montesinos [12], the cyclic behavior of precast post-tensioned segmental concrete columns with ECC Billington and Yoon [13], effectiveness of low-cost fiber-reinforced cement composite in hollow columns under cyclic loading Shin et al. [14]. Bengi Arisoy and Hwai-Chung Wu [15] investigated mixing PVA fibers into reinforced lightweight concrete. From these experimental investigations it was found that the use of HPFRCC has a favorable effect on the resistance of the column member. For instance, HPFRCC exhibited increased strength, displacement capacity and damage tolerance in members subjected to larger deformations [1–6,16,17]. In short, HPFRCC may be effective when used in RC elements with the main aim of improving the seismic behavior of structural members.

In view of the above, tests were conducted on six 2/3 scale column specimens, including three columns using fibers and three standard RC column specimens, subjected to biaxial loads. It is worthwhile to note that this study considered that a column consisted of an upper and lower part divided at the point of inflection and specimens in this paper represent for upper part of columns. The main purpose of the experimental investigations presented in this paper to estimate the increase in strength, ductility, energy dissipation, cracking and failure mode of column specimens with added PVA (2% of volume), as well as to observe deformation of specimens under biaxial loading.

2. Experimental program

2.1. Material properties

Table 2.1 summarizes the test results of the compressive strength of concrete specimens, and the tensile strength of reinforced specimens. The compressive tests followed ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens". The compressive strength of the concrete was determined as the average of at least three cylinder specimens with sizes of 200 mm × 100 mm (height × diameter). The top and bottom of the cylinder specimens were properly ground and capped with neoprene pad caps (ASTM C1231) to ensure a uniform load distribution.

Tensile tests were conducted in order to determine the material properties of the reinforced specimens. Based on the test results, the tensile strength of the steel was determined as the average of three specimens. The Young's modulus of elasticity of reinforcement was calculated based on a stress–strain curve in the elastic limitations. The compressive strength of concrete at 28 days is 27.3 MPa for normal concrete and 48.3 MPa for HPFRCC specimens and the tensile strength (f_y) of reinforcement for D19 and D10 are 484.7 MPa and 528.3 MPa respectively.

Table 2.3
Properties of fibers included in PVA.

Tensile strength (MPa)	Elastic modulus (GPa)	Diameter (mm)	Length (mm)	Volume fraction (%)
1600	25	0.039	12	2.0

Table 2.2 shows the HPFRCC mix proportions for the specimen's detailed materials, and the physical properties of the PVA fibers used are shown in Table 2.3. A total of six HPFRCC mix proportions were examined, in which the volumetric ratio of PVA fibers were approximately 2.0%, and the water/PCM ratio was kept roughly 20–22%. The direct tensile test used at least two dog-bone shaped specimens for each of HPFRCC mixture type, as shown in Fig. 2.1. Two LVDTs were mounted along the sides of the specimen in the loading direction, in which the gage length was equal to 76 mm (3 in.). One or two layers of steel wire mesh were used to reinforce each end of the specimen to avoid failure outside the LVDT gage length. The direct tensile tests were displacement-controlled, with an actuator travel velocity of roughly 0.5 mm/min based on the JSCE recommendations [18].

The stress–strain responses of the six types of HPFRCC specimens are compared, in which two or three similar results were acquired, and one of them is selected for the comparison. In general, the specimen No.6 presented the highest ductility, developing numerous well-distributed micro-cracks (Fig. 2.1); the maximum tensile strain exceeded 5%, and the tensile strength was approximately 7 MPa. Therefore, specimen No.6 mixture was used for the column specimens.

2.2. Specimen description

All of the column specimens in this experiment have all details in common but one with the only difference being in stirrup spacing. Transverse reinforcement is generally considered to serve three main functions, of confining the concrete core, restraining buckling of longitudinal bars and avoiding shear failure. Hence, different stirrup spacing in the column specimens can lead to serious effects corresponding to the three above mentioned behaviors. More specifically, the wider the stirrup spacing is, the less confinement it provides to the core concrete, and the main reinforcements are also poorly supported to prevent buckling as well, resulting in non-ductile behavior and the sudden brittle failure of the columns. That feature was exploited to intentionally control the failure modes of column specimens: flexure-controlled (FC) and shear–flexure controlled (SF).

In this study, six 2/3-scale column specimens with sections of 300 mm × 300 mm and 900 mm in height were tested to investigate the behavior of concrete columns under seismic load. Three columns, which were flexure-control (FC) specimens, were tested to assess flexural behavior and the three remaining specimens called shear–flexure (SF) specimens were tested to consider the shear and flexure behavior simultaneously. Though there is different between full and scaled models in the maximum shear strength, but the crack pattern and hysteresis loops were quite similar. Also, the flexural and shear deformation

Table 2.1
Test results of reinforcing bars and concrete (all units are MPa).

	Longitudinal bar (D19)		Stirrup (D10)		Concrete	
	Tensile strength	Young's modulus	Tensile strength	Young's modulus	Compressive strength (normal concrete)	Compressive strength (HPFRCC)
Specified	400.0	200,000	400.0	200,000		
Measured	484.7	190,870	528.3	183,697	27.3	48.3
Difference (%)	21.2	−4.6	32.1	−8.2		

Table 2.2
HPFRCC mix proportions for the detailed material specimens.

Material		No.01	No.02	No.03	No.04	No.05	No.06	Note
Binder (wt.%)		72.3	67.4	67.1	64.2	57.8	56.2	
Filler (wt.%)	Silica sand	25.0	30.0	10.0	13.0	–	–	
	$CaCO_3$	–	–	20.0	20.0	40.0	41.0	
	CW150	–	–	–	–	0.5	1.0	
CA (wt.%)		2.7	2.6	2.9	2.8	1.7	1.8	Chemical admixture
PVA fiber (Vol. %)		2.0	2.0	2.0	2.0	2.1	2.1	
W/PCM (wt.%)		20.0	20.0	20.0	20.5	22.0	22.0	

1. Binder: cement, fly ash, and powdered slag, silica fume, consisting expandable.
2. PCM: Premixed Cement Mortar (dry mortar), Binder + Filler + CA.