Cyclic behaviour of older concrete columns reinforced with high-performance fiber reinforced cementitious composites

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ABSTRACT

Many older existing reinforced concrete (RC) buildings were designed without considering seismic loads. In such buildings, columns may be the most vulnerable element because they generally have insufficient reinforcement details that do not meet current code requirements. The objective of this study is to explore the potential of using high-performance fiber reinforced cementitious composites (HPFRCC) for lightly reinforced columns. Experimental studies were conducted with full scaled specimens. The cyclic behaviour of columns was improved by using HPFRCC. In addition, the onset of damage states and failure were delayed by using HPFRCC.

1 INTRODUCTION

Many older reinforced concrete (RC) buildings were designed only considering gravity loads (Lynn et al., 1996). Columns in those buildings generally have limited reinforcement: short lap splices at potential plastic hinge locations, wide transverse reinforcement spacing, 90-degree hooks used for transverse reinforcement (Lee and Han, 2019). Such reinforcement details do not meet the requirement specified in current seismic design standard (Sezen and Moehle, 2004) such as ACI 318-19 (ACI, 2019). Columns in older RC buildings could be vulnerable during earthquakes, which may lead to catastrophic story mechanism.

To improve the seismic behaviour of older columns, the columns could be retrofitted to satisfy the design and reinforcement detail requirements specified in current codes. However, it is complex task to add more reinforcement and increase the lap splice length in existing columns due to interference between existing and new reinforcements and reinforcement congestion. In this study, high-performance fiber reinforced cementitious composites (HPFRCC) were applied to the potential plastic hinge region of the columns, by which drawbacks arisen from the use of conventional retrofit methods could be averted. Because HPFRCC have crack control capability, and high tensile ductility, and tensile strength (Parra-Montesinos, 2005; Han et al., 2015; Zhang et al. 2020), the application of the HPFRCC to columns may improve the shear strength, crack resistance, confinement effect, and bond slip resistance of short lap spliced reinforcements in older columns.

To investigate the effect of HPFRCC on older columns, we conducted experimental tests. For this purpose, four full–scale column specimens were made: two older RC specimens and two HPFRCC specimens. All specimens had the same reinforcement details, which generally used in older RC columns. Column specimens were tested under unidirectional and bidirectional lateral loading.

2 TEST PROGRAM

Two types of columns were fabricated: older RC columns with limited reinforcement details (NC) and HPFRCC specimens with the same reinforcement details as the NC specimens. Four full-scale specimens were tested under unidirectional loading (U) and bidirectional loading(B): specimens NC-U and HC-U represent older columns and HPFRCC columns tested under unidirectional lateral loading, respectively, whereas specimens NC-B and HC-B were bidirectionally loaded older and HPFRCC specimens, respectively. Figure 1 presents the column specimens. The dimensions and reinforcement details of the specimens were adopted from Lynn et al. (1996). In specimens HC-U and HC-B, the HPFRCC was poured up to 775 mm from the base, which is 1.3× the length where flexural yielding normally occurs according to Section 18.7.5.1 of ACI 318-19: the greatest of column depth, 1/6 of column clear span, and 450mm.

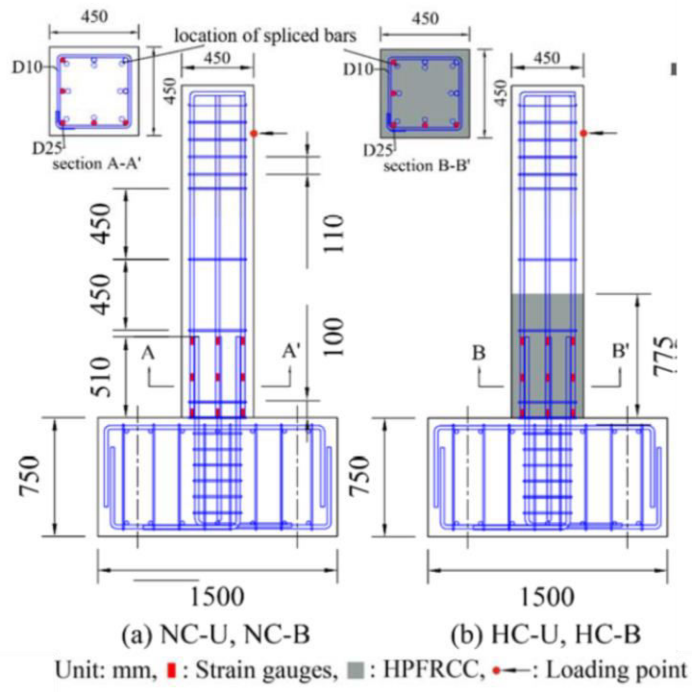

Figure 1: Test specimens

Reinforcing rebars (D25) with d_b= 25.4 mm was used for longitudinal reinforcements (ρ_l= 0.02), and a lap splice length (l_d)= $20d_b$ (= 510 mm) was used (53% of the l_d required by ACI 318-19 (= $38d_b$), where d_b is the diameter of the reinforcement, ρ_l is the ratio of the area of the longitudinal reinforcement (A_{st}) to the column gross sectional area (A_g). Transverse reinforcement with d_b = 9.5 mm (D10) were used with spacings of 450 mm (ρ_t= 0.007) where ρ_t is the ratio of the transverse reinforcement area to the gross concrete area perpendicular to the reinforcement. The design concrete compressive strength (f'_c) was 23 MPa and the reinforcement specified yield strength (f_y) was 420 MPa.

Figure 2 shows the test setup, which was developed to effectively conduct unidirectional and bidirectional column tests. A swivel joint was installed between the loading frame and top of the column to accurately apply constant gravity loads under bidirectional lateral loading. A constant axial load ($P/A_g f_c'$= 20%) was used (Han and Jee, 2005) for each specimen; in the above calculation, P is the column axial load, A_g is the gross area of column, and f_c' is the concrete compressive strength. Unidirectional and bidirectional lateral loading was applied according to FEMA 461 (FEMA, 2017).

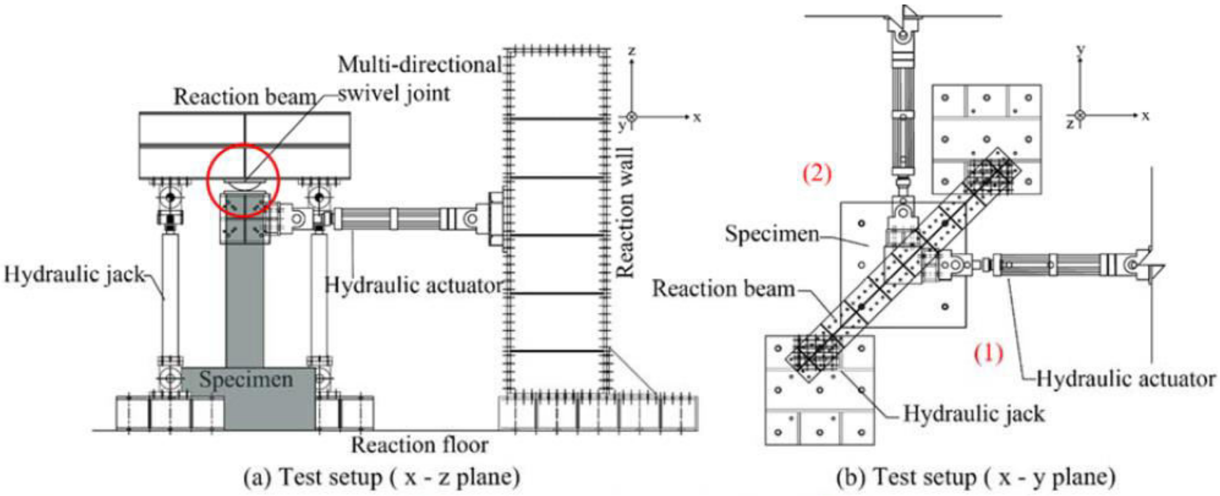

Figure 2: Test setup

3 DAMAGE PROGRESSION

Figure 3 shows the damage in the specimens at failure (θ_f).

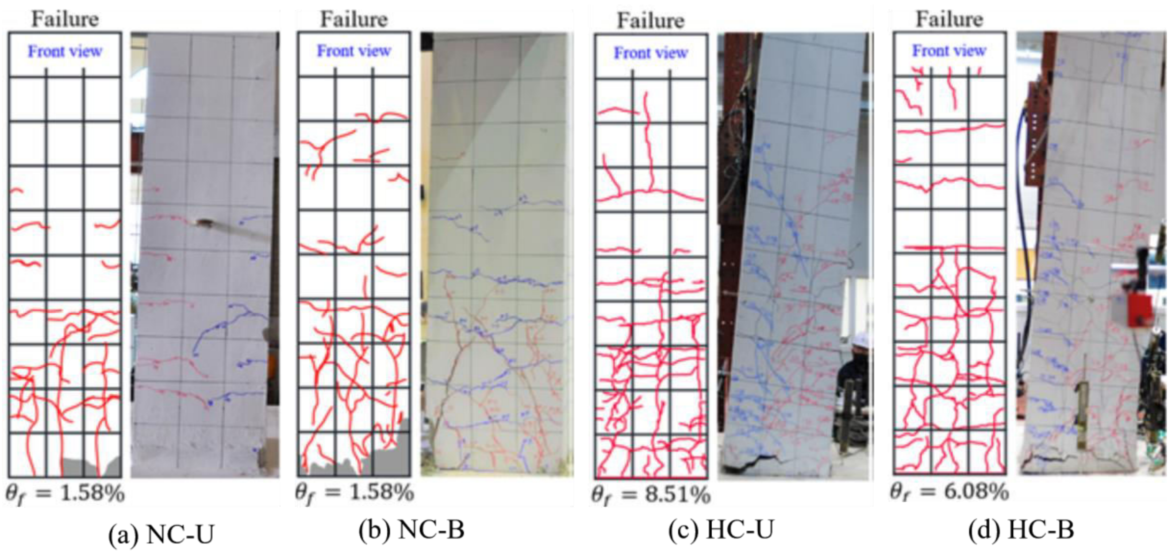

Figure 3: Damage in column specimen at failure (θ_f)

The test was terminated at θ= 1.58% for specimens NC-U and NC-B. A separation between the column base and base concrete block was detected in both specimens, indicating a lap-splice failure owing to a loss of bond strength between the concrete and longitudinal reinforcement. Because the lap-splice failure occurred at early loading stages, the concrete spalling did not occur severely in those specimens. Specimens HC-U and HC-B failed at θ= 8.51 % and 6.08 %, respectively. The HPFRCC specimens did not experience concrete spalling until test termination, irrespective of the loading direction. The incidences of vertical cracks in HC-U and HC-B specimens were delayed compared to those in corresponding NC specimens. Separation between the column base and concrete base block was also detected near failure, but it is not as significant as that in the NC specimens. Such phenomenon may be because of the effect of the fibers in the HPFRCCs.

4 CYCLIC CURVES

Figure 4 shows the cyclic curves of the specimens. The maximum strength (V_u), maximum drift ratio (θ_u), and θ values at failure (θ_f) can be determined from the cyclic curves. The maximum drift ratio (θ_u) denotes the θ value when the strength of the specimen decreases by 20% (ASCE, 2017). The seismic behaviour of the HC specimens was significantly improved compared with the NC specimens owing to the effect of the HPFRCC (NC-U versus HC-U, and NC-B versus HC-B).

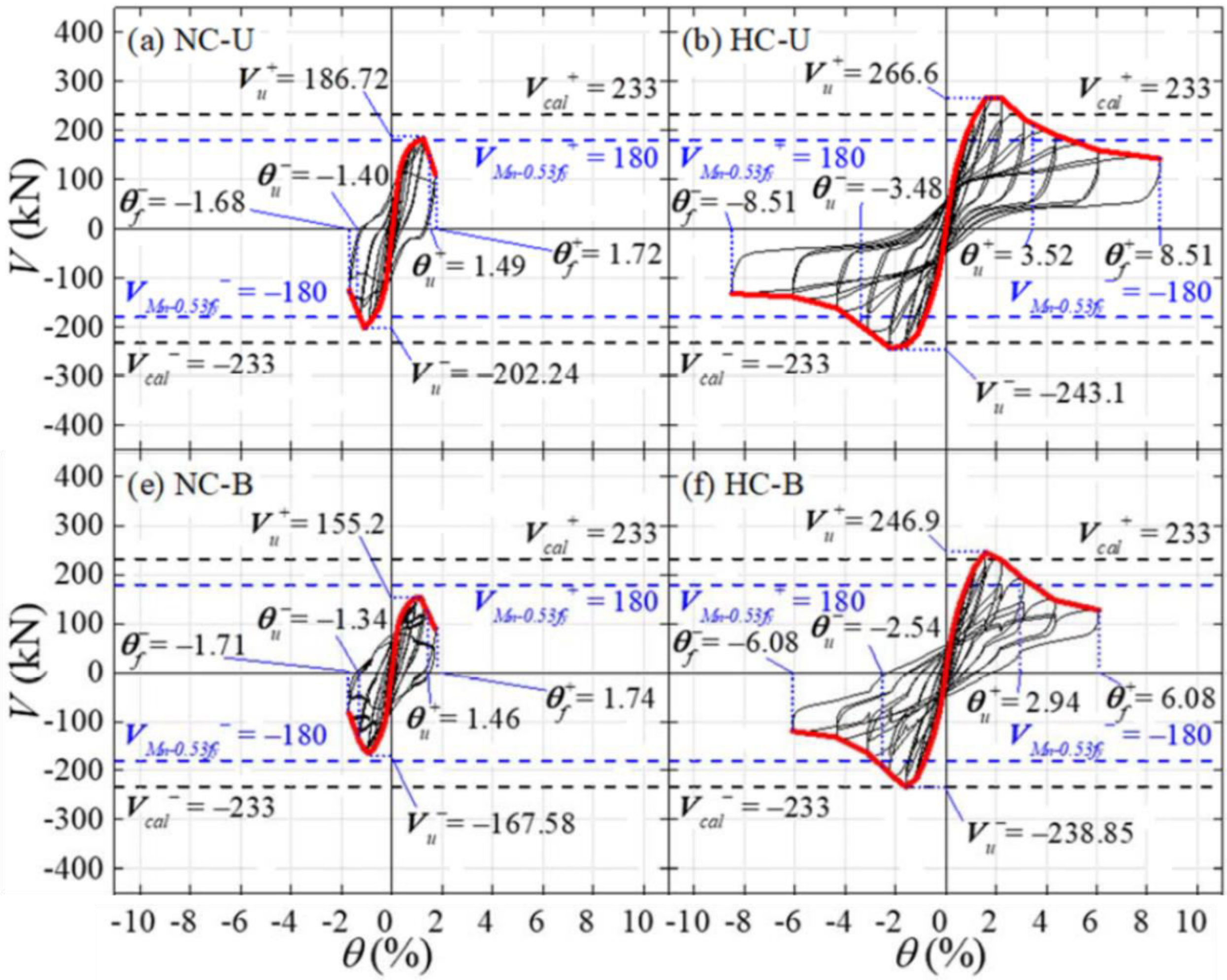

Figure 4: Cyclic curves

5 STRENGTH AND DEFORMATION CAPACITY

The measured shear strengths (V_u) and drift capacities (θ_u, θ_f), and calculated strengths (V_{cal}) were summarized in Table 1. The measured values were estimated from the cyclic curves. The V_{cal} value was determined as the lower of shear strength (V_{shear}) and moment-induced shear strength (V_{M_n}).

All specimens had V_{M_n} values lower than V_{shear} values, indicating that all specimens were expected to experience flexural failure. NC specimens had V_u smaller than V_{cal} whereas HC specimens had larger V_u than V_{cal}. The lap–splice length of all specimens was 53% of that required by ACI 318-19. The moment strength $M_{n-0.53f_y}$ was also calculated using $0.53f_y$ instead of f_y to consider the short lap splice length. The shear strength ($V_{M_n-0.53f_y}$) in Table 1 corresponds to $M_{n-0.53f_y}$ ($=M_{n-0.53f_y}/l_c$). The V_u value of the unidirectional specimen NC-U was close to $V_{M_n-0.53f_y}$: $V_u/V_{M_n-0.53f_y}$ = 1.03 (+loading direction) and 1.12 (−loading direction). The bidirectional specimen NC-B had even less strength than $V_{M_n-0.53f_y}$: $V_u/V_{M_n-0.53f_y}$ = 0.86 (+loading direction) and 0.92 (−loading direction). This indicates that premature lap–splice failure in older RC columns may occur earlier under bidirectional loading conditions than under unidirectional loading conditions. The V_u of specimen NC-B was 83 % of that of specimen NC-U.

Although the HC specimens had the same lap–splice length as the NC specimens, they had V_u values close to V_{cal} ($>V_{M_n-0.53f_y}$): V_u/V_{cal} = 1.13 (+loading direction) and 1.04 (− loading direction) for specimen HC-U, and V_u/V_{cal}= 1.05 (+loading direction) and 1.02 (− loading direction) for specimen HC-B. The shear strength (V_u) did not decrease significantly according to the loading type (unidirectional and bidirectional loadings) in the HC specimens, unlike in the NC specimens.

Specimens HC-U and HC-B had 2.4 and 2.0 times larger θ_u than specimen NC-U (NC-B) due to the effect of HPFRCC. The effect of HPFRCC was the most distinctive for θ_f. Specimens HC-U and HC-B had 8.5 and 6.0 times larger θ_f values than specimen NC-U. This may be attributed to the fiber bringing effect of HPFRCC that effectively resist cracks and failure.

Table 1 Test results for specimens

Specimen	Loading direction		Measured V_u (kN)	Measured θ_u (%)	Measured θ_f (%)	Calculated strength (kN) V_{shear} ①	V_{M_n} ②	V_{cal} =min(①,②)	$\frac{V_u}{V_{cal}}$	$\frac{V_u}{V_{M_n-0.53f_y}}$
NC-U	x	(+)	186	1.49	1.72	330	233	233	0.79	1.03
		(–)	202	1.40	1.68				0.86	1.12
HC-U	x	(+)	265	3.52	8.51	330	233	233	1.13	1.47
		(–)	243	3.48	8.51				1.04	1.35
NC-B	x	(+)	155	1.46	1.74	330	233	233	0.66	0.86
		(–)	167	1.34	1.71				0.71	0.92
HC-B	x	(+)	246	2.94	6.08	330	233	233	1.05	1.36
		(–)	238	2.54	6.08				1.02	1.32

6 CONCLUSIONS

In this study, experimental tests were conducted using four full-scale column specimens to evaluate the effect of HPFRCCs on the cyclic behaviour of concrete columns with limited reinforcement. The conclusions are summarized as follows:

The cyclic behaviour of HC specimens was superior to those of NC specimens. Although the HC specimens had the same reinforcement detail as the NC specimens, the shear strengths (V_u) of specimens HC-U and HC-B were 43% and 59% higher than those of the corresponding NC specimens (NC-U and NC-B)**,** respectively. The θ_u values of the HC-U and HC-B specimens were 2.4 and 2.0 times larger than those of the corresponding NC specimens, respectively. The effect of HPFRCC was the most apparent in prominent for θ_f: specimens HC-U and HC-B had θ_f as large as 5.0 and 3.5 times those of the corresponding NC specimens, respectively. Thus, the use of HPFRCC could be means to improve the cyclic behaviour of older concrete columns.

7 ACKNOWLEDGEMENTS

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