Experimental Testing of Limited Ductile High-Strength Reinforced Concrete Columns under Bi-Directional Cyclic Actions

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Abstract

Collapse prevention is one of the main goals of the performance-based seismic design of structures; hence it is of utmost importance to understand the collapse behaviour of critical building components (columns and walls). Recent studies have shown that collapse drift capacity of RC column is significantly reduced under bi-directional cyclic actions, thereby making it more prone to collapse. Moreover, high-strength RC (HSRC) columns prevalent in regions of low to moderate seismicity are generally considered more vulnerable to collapse due to inadequate confinement provided to the column core. Hence, a comprehensive experimental study is conducted to investigate the collapse behaviour of limited ductile HSRC columns, under both uni-directional and bi-directional cyclic loading. This paper presents the experimental results of two identical columns tested under uni-directional and bi-directional cyclic loading and discusses the influence of bi-directional cyclic actions on the collapse drift capacity of limited ductile HSRC columns.

Keywords: collapse drift capacity, bi-directional cyclic loading, high-strength RC columns, limited ductility

1 Introduction

During an earthquake, the multi-directional ground motion excitations result in biaxial bending of columns in a building frame structure. Whilst seismic performance of RC columns under uni-directional cyclic loading has been widely investigated, there have been relatively fewer experimental studies investigating the seismic behaviour of RC columns under bi-directional cyclic loading. Moreover, the biaxial collapse performance of normal-strength RC (NSRC) columns had been the prime focus of the majority of experimental testing conducted previously (Rodrigues et al. 2013c), thereby leaving the biaxial collapse behaviour of high-strength RC columns (HSRC) almost uninvestigated. On the other hand, HSRC columns are believed to have less displacement capacity than corresponding normal-strength RC columns due to the brittle nature of high-strength concrete (Bjerkeli et al., 1990). The drift prediction models developed by the authors (Raza et al., 2018a) also indicated that HSRC columns have a significantly lower drift capacity than NSRC columns. To make matters worse, 'limited ductile' detailing (refer AS 1170.4 and AS 3600) is adopted in regions of low to moderate seismicity (eg. Australia), thereby making an HSRC column more susceptible to collapse in an event of an earthquake.

Moreover, previous experimental studies have demonstrated a rapid degradation of strength and stiffness of the NSRC columns under bi-directional cyclic actions (Li et al. 1988). Some of the recent studies have also exhibited a considerable reduction in the collapse drift capacity of NSRC column under biaxial bending in comparison to uniaxial bending (Pham and Li 2013). In view of this, there is a dire need to investigate the collapse behaviour of limited ductile HSRC columns under bi-directional cyclic actions.

Hence, a comprehensive experimental testing program is currently being carried out in smart structures laboratory at the Swinburne University of Technology to investigate the seismic collapse performance of limited ductile HSRC columns under uniaxial and biaxial cyclic displacement load histories. This paper presents the preliminary results of two identical HSRC columns tested under uni-directional and bi-directional cyclic loading, respectively, with a constant axial load ratio.

2 Overview of the Experimental Program

A total of 10 limited ductile HSRC columns are being tested as part of this testing program. The variable parameters of the study are axial load ratio, transverse reinforcement ratio, concrete compressive strength and the direction of loading. Table 1 provides brief details about the testing program. More details regarding specimen design, instrumentation and test set up can be found in the companion paper (Raza et al. 2018b)

3 Bi-Directional Loading Protocols

A number of different bi-directional loading protocols have been employed by various researchers in the previous studies. Rodrigues et al. (2013c) listed seven commonly used loading paths namely, cruciform, diagonal cruciform, Rhombus, expanding square, square in each quadrant, circular and elliptical paths. ACI 374.2R-13 has also proposed a hexagonal orbital pattern for bi-directional testing. The displacement histories of these loading paths are presented in Figure 1.

In order to select a realistic bi-directional loading path that is representative of actual displacement path of an RC column during an earthquake, a numerical study is conducted, the details of which are presented in the next subsection.

Table 1: Details of the Experimental Program

Specimen	Width × Depth × Height (mm)	Concrete Grade Strength f_c' (MPa)	Longitudinal Reinforcement ρ_v (%)	Stirrups (mm) ρ_h (%)	Axial Load Ratio n
S1 (Uniaxial)	250×300×2550	65.0	6N16(1.6%)	N10@150 (0.35%)	0.15
S2 (Uniaxial)	250×300×2550	65.0	6N16(1.6%)	N10@150 (0.35%)	0.3
S3 (Uniaxial)	250×300×2550	65.0	6N16(1.6%)	N10@150 (0.35%)	0.45
S4 (Uniaxial)	250×300×2550	65.0	6N16(1.6%)	N10@300 (0.18%)	0.3
S5 (Uniaxial)	250×300×2550	65.0	6N16(1.6%)	N10@100 (0.52%)	0.45
S6 (Uniaxial)	250×300×2450	100.0	6N16(1.6%)	N10@150 (0.35%)	0.25
S7 (Biaxial) Linearised Circle	250×300×2550	65.0	6N16(1.6%)	N10@150 (0.35%)	0.15
S8 (Biaxial) Linearised Circle	250×300×2550	65.0	6N16(1.6%)	N10@150 (0.35%)	0.3
S9 (Biaxial) Randomised Ellipses	250×300×2550	65.0	6N16(1.6%)	N10@150 (0.35%)	0.15
S10(Biaxial) Randomised Ellipses	250×300×2550	65.0	6N16(1.6%)	N10@150 (0.35%)	0.3

3.1 Numerical Study

A cantilever HSRC column with the same material, reinforcement and cross-section properties as specimen S1 in table 1 is subjected to a suite of scaled and unscaled 25 ground motions in OpenSees software (50 acceleration time history files) and the resulting displacement path is plotted. The amplitude of ground motions is scaled as such to produce some non-linear behaviour in the column. The specimen is subjected to ground motion accelerations in X and Y axis only and the displacement behaviour of the column is studied at an axial load ratio of 0.15. The ground motion accelerations considered in this study are obtained from PEER ground motion database (PEER 2013) and are representative of low to moderate seismic regions. The ground motions are selected based on the following criteria:

- Moment magnitude (M_w): 4.5-6.5
- Distance to rupture surface R_rup (km):10-40 km
- Shear wave velocity: 180 m/s -1500 m/s

It is noted that the vertical component of the ground motion is not included in the analysis for the sake of simplicity.

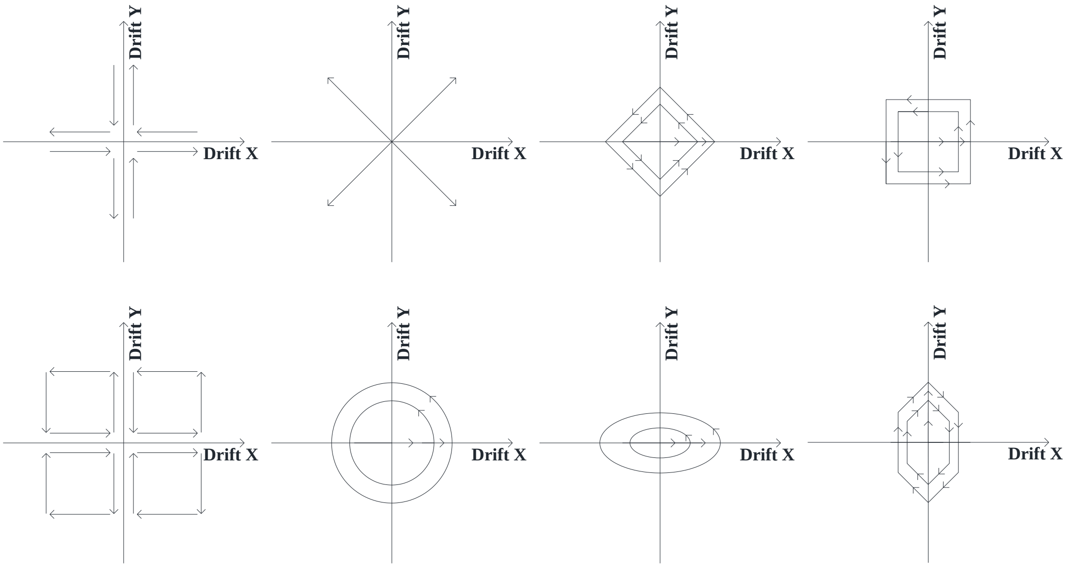

Figure 1: Bi-directional loading paths

The displacement path of the column under unscaled and scaled Christchurch (2011) ground motion at an axial load ratio of 0.15 is shown in Figure 2. It can be seen that the biaxial displacement path of the column generally comprised of loops of different orientations and aspect ratios under Christchurch ground motion. Similar behaviour is observed for other ground motions as well. Diagonal orientation of the loops are predominantly observed in the displacement path of the column under different ground motions. Different orientations of loops can be attributed to the phase shift between x and y-axis displacement of the column.

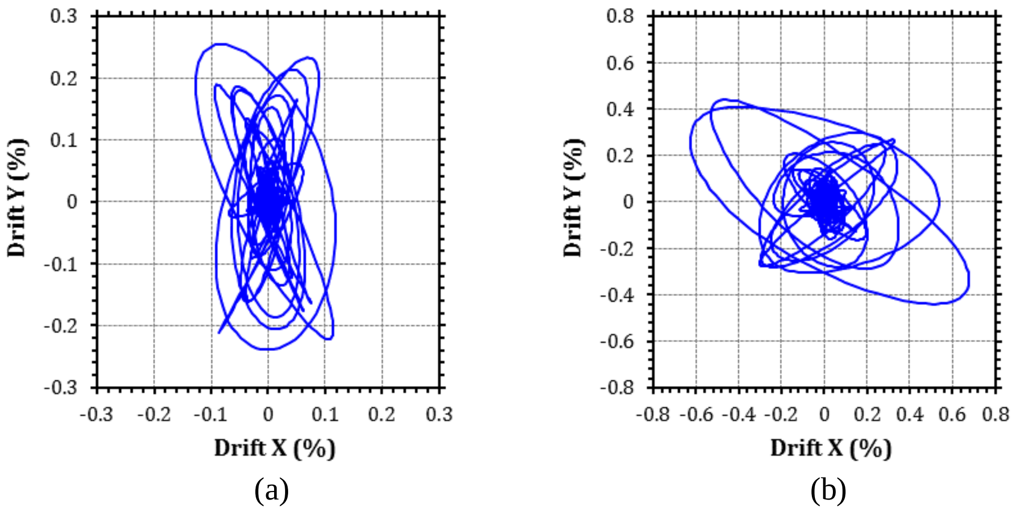

Figure 2: Biaxial displacement path of the column a) Christchurch (unscaled) b) Christchurch (Scaled 3 times)

3.2 Selection of Bi-directional Protocol

Based on the results of the numerical study presented above, a bi-directional displacement protocol comprising of diagonal loops is considered in this testing. The selected protocol is shown in Figure 3 of the paper. The loading protocol consists of a linearised quarter of a circle in each quadrant. Each quarter circle starts and finishes at the origin. In this protocol, the column is first displaced in the first quadrant, from where it goes to the third quadrant, then to second and fourth quadrant, respectively, before finally finishing back at the origin.

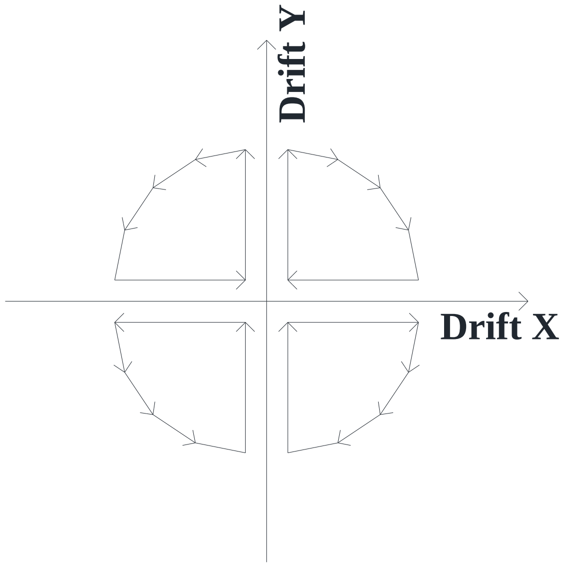

Figure 3: Selected Bi-Directional Loading Protocol

4 Experimental Results

In this section, hysteretic results of two identical specimens i.e. S1 and S7 from table 1 are presented. S1 is tested under incrementally increasing uni-directional cyclic loading (Y-direction), whereas S7 is tested under incrementally increasing bi-directional cyclic loading protocol shown in Figure 3. In the uni-directional cyclic loading protocol, each displacement increment is repeated twice. Similarly, in bi-directional cyclic loading protocol after completion of one cycle of quarter circles in all the quadrants, the specimen is subjected to the second cycle of quarter circles. The cylinder strengths of specimen S1 and S7 on test day were 75MPa and 86 MPa, respectively. Both specimens are tested at an axial load ratio of 0.15. The hysteretic curves for both specimens are shown in Figure 4.

A considerable reduction in the displacement capacity of the column is observed under bi-directional cyclic loading. The lateral load and axial load failure drifts (collapse drift) of the column under bi-directional loading are observed to be 43% and 50% of the corresponding drifts in the uni-directional loading and the column is able to withstand the same drift level at the collapse in both the strong and weak directions. It is also observed that each damage state such as cracking, concrete spalling, longitudinal bar buckling and transverse bar fracture occurred at a considerably less drift in the biaxial test as compared to the uniaxial test. Table 2 provides a summary of the drifts at lateral load failure (20% degradation of peak force) and axial load failure (10% or more loss in axial load carrying capacity of column) of column S1 and S7.

Despite the fact that concrete cylinder strength for specimen S7 is slightly more than specimen S1 and both have identical longitudinal and transverse reinforcement, the peak shear force of specimen S7 is around 10% less than specimen S1. This reduction in peak force is because, under biaxial cyclic loading, the damage accumulated in one direction reduces the strength capacity of the other direction. It is also noted that

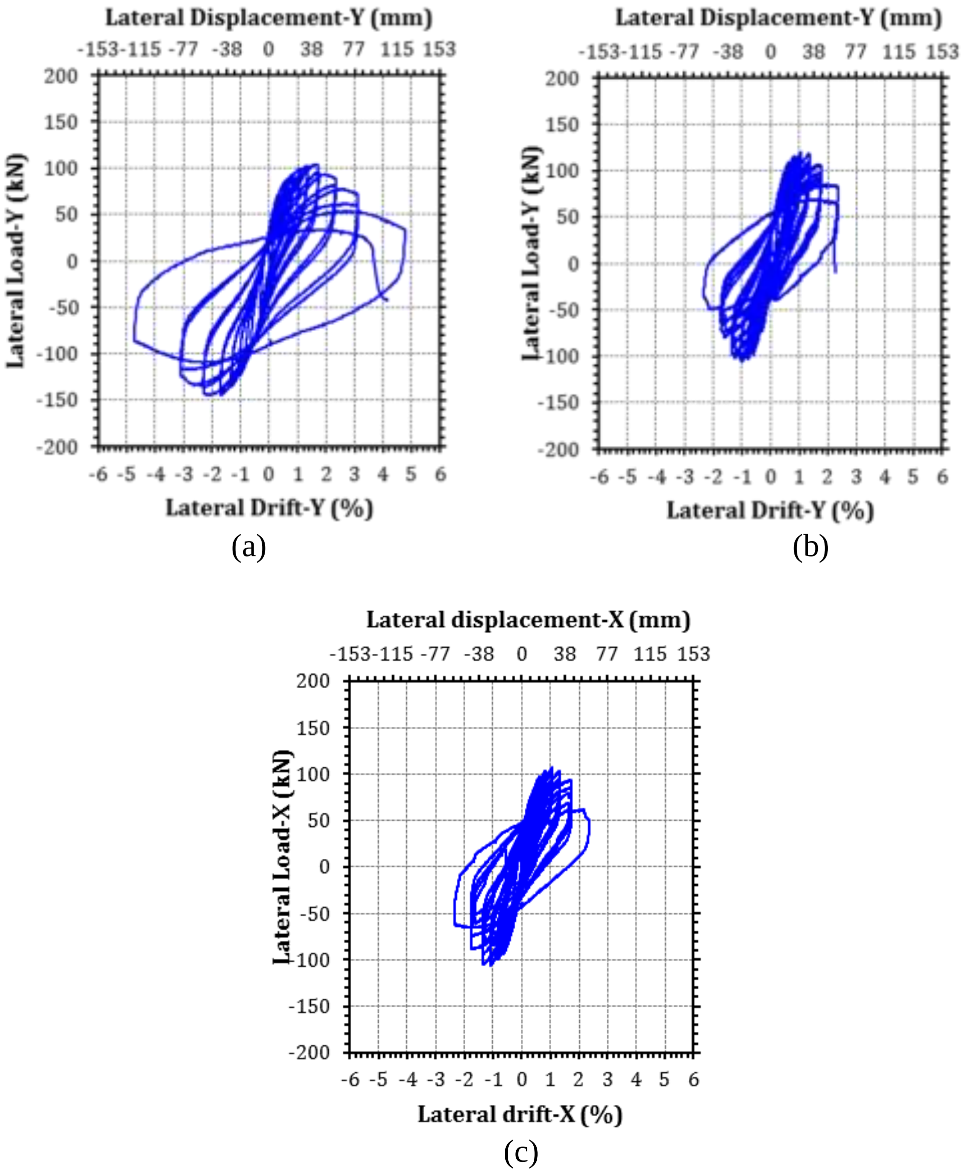

Figure 4: Hysteretic curves a) Specimen S1 (Y-Direction) b) Specimen S7 (Y-Direction) c) Specimen S7 (X-Direction)

uniaxial specimen S1 reached its peak strength at a drift of 1.76%, whereas biaxial specimen S7 attained its peak strength at a drift of 1.1%. It is noteworthy that according to the performance criteria of FEMA 356(2000), the column is able to meet the performance requirement of structural stability (defined at 4.0% drift level) under uniaxial loading, whereas, under biaxial loading, the column is able to satisfy the performance requirement of life safety only (defined at 2.0% drift level). The axial load collapse of the specimens is shown in Figure 5.

Table 2 Summary of Experimental Drifts in Y-direction

Specimen	Lateral load failure drift δ_{lf} (%)	Axial load failure drift δ_{af} (%)
Specimen 1(Uniaxial)	3.1	4.72
Specimen 7 (Biaxial)	1.76	2.36

(a) (b)

Figure 5 Axial Load Collapse a) Specimen S1 (Uniaxial) b) Specimen S7 (Biaxial)

5 Conclusion

Loading path plays an important role in affecting seismic performance and collapse behaviour of RC columns. This paper presents a comparative assessment of the collapse behaviour of limited-ductile high-strength RC columns under uni-directional and bi-directional cyclic loading. To this end, hysteretic results of two identical high-strength RC columns, tested under the same axial load ratio are compared. The results indicate that the collapse drift capacity of limited-ductile high-strength RC columns reduced by 50% under biaxial cyclic loading in comparison to the uniaxial cyclic loading. It is also observed that each damage state such as cracking, concrete spalling, longitudinal bar buckling and transverse bar fracture occurred at considerably less drift levels in the biaxial test as compared to the uniaxial test.

Acknowledgement

The authors greatly acknowledge Bushfire and Natural Hazards CRC for providing financial support and Swinburne Smart Structures Lab staff for providing technical assistance to conduct this experimental testing program successfully.

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