Research Article

Seismic Performance of High-Ductile Fiber-Reinforced Concrete Short Columns

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This study mainly aims to investigate the effectiveness of high-ductile fiber-reinforced concrete (HDC) as a means to enhance the seismic performance of short columns. Six HDC short columns and one reinforced concrete (RC) short column were designed and tested under lateral cyclic loading. The influence of the material type (concrete or HDC), axial load, stirrup ratio, and shear span ratio on crack patterns, hysteresis behavior, shear strength, deformation capacity, energy dissipation, and stiffness degradation was presented and discussed, respectively. The test results show that the RC short column failed in brittle shear with poor energy dissipation, while using HDC to replace concrete can effectively improve the seismic behavior of the short columns. Compared with the RC short column, the shear strength of HDC specimens was improved by 12.6–30.2%, and the drift ratio and the energy dissipation increases were 56.9–88.5% and 237.7–336.7%, respectively, at the ultimate displacement. Additionally, the prediction model of the shear strength for RC columns based on GB50010-2010 (Chinese code) can be safely adopted to evaluate the shear strength of HDC short columns.

1. Introduction

Reinforced concrete (RC) short columns are structural members with high lateral stiffness but often failed in shear with low energy dissipation in strong earthquakes [1], which causes serious damage to the structure and great difficulty for the postearthquake repairing. Therefore, investigating practical and effective methods to enhance the seismic behavior of short columns is very important.

Incorporation of fibers into concrete is a feasible method to reduce the brittleness of concrete and improve the seismic behavior of short columns. Research works [2, 3] have shown that the steel fiber and polyvinyl alcohol (PVA) fiber incorporated into concrete can improve the seismic performance of short columns. However, with the increase of concrete strength, incorporation of fibers would be of no avail.

High-ductile fiber-reinforced concrete (HDC) [4, 5] is a kind of fiber-reinforced cement composites like engineering cementitious composites (ECC) [6, 7] and

high-performance fiber-reinforced cement composites (HPFRCCs) [8, 9], which shows steady propagation of multiple fine cracks and excellent tensile strain-hardening behavior due to the fiber-bridging effect [6]. Those materials provide a new method to solve the brittleness of concrete; thus, they have been paid more and more attention in structural engineering. Application of fiber-reinforced cement composite materials in beams [10–12], beam-column joints [13, 14], slabs [15], and masonry structures [16, 17] has been widely studied, while there are limited researches about fiber-reinforced cement composites used in short columns. Research work by Wu et al. [18] shows that the seismic behavior of steel-reinforced ECC short columns is much better than that of RC columns, while the axial load of the columns in this work is relative low.

The present study investigates the use of HDC as an alternative design of seismic short columns, where the use of the HDC as replacement of concrete is expected to improve the deformation capacity and energy dissipation ability of short columns. Six HDC short columns and one RC short

TABLE 1: Mix proportion of HDC (kg/m³).

Binder	Sand	Water	PVA fiber	Water reducers
1186 kg	427 kg	344 kg	26 kg	8 kg

TABLE 2: Properties of PVA fibers.

Fiber type	Length	Diameter	Tensile strength	Tensile modulus
PVA	12 mm	0.39 μm	1600 MPa	40 GPa

FIGURE 1: Stress-strain curves and the crack pattern of HDC. (a) Stress-strain curves and (b) crack pattern.

column were prepared to study the seismic performance of short columns under cyclic loading. The outcome of this paper would be helpful to demonstrate the advantages of fiber-reinforced cement composites like ECC and HDC compared with concrete.

2. Experimental Programs

2.1. HDC Materials. The mixed proportions of the HDC used in this study are summarized in Table 1. The components of HDC include binder (cement and fly ash), river sand, water, and polyvinyl alcohol (PVA) fibers. A 2% volume incorporation of PVA fibers is used in the HDC, and the mechanical properties of the PVA fibers are shown in Table 2. Figure 1 shows the stress-strain curves and the crack pattern of HDC specimens in direct tension, which indicates that the average crack strength of HDC is 5.73 MPa, the average tensile strength is 6.14 MPa, and the ultimate tensile strain is about 1.0%. In this paper, the tensile strength of HDC is conservatively taken as the cracking strength.

2.2. Specimen Design. Six HDC short columns and one RC short column employed as a control specimen were prepared. The columns had a cross section of 250 mm $\times$ 250 mm

with a height H of 500/375 mm, and the foundation beams had a cross section of 450 mm $\times$ 450 mm with a total length of 1200 mm. The longitudinal reinforcements for the short columns consisted of 6HRB400($d = 22$ mm) bars, while those for the foundation beams consisted of 8HRB400($d = 22$ mm) bars. Transverse reinforcements for the short columns and foundation beams consisted of 8 mm diameter hoops. As shown in Table 3, the key parameters of this study are the shear span ratio $\lambda = H/h$, the axial load N , and the stirrup spacing s .

Figure 2 shows the geometric size and reinforcement details of the specimens. The HDC material was cast in the connection of the foundation beams to avoid interface failure. The strengths of bars (yielding strength) and concrete and HDC (cubic compressive strength f_{cu}) are listed in Table 4. The cubic compressive strength of concrete and HDC was tested by three cubic blocks (100 mm $\times$ 100 mm $\times$ 100 mm), respectively.

2.3. Test Equipment and Loading Procedure. The loading devices for the cyclic loading tests are shown in Figure 3. The constant vertical load was applied on the top of each column first through a hydraulic jack, and the lateral cycle load imposed on the columns was then applied by a 1000 kN (MTS1000) hydraulic actuator.

TABLE 3: Parameters of short columns.

Specimen	Material	λ	H (mm)	s (mm)	ρ_{sv}	N (kN)
RC1	Concrete	2	500	80	1.26%	515.6
HDC2	HDC	2	500	80	1.26%	343.7
HDC3	HDC	2	500	80	1.26%	515.6
HDC4	HDC	2	500	80	1.26%	687.5
HDC5	HDC	2	500	100	1.01%	515.6
HDC6	HDC	2	500	120	0.84%	515.6
HDC7	HDC	1.5	375	80	1.26%	515.6

FIGURE 2: Geometry and reinforcement details (unit: mm).

According to the Specification of Testing Methods for Earthquake Resistant Building [19] protocol, a force-displacement hybrid control program was used. Figure 4 shows the loading procedure of the test, which involved a force control step and a displacement control step. In the force control stage, the increment of lateral load was 20 kN until the first yielding of the longitudinal steel bars during the tests. Then, the loading procedure was changed into the displacement control stage, and the increment of the displacement was 2 mm; n is the step number of displacement load. Each displacement load step was repeated thrice until the lateral load of the specimens dropped below 85% of the peak value.

2.4. Measurement and Data Acquisition. Figure 5 shows the installation position of the measurement devices on the short columns. A linear variable differential transducer (LVDT-1) was installed at the lateral loading point. The lateral slip of the foundation beam was monitored by LVDT-2. The shear deformation of each specimen was measured by two cross dial gauges located at the midheight of it. The strains in the longitudinal reinforcements and stirrups were measured using 24 strain foils attached on the reinforcement bars.

3. Results and Analysis

3.1. Test Observation

3.1.1. Specimen RC1. The cracking (a horizontal crack at the column foot) load of the control specimen RC1 was 80 kN.

TABLE 4: Strength of materials.

Material	HRB400	HPB235	Concrete	HDC
Strength (MPa)	439	315	68.9	65.7

FIGURE 3: Test setup.

When the lateral load reached 140 kN, the first diagonal crack appeared in the midheight of the short column. The major diagonal cracks formed at a load equaled 220 kN whilst the stirrups yielded. When the load reached 260 kN, the major diagonal crack widened to about 1 mm and the short column yielded; subsequently, the loading procedure was changed into the displacement control stage. When the displacement pulled to 8.5 cm, specimen RC1 reached its peak load (299 kN). After that, the shear strength of RC1 declined sharply with the widening of the major diagonal

FIGURE 4: Loading procedure.

FIGURE 5: Measurement position.

cracks and the spalling of the concrete cover. No more cracks appeared with the process of cyclic loading. Finally, specimen RC1 failed in brittle shear with its concrete cover crushed and the steel bars exposed.

3.1.2. Specimen HDC3. For specimen HDC3, the stirrup ratio and axial load applied on it are the same with that for specimen RC1. The cracking (three horizontal cracks) load of the specimen was 130 kN, which was 50 kN (62.5%) higher than that of specimen RC1. When the lateral load equaled 180 kN, many tiny shear diagonal cracks appeared at the midheight of the specimen. The longitudinal reinforcements and stirrup yielded when the load increased to 280 kN; meanwhile, the horizontal cracks extending and diagonal cracks widening. Then, the displacement control loading was adopted. The peak load of specimen HDC3 was 366 kN when the displacement pulled to 11.2 mm, and a dense network of tiny cracks was observed near the major diagonal cracks. With the loading displacement increased, the lateral load decreased slower than that of specimen RC1. No crushing of the HDC cover was observed at the failure stage of the HDC short column, and the specimen failed in shear with moderate ductility.

The other HDC short columns behaved similar to specimen HDC3. Due to the fiber-bridging effect, HDC materials exhibited a higher tensile strength and higher toughness compared to concrete. As a result, the cracking

loads of the HDC short columns were at least 50% higher than those of the RC specimen, and no spalling of covers in HDC short columns occurred.

3.2. Crack Distribution and Failure Modes. Figure 6 shows the crack distribution of the short columns when longitudinal bars yield. X-shaped diagonal cracks and few horizontal cracks were observed in specimen RC1; however, a dense network of diagonal cracks appeared at the mid-height of the HDC short columns with much smaller crack width than that of specimen RC1. This phenomenon is due to the multiple crack mechanism of HDC materials caused by the fiber-bridging effect. The angle between the diagonal crack and vertical axis decreased with the increase of axial load. With the decrease of stirrup ratio, the diagonal cracks became denser. In addition, the number of diagonal cracks decreased when the column had a smaller shear span ratio.

Figure 7 shows the final failure patterns of the short columns. For specimen RC1, the failure mode was dominated by shear at a drift of 1.8%. Additionally, the concrete cover was severely crushed, and the reinforcement bars were exposed to the air, which indicates that specimen RC1 failed in brittle mode. While for the HDC short columns, even specimen HDC 6 (with the lowest stirrup ratio) reached a 2.8% drift at the failure stage, which is 55.5% higher than that of specimen RC1. Though significant X-shaped diagonal cracks were observed in HDC short columns, the dense

FIGURE 6: Crack distribution: (a) RC1, (b) HDC2, (c) HDC3, (d) HDC4, (e) HDC5, (f) HDC6, and (g) HDC7.

FIGURE 7: Final failure patterns: (a) RC1, (b) HDC2, (c) HDC3, (d) HDC4, (e) HDC5, (f) HDC6, and (g) HDC7.

network of diagonal cracks was distributed around the X-shaped cross cracks, and the HDC short columns behaved much better in sustaining the intactness of the column section under the cyclic loading.

Compared with concrete, HDC exhibited excellent crack-controlling properties (multiple crack mechanism and strain-hardening behavior) due to the bridging effect of the PVA fibers. When the short columns cracked, the fibers between the cracks of HDC specimens could still transfer the tensile stress until the ultimate tensile strain. The behavior of the HDC short columns was dominated by shear because the design flexural capacity was relative high, but the ductility and the damage tolerance capacity of the short columns were effectively improved.

3.3. Hysteretic Behavior. Figure 8 shows the hysteretic curves of the short columns. It can be seen from this figure that the area of the hysteretic loops was small and narrow before cracking, which indicates that the columns were in the elastic state. After the cracking load, the lateral stiffness of each specimen decreased gradually due to the development of cracks, and the area of hysteretic loops increased. The peak load of each HDC short column was larger than that of specimen RC1 though the compressive strength of HDC was lower than that of concrete (in this study). After the peak

load, the shear strength of specimen RC1 dropped rapidly, and the area of its hysteretic loops decreased at a high rate; however, the HDC short columns behaved much better in shear strength retention. Moreover, the HDC short columns were able to suffer more cycles of lateral loading than specimen RC1; thus, the HDC short columns had much larger amounts of hysteretic loops, namely, higher energy dissipation capacity, which is very favorable for earthquake resistance.

The hysteretic loops of HDC short columns were similar in shapes. With the increase of the axial load and the stirrup spacing, the area of the hysteretic loops of HDC short columns became narrower. When the HDC short column had a smaller shear span ratio, the area of the hysteretic loops decreased.

3.4. Skeleton Curves and Performance Indexes. Figure 9 shows the skeleton curves of the specimens, and Table 5 lists the characteristic loads (i.e., the crack load P_{cr} , yield load P_y , peak load P_m , and ultimate load P_u) and their corresponding displacements obtained from Figure 9. The yield loads of the short columns are defined by the energy method proposed by Mahin and Bertero [20], and the ultimate loads equal to the lateral loads decline to 85% of their peak value. The displacement ductility factor $\mu = \Delta_u / \Delta_y$, and the ultimate

FIGURE 8: Hysteretic loops of specimens: (a) specimen RC1, (b) specimen HDC2, (c) specimen HDC3, (d) specimen HDC4, (e) specimen HDC5, (f) specimen HDC6, and (g) specimen HDC7.

FIGURE 9: Skeleton curves of specimens: (a) effect of the material, (b) effect of the axial load ratio, (c) effect of the stirrup ratio, and (d) effect of the shear span ratio.

TABLE 5: Comparisons of the characteristic load and displacement.

Specimen	P_{cr} (kN)	Δ_{cr} (mm)	P_y (kN)	Δ_y (mm)	P_m (kN)	Δ_m (mm)	Δ_u (mm)	$\theta_u = \Delta_u/H$	$\mu = \Delta_u/\Delta_y$
RC1	80	0.90	240.05	5.42	289.49	8.51	9.17	1/55	1.69
HDC2	120	2.39	268.51	7.12	326.05	13.65	17.29	1/29	2.42
HDC3	130	2.24	270.62	6.65	358.20	11.23	15.43	1/32	2.32
HDC4	150	2.54	318.83	7.16	376.85	13.06	16.20	1/31	2.26
HDC5	130	2.34	279.74	6.72	342.39	11.55	14.39	1/35	2.14
HDC6	140	2.79	261.31	6.38	334.26	11.71	14.48	1/35	2.27
HDC7	150	1.81	394.01	5.73	443.92	7.37	13.89	1/27	2.75

drift ratio $\theta_u = \Delta_u/H$ are used to evaluate the ductility and deformation capacity of the short columns, as shown in Table 5. Based on Figure 9 and Table 5, the following observations can be drawn:

- (1) The axial load and stirrup ratio of specimen HDC3 were the same with those of specimen RC1. The peak load of specimen HDC3 was 24% higher, and the lateral load decreased at a slower rate than that of specimen RC1 (Figure 9(a)). Both (RC1 and HDC3) failed in shear, the displacement ductility factor of specimen HDC3 increased by 37%, and the ultimate drift ratio increased

by 72%. It means that using HDC can significantly improve the plastic deformation ability of short columns.

- (2) The peak loads of HDC short columns increased with the rise of axial load, while there were no big differences in the ultimate drift ratios and displacement ductility factors of HDC2, HDC3, and HDC4, indicating that the influence of axial load on the ductility and deformation capacity of HDC short columns is relatively small.
- (3) Compared with specimen RC1, the peak load, displacement ductility factor, and ultimate drift ratio of

specimen HDC6 were improved by 15.5%, 34.3%, and 57.9%, respectively, which indicates that using HDC to replace concrete can significantly reduce the stirrup ratio.

- (4) Compared with specimen HDC3, the stirrup ratio of specimens HDC5 and HDC6 was reduced by 20% and 33%, respectively, while the peak loads of specimens HDC5 and HDC6 were only reduced by 4.4% and 6.6%, respectively; meanwhile, the displacement ductility factor of specimens HDC5 and HDC6 was reduced by 7.7% and 2.1%, respectively, which means that the influence of the stirrup ratio on the shear strength and ductility of HDC short columns is relatively small. Additionally, the ultimate drift ratio of specimen HDC5 was about 57% higher than that of specimen RC1, which again certified that using HDC to replace concrete could reduce the amount of the stirrups.
- (5) The shear strength of specimen HDC7 was 23.9% higher than that of specimen HDC3. Besides, the ultimate drift ratio and the displacement ductility factor of specimen HDC7 are 18.5% and 18.5% higher than those of specimen HDC3, respectively, which indicates that HDC can be used to improve the strength and deformation capacity of high shear stress components.

Above all, using HDC to replace concrete in short columns can greatly enhance their shear strength and deformation capacity and also reduce the stirrup ratio due to the significant tensile performance of HDC, namely, the strain-hardening behavior due to the fiber-bridging effect. These results indicate that the ductility of the HDC material achieves the ductility of the structural members.

3.5. Energy Dissipation Capacity. The energy dissipation capacity of the specimens under cyclic loading is an important indicator to evaluate the seismic behavior of short columns. In lateral reversed cyclic loading tests, the energy dissipation capacity can be reflected by the cumulative energy absorption at characteristic points, which are the yield point, peak point, and ultimate point. Table 6 shows the cumulative energy dissipation at the characteristic points mentioned above. It can be seen that

- (1) the HDC short columns exhibited a significant increase in cumulative energy dissipation in comparison to RC1 ranging between 109% and 239% at the yield displacement, and from 134% to 247% at the peak displacement, and from 181% to 337% at the ultimate displacement, indicating that using HDC to replace concrete could improve the cumulative energy dissipation of short columns tremendously, especially when the specimens were in the failure stage;
- (2) the cumulative energy dissipation by specimen HDC3 at the yield load, peak load, and ultimate load were 2.39 times, 2.02 times, and 2.9 times higher than that by specimen RC1, respectively, which means that the energy dissipation capacity of short columns

TABLE 6: Energy dissipation of short columns.

Specimen	Accumulated energy dissipation (kN·mm)		
	Δ_y	Δ_m	Δ_u
RC1	241.63	1581.07	3547.57
HDC2	747.54	5492.02	15,494.21
HDC3	819.38	4782.07	13,868.88
HDC4	748.34	4204.59	12,331.63
HDC5	900.75	4363.54	12,158.34
HDC6	720.46	4251.20	11,981.61
HDC7	506.12	3713.31	9997.16

at different performance levels can be improved considerably by replacing concrete with HDC;

- (3) the energy dissipation capacity of HDC short columns at different displacements decreased with the rise of axial load ratio while increased with the rise of stirrup ratio. Even specimen HDC7 with a smaller shear span ratio dissipated more energy than that of specimen RC1, which indicates that the energy dissipation capacity of the HDC short columns is mainly dominated by the properties of the HDC materials.

3.6. Stiffness Degradation. The secant stiffness K_i is used to analyze the stiffness degradation of the short columns, which is defined as the slope of the line from the origin of coordinates to the peak load of each (i th) cycle:

$$K_i = \frac{|+P_i| + |-P_i|}{|+\Delta_i| + |-\Delta_i|}, \quad (1)$$

where $+P_i$ and $-P_i$ are the peak load of the i th cycle in pushing and pulling, respectively, and $+\Delta_i$ and $-\Delta_i$ are the corresponding displacement to $+P_i$ and $-P_i$. The stiffness degradation curves of the short columns are shown in Figure 10. It can be concluded from Figure 10 that

- (1) as the elasticity modulus of HDC is lower than that of the concrete, the initial stiffness of HDC3 is lower than that of RC1. The initial stiffness of HDC short columns increases with the rise of axial load ratio, while the stirrup ratio has little effect on the initial stiffness. Besides, the initial stiffness of the HDC short column increases significantly with the decrease of shear span ratio;
- (2) under the cyclic loading, the lateral stiffness of specimen RC1 decreased rapidly due to the development of cracks and the softening of concrete. In contrast, the lateral stiffness of the HDC short columns decreased much slower than that of RC1 due to the strain-hardening behavior of HDC materials. Namely, the fiber-bridging effect between the diagonal cracks effectively sustained the shear strength of the cracked HDC short columns;
- (3) HDC is a material with high compressive toughness and shear deformation ability; thus, the influence of

FIGURE 10: Curves of stiffness degradation: (a) effect of the material, (b) effect of the axial load ratio, (c) effect of the stirrup ratio, and (d) effect of the shear span ratio.

the axial load and stirrup ratio on the stiffness degradation rate is relatively small. However, the stiffness degradation rate is much higher when the shear span ratio becomes smaller.

4. Shear Strength

Most current design codes such as ACI 318 [21] and GB 50010-2010 [22] consider that the shear strength V_n of RC columns consists of concrete shear contribution V_c and transverse stirrup shear contribution V_s . The calculation formulas of the ACI 318 model and GB 50010-2010 proposal can be expressed as (2) and (3), respectively, and the effect of axial load on the shear strength in these two models is considered:

$$V_n = V_c + V_s = 0.17 \left(1 + \frac{N}{14A} \right) \sqrt{f'_c} b h_0 + \frac{A_{sv} f_{yv} h_0}{s}, \quad (2)$$

$$V_n = V_c + V_s = \frac{1.75}{\lambda + 1} f_t b h_0 + \frac{A_{sv} f_{yv} h_0}{s} + 0.07 N. \quad (3)$$

TABLE 7: Test results and calculated results (kN).

Specimen	P_m	V_n (ACI)	P_m/V_n (ACI)	V_n (GB)	P_m/V_n (GB)
RC1	289.5	206.5	1.40	258.0	1.12
HDC2	326.0	196.2	1.66	301.1	1.08
HDC3	358.2	212.5	1.68	313.1	1.14
HDC4	376.9	228.7	1.64	325.2	1.16
HDC5	342.4	194.7	1.76	295.3	1.16
HDC6	334.3	182.8	1.82	283.5	1.18
HDC7	443.9	212.5	2.08	350.7	1.26

According to GB 50010-2010, the cylinder compressive strength, the axial compressive strength, and the tensile strength of the concrete are calculated based on the relationships $f'_c = 0.8 f_{cu}$, $f_c = 0.76 f_{cu}$, and $f_t = 0.395 f_{cu}^{0.55}$,

respectively. Equations (2) and (3) are used to predict the shear strength of ordinary RC columns, and the effectiveness of the formulas mentioned above for calculating the shear strength of HDC short columns is not known. The test results and the calculated results based on (2) and (3) are listed in Table 7.

As shown in Table 7, the results calculated by (2) are at least 40% smaller than the test results. This is because the ACI 318 calculating model does not take into account the effect of the shear span ratio and the tensile stress transferred by the fiber between the diagonal cracks. The results calculated by (3) agree better with the test results compared with (2). However, the results calculated by (3) are still 8–26% lower than the test values. This is because the GB 50010-2010 calculating model does not take into account the dowel action of the longitudinal bars (the longitudinal reinforcement ratio of the short columns is 3.65%). In all, the calculating model of GB 50010-2010 can be adopted to predict the shear strength of the HDC short columns safely.

5. Conclusions

Based on the results and analysis obtained by the cyclic loading tests, the following conclusions can be made:

- (1) The failure mode of RC short columns was dominated by brittle shear, while the HDC short columns failed in relatively ductile shear with the dense network of diagonal cracks observed. Severe crushing of the concrete cover occurred in RC short columns at the failure stage, while the HDC short columns effectively sustained the intactness of the column section due to the fiber-bridging effect in HDC materials.
- (2) Compared with the RC short column, the hysteretic performance of the HDC short columns was significantly improved, and the HDC short columns were able to suffer more cycles of lateral loading and dissipate more earthquake energy than those of the RC specimen before failure. At the ultimate displacement, the cumulative energy dissipation of the HDC short column was at least 237% higher than that of the RC specimen, which is very favorable for earthquake resistance.
- (3) Using HDC to replace concrete in short columns could significantly enhance the crack load and the peak load and also considerably improve the displacement ductility factor and the ultimate drift ratio of the specimens. The increase of ultimate drift ratio of HDC short columns was at least 56.9% compared with the RC short column, which means that there is effective improvement in the plastic deformation capacity of the short columns.
- (4) The influence of the axial load on the deformation capacity and the energy dissipation capacity of HDC short columns is relatively small. The ultimate drift ratio and energy dissipation capacity of the columns mainly depend on the property of the HDC materials. When the column has a smaller shear span ratio, the energy dissipation capacity decreased but the ultimate drift ratio increased.
- (5) Under the lateral cyclic loading, the lateral stiffness of the RC short column decreases rapidly due to the crack opening and concrete softening. In contrast, the lateral stiffness of the HDC short columns decreases relatively slower than that of the RC specimen due to the good tensile behavior of the HDC materials. Namely, the fiber-bridging effect between the cracks effectively sustains the shear strength of the cracked HDC short columns.
- (6) The shear strength of HDC short columns predicted based on the GB 50010-2010 method agrees well with the test results; thus, the proposed method can be safely used in the design of HDC short columns.

Nomenclature

H :	Height of the column
ρ_s :	Longitudinal reinforcement ratio
b :	Column width
ρ_{sv} :	Stirrup ratio
h :	Column depth
P_{cr}, Δ_{cr} :	Crack load, crack displacement
h_0 :	Effective column depth
P_y, Δ_y :	Yield load, yield displacement
λ :	Shear span ratio
P_m, Δ_m :	Peak load, peak displacement
s :	Stirrup spacing
Δ_u :	Ultimate displacement
f_t :	Tensile strength of concrete
μ :	Displacement ductility factor
f_y :	Yield strength of longitudinal bars
θ_m :	Peak drift ratio
f_{yv} :	Yield strength of stirrups
θ_u :	Ultimate drift ratio
f_{cu} :	Cube compressive strength of concrete
A_c :	Cross section area of the column
f_c :	Cylinder compressive strength of concrete
A_{sv} :	Total cross section area of stirrups
f_c :	Axial compressive strength of concrete
V_n :	Nominal shear strength
N :	Axial load on the top of the column
V_c, V_s :	Shear strength of concrete, stirrup.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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