Seismic Collapse Assessment of Concrete-Filled Steel Tube Columns through Multi-Axis Hybrid Simulation

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Abstract

Concrete-filled steel tube (CFT) columns have been widely used, both in low and high seismic regions. These elements combine the high strength and ductility of steel with the ability of concrete to efficiently carry compressive loads. Numerous experimental studies have been performed to examine the behaviour of CFT columns under either pure axial or combined axial-lateral loads. Due to testing difficulties, however, limited data is available on the response of CFT columns under complex time-varying six-degrees-of-freedom (6-DOF) boundary forces during seismic events. In this paper, experimental studies are conducted to investigate the three-dimensional seismic response of CFT columns from the onset of damage to the state of complete collapse. The experiments include a series of large-scale quasi-static cyclic and hybrid simulation tests carried out on square and circular CFT columns. In the quasi-static tests, the specimens are subjected to bidirectional lateral deformation reversals that follows the hexagonal orbital pattern suggested in FEMA 461, combined with varying axial load. Hybrid simulation is then used to provide more insight into the three-dimensional response of these elements under realistic scenarios of seismic events. In the hybrid model, each test specimen serves as the first-story column of a symmetrical 5×5 bay 5-story framed building that is subjected to sequential biaxial ground motions with increasing intensities to collapse. The results of this study provide significant insight into the response of these columns from initial linear-elastic range to the state of complete collapse.

Keywords: CFT columns, Collapse experiments, Hybrid simulation, MAST system

INTRODUCTION

Concrete-filled steel tubes (CFTs) have been widely used in the structures and have been shown to be a high performance resistant structural system during earthquake. Several experimental and numerical studies have been carried out on different shapes and configurations of CFT columns with various material properties of steel and infill concrete to determine their seismic performance (Hatzigeorgiou, 2008; Perea, Leon, Hajjar, & Denavit, 2014; Skalomenos, Hayashi, Nishi, Inamasu, & Nakashima, 2016; Tort & Hajjar, 2007). Most of these studies, however, investigated the behaviour of CFT columns under pure axial or a combination of axial and lateral loads. Therefore, limited data is available from the response of CFT columns under complex time-varying six-degrees-of-freedom (6-DOF) boundary forces during seismic events. This project attempts to address this issue by conducting a series of large-scale multi-axis tests on square and circular CFT columns using a recently developed multi-axis substructure testing (MAST) system at Swinburne University of Technology. A total of four half-scale columns including two circular and two square concrete-filled steel tubes (CCFT and SCFT) were constructed. All specimens had similar axial load bearing capacity and for each of the two types (i.e. square and circular), two identical specimens were tested using quasi-static cyclic and hybrid simulation methods. Based on the tests results, comparisons between the column specimens were made to evaluate the influence of the different cross –section shapes, axial load variation and different lateral loading histories on seismic behaviour of CFTs.

HYBRID SIMULATION FRAMEWORK AND TEST SETUP

In order to conduct the experimental tests, the multi-axis substructure testing (MAST) system at Swinburne University of Technology was used. This facility consists of a stiff steel crosshead in the shape of a cruciform connected to the strong floor with four vertical hydraulic actuators and to the L-shaped strong wall with four horizontal actuators (two in each wall). This facility has the capability of controlling the top control-point 6-DOF independently in switched and mixed mode displacement and force control. The actuators provide a total lateral load of ±1000 kN along per loading direction (X- and Y-axis) and vertical load of ±4000 kN (Z-axis) (Al-Mahaidi, Hashemi, Kalfat, Burnett, & Wilson, 2018) . The control system of this facility was employed to evaluate the three-dimensional response of CFT columns under complex time-varying realistic boundary forces for large-scale quasi-static (QS) cyclic and hybrid simulation (HS) experiments.

Figure 1 presents the details of the test setup configuration for a typical half scale CFT column specimen to simulate a critical firs-story column in a prototype steel building. In order to test the column with a fixed base and fixed top (fixed-fixed) boundary conditions and meet the MAST system dimension requirements, the test specimen was attached to the strong floor and the crosshead using two relatively thick and rigid concrete pedestals. The steel tube was welded with complete penetration welds to the base plates at both ends and then was filled with concrete from a small hole at the top plate using a pumper truck. To assemble the column under the MAST system, it was bolted to the foundations at the top and base using high strength bolts.

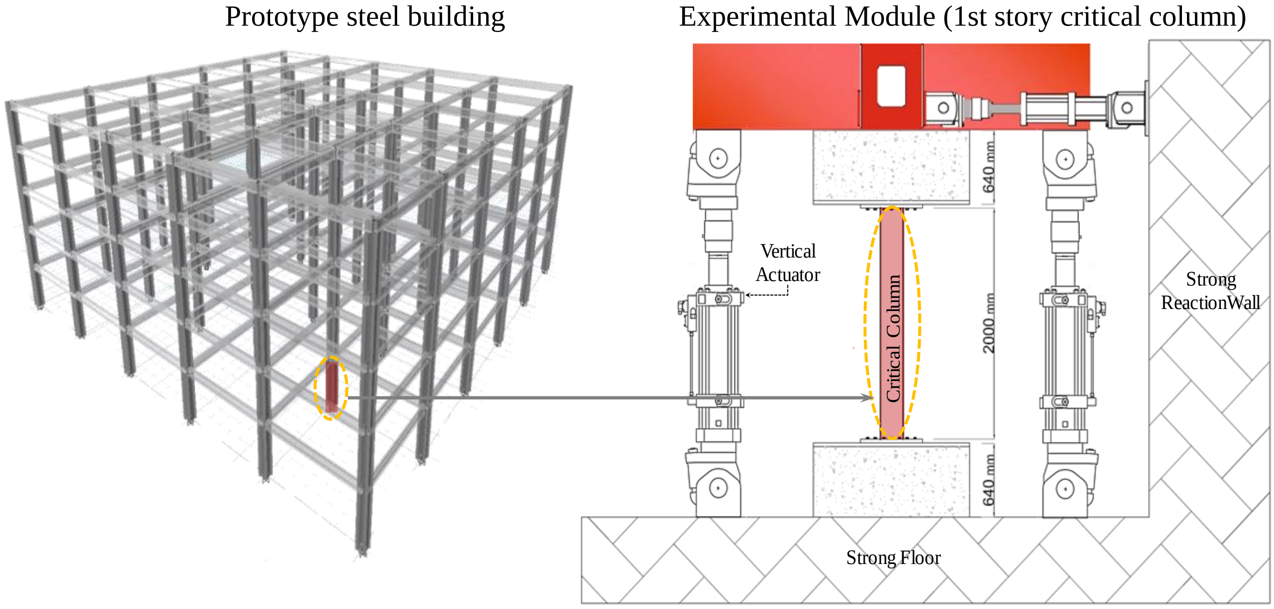

Figure 1. Schematic drawing of the test setup for QS and HS experiments

Steel Frame with Critical Column

Two half-scale symmetrical five-story (height of first story h1 = 2 m; height of other stories htyp = 1.75 m) five-by-five-bay (column spacing b = 4.2 m) steel frame buildings with critical columns were considered as the prototype buildings. The first and second frames were designed with CCFT and SCFT columns, respectively. For conducting two three-dimensional hybrid simulation tests, the physical specimen (experimental module) for each test was served as the first-story interior column of the building, considered as the critical element of the structure. The rest of the structural elements were modelled numerically using OpenSees finite element software framework. It is important to note that, in order to get a better understanding of the realistic behaviour and ultimate flexural capacity of the selected columns, soft story collapse mechanism was assumed in designing and modelling of the prototype steel buildings. Therefore, all energy dissipations are concentrated at columns ends in the first floor.

In order to accurately model and replicate the actual response of a CFT member, the material properties of the numerical model of column elements should be similar to that column exhibited as the experimental element.

Table *1* provides an overview of the selected cross sections material and geometric properties were measured for the CFT column specimens. The stress-strain results were developed using the data obtained from associated coupon tests. Regarding the concrete infill, concrete with compressive design strengths of 50 MPa was used in this study. The concrete mix properties and the actual cylinder strengths at the day of the tests (QS test at 76th day, HS at 165th day) are listed in Table 1.

Table 1. Geometry and material properties of test specimens

Steel Tubes								
Specimen Name	Standard Section	D (mm)	t (mm)	A_s (mm^2)	A_c (mm^2)	F_y (MPa)	F_u (MPa)	E_s (MPa)
CCFT	CHS	219.1	8.2	5433	32270	412	499	197000
SCFT	SHS	200	9	6597	32967	352	471	210000

Concrete Infill								
f_c (MPa)	Cement (kg)	Wate (kg)	Slag (kg)	Aggregate (kg)	Sand (kg)	Admixture (ml)	f_{cQS} (MPa)	f_{cHS} (MPa)
50	349	192	149	1011	654	1743	53	58

QUASI-STATIC CYCLIC TEST

The first set of experiments conducted on the CFT columns were three-dimensional mixed-mode quasi-static cyclic tests. The loading protocol consisted of applying a variable force-controlled gravity load (equal to 14% of ultimate compressive load capacity at balance point) while imposing displacement-controlled bidirectional lateral deformation reversals that follow the hexagonal orbital pattern suggested in FEMA 461 and shown in Figure 2(a). The bidirectional hexagonal orbital lateral protocol reaches a maximum drift ratio of 4% (X-loading direction) and 8% (Y-loading direction) at the column's top. The axial load was varied around the gravity load value and proportional to the lateral drift acting on the column. This variation was a function of the building geometry and derived by simple sequential sign wave analyses of the designed steel framed building. The average of 571 kN (0.14 Py) compression load was considered to represent the initial gravity load on the column at balance point. According to the adopted axial variation protocol, positive and negative drift correspond to decrease and increase of the compressive axial load, respectively. The axial load variation scheme is presented in Figure 2(b) where the maximum compression load is 874 kN (0.2 Py: the target load).

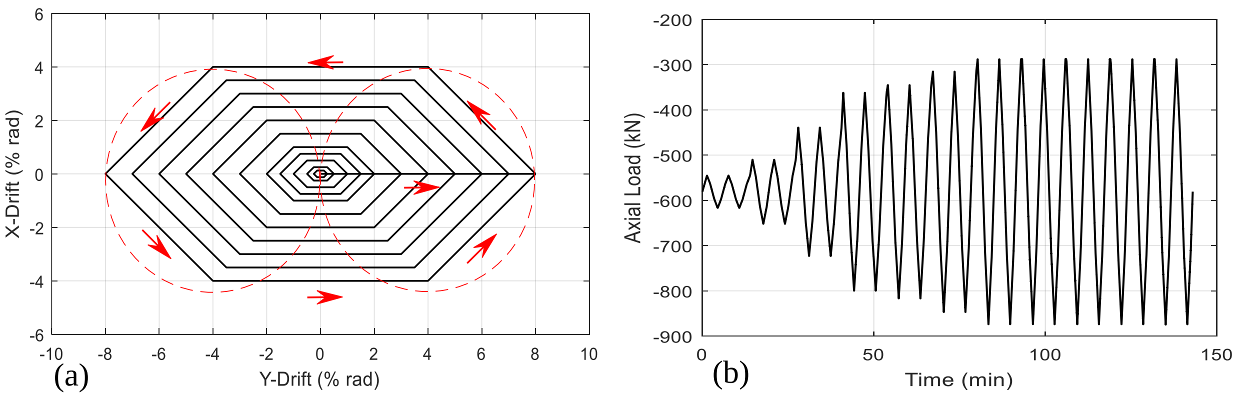

Figure 2. Loading protocol for the QS experiments: (a) bidirectional hexagonal orbital pattern, (b) axial load variation after applying initial axial gravity load

The results from QS tests were used to accurately simulate and calibrate the OpenSees model of the buildings for HS tests. The steel building's columns were modelled using beam-with hinges elements, the nonlinear behaviour of which is assumed to occur within a finite length at both ends based on the distributed plasticity concept (Ibarra, Medina, & Krawinkler, 2005). The plasticity model follows a bilin hysteresis response based on the Modified Ibarra-Medina-Krawinkler (IMK) deterioration model of flexural behaviour (Lignos & Krawinkler, 2011). This model was chosen because it is capable of capturing the important modes of deterioration that participate in sideway collapse of CFT framed structures. The model requires the specification of a range of parameters to control the trilinear monotonic backbone curve and different modes of cyclic deteriorations. Figure 3 shows the results of QS tests on CCFT and SCFT columns including the hysteresis behaviour in the X and Y directions and the numerical model of the column elements calibration results.

In both specimens, cyclic strength deterioration were observed after local buckling occurred. The failure of the specimens occurred when they were subjected to the maximum of 8.0% and 4.0% drift ratios in the Y- and X-axis, respectively. A gentle local buckling occurred at both ends of the CCFT and SCFT columns after the last cycle of 6% and 5% drift ratios in Y-axis, respectively. Fracture of the columns and plastic hinge formation close to the base plates occurred at the end cycle of 8% drift ratio in the both columns that are correspond to the 50% decrease of the ultimate capacity of each column.

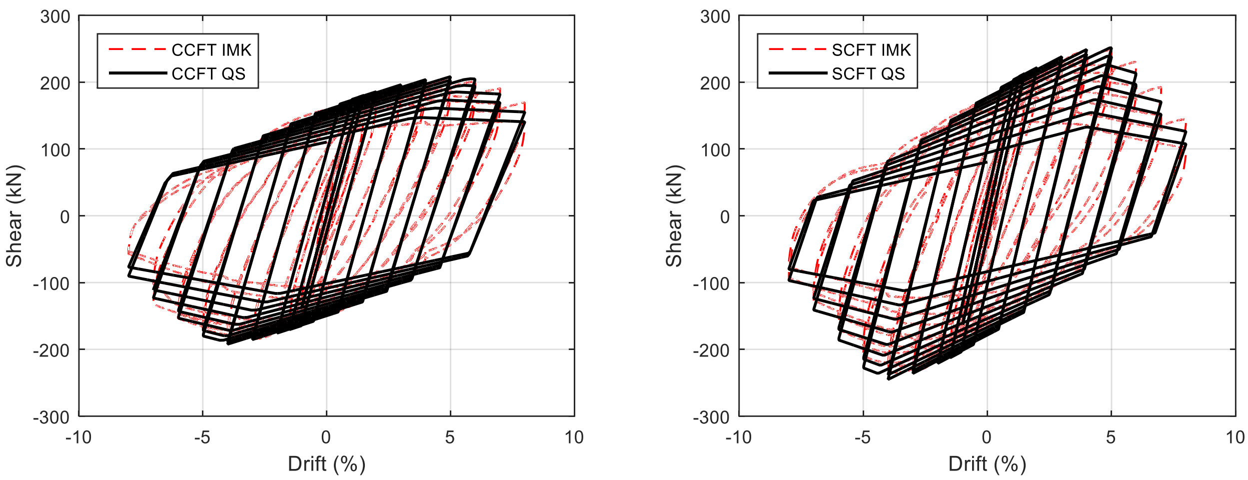

Figure 3. Calibration of SDOF model of the CCFT and SCFT columns to QS experiments

After developing the numerical model of the buildings based on QS tests results, the elastic fundamental period of vibration (T1 = 0.74s and 0.68s for CCFT and SCFT buildings, respectively) and the corresponding first mode shape were obtained through eigenvalue analysis. Nonlinear static pushover analysis were performed on each frame with the lateral loads distribution at each story in fixed ratios based on the story mass and the mode shape of the structure with the consideration of second-order P-Δ effects. The lateral loading was conducted in displacement control until at least a 20% drop in strength after the peak was observed. Figure 4 presents the results of the pushover analysis for the buildings with CCFT and SCFT columns that show most of the energy dissipation occurs in the first story.

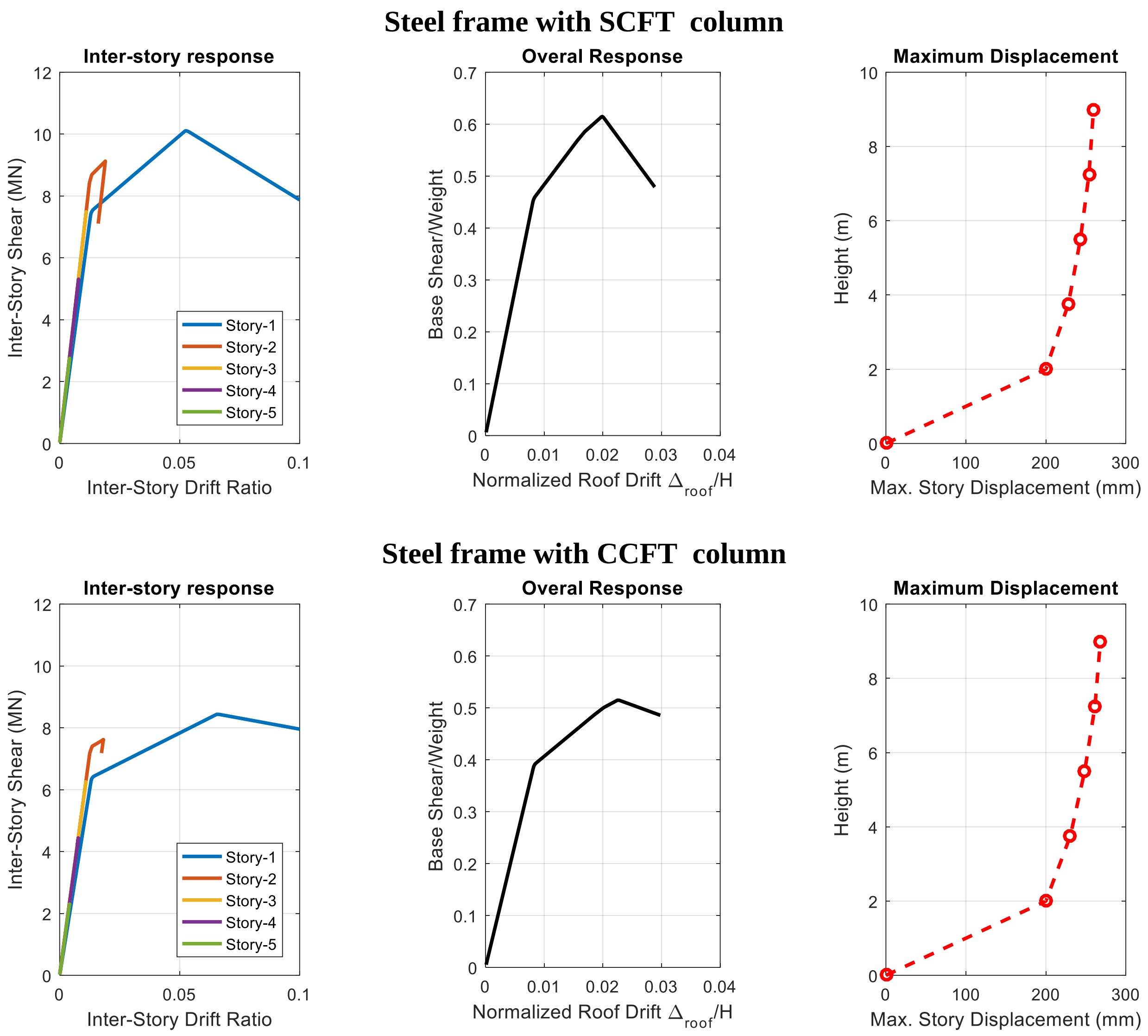

Figure 4. Static pushover analysis results for frame buildings with CCFT and SCFT columns

Hybrid Simulation Tests

The second set of experiments were two three-dimensional hybrid simulation tests that included the physical CCFT and SCFT column elements identical to the previously tested CFT columns in the quasi-static cyclic tests. For this purpose, the physical specimen served as the first-story interior column of the building, considered as the critical element of the structure. The rest of the structural elements, inertial and damping forces, gravity and` dynamic loads, and second-order effects are modelled numerically in the computer. An advanced three-loop hybrid simulation architecture that uses OpenSees, OpenFresco, and the xPC-Target real-time digital signal processor was implemented (Figure 5) (Hashemi, Tsang, Al-Ogaidi, Wilson, & Al-Mahaidi, 2017).

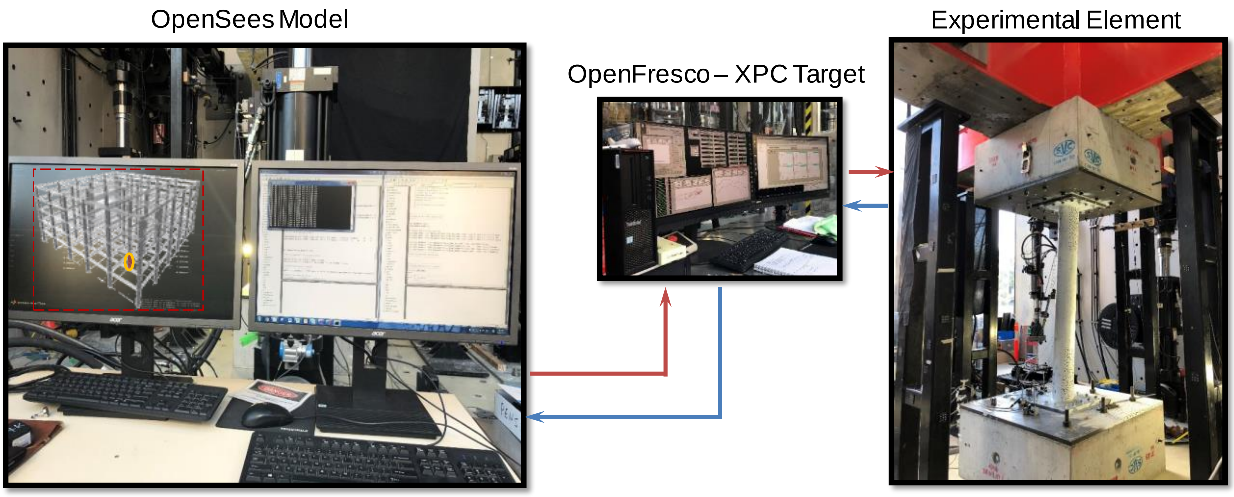

Figure 5. Hybrid simulation components including numerical and experimental substructures

For the HS test, the two horizontal components of the 1979 Imperial Valley earthquake ground motions recorded at El Centro station with a peak ground acceleration of 0.15g were used. Prior to conducting the actual HS test with the physical subassembly in the laboratory, a series of FE-coupled sensitivity numerical simulations was conducted to evaluate the ground motion intensity levels and integration scheme parameters for the actual experiments. Accordingly, four levels of intensities were considered to capture the full range of structural response from linear-elastic range to collapse. The selected scale factors were 0.25, 1.9, 3.4, and 4.0 for CCFT HS test and 0.25, 2.0, 3.7 and 4.3 for SCFT HS test which pushed the structure to nearly 0.5%, 1.5%, 5%, and 8% interstory drift ratios in Y-axis, respectively. Furthermore, Generalized Alpha-OS was selected as the integration scheme, and the integration time-step was optimized to preserve the accuracy and stability of the simulation while allowing the completion of the entire test during the regular operation time of the laboratory (Hashemi et al., 2017). Five percent Rayleigh damping was specified to the first and third modes of vibration, corresponding to the primary translational modes in the X- and Y-directions. Additional damping was also assigned to free vibration time intervals between the forced vibrations to quickly bring the structure to rest.

The hybrid simulation started with applying the gravity load on the specimen using a ramp function followed by sequential ground motions. The entire sequence of loading was performed and automated using OpenSees. Considering the 30 msecond delay in the hydraulic system, 256 msecond was specified as the simulation time step in xPC-Target predictor-corrector to provide sufficient time for integration computation, communication, actuator motions, and data acquisition. This scaled the 30 seconds of sequential ground motions to 5 hours in laboratory time. Similar to the QS test, the rotational axes (roll, pitch, and yaw) were controlled in zero angle, forming a double-curvature deformation of the column. Figure 6 compares the biaxial deformations in terms of lateral drifts in the X- and Y-axes, and biaxial moment interactions in the Rx- and Ry-axes.

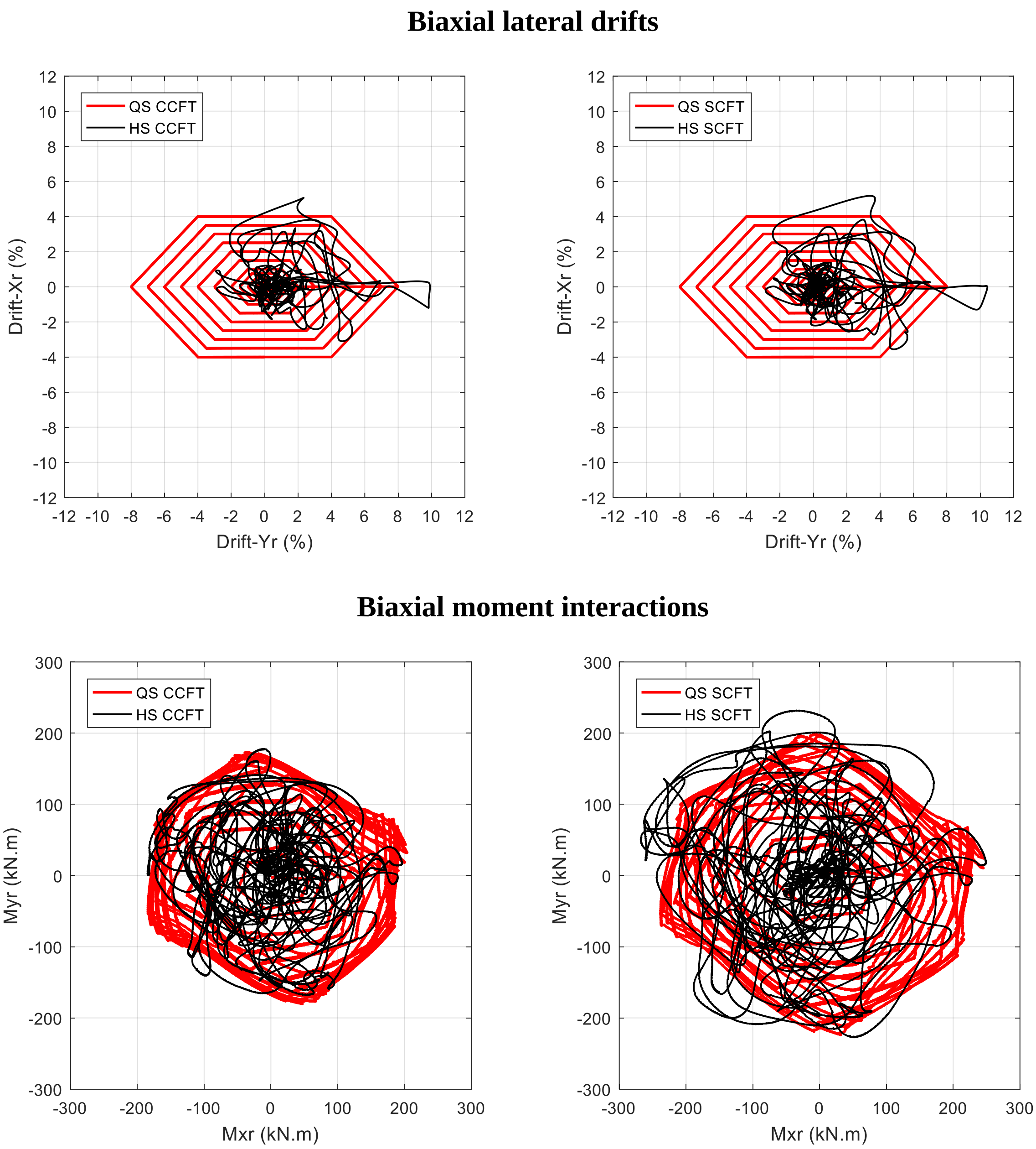

Figure 6. Comparison of biaxial drifts and moment interactions in QS and HS tests

Figure 7 compares the shear-drift responses of CCFT and SCFT columns in the QS and HS tests, including hysteresis in the X- and Y-axes. By comparing the hysteresis plots from the HS test, it can be seen that the columns suffered damage as the structure progressively moved in one direction, while in the QS test, the pattern of damage was symmetrical due to load reversals in cyclic deformations. Figure 8 shows the flexural failure of columns for QS and HS tests by comparing the plastic hinges developed at the top and the base of the columns.

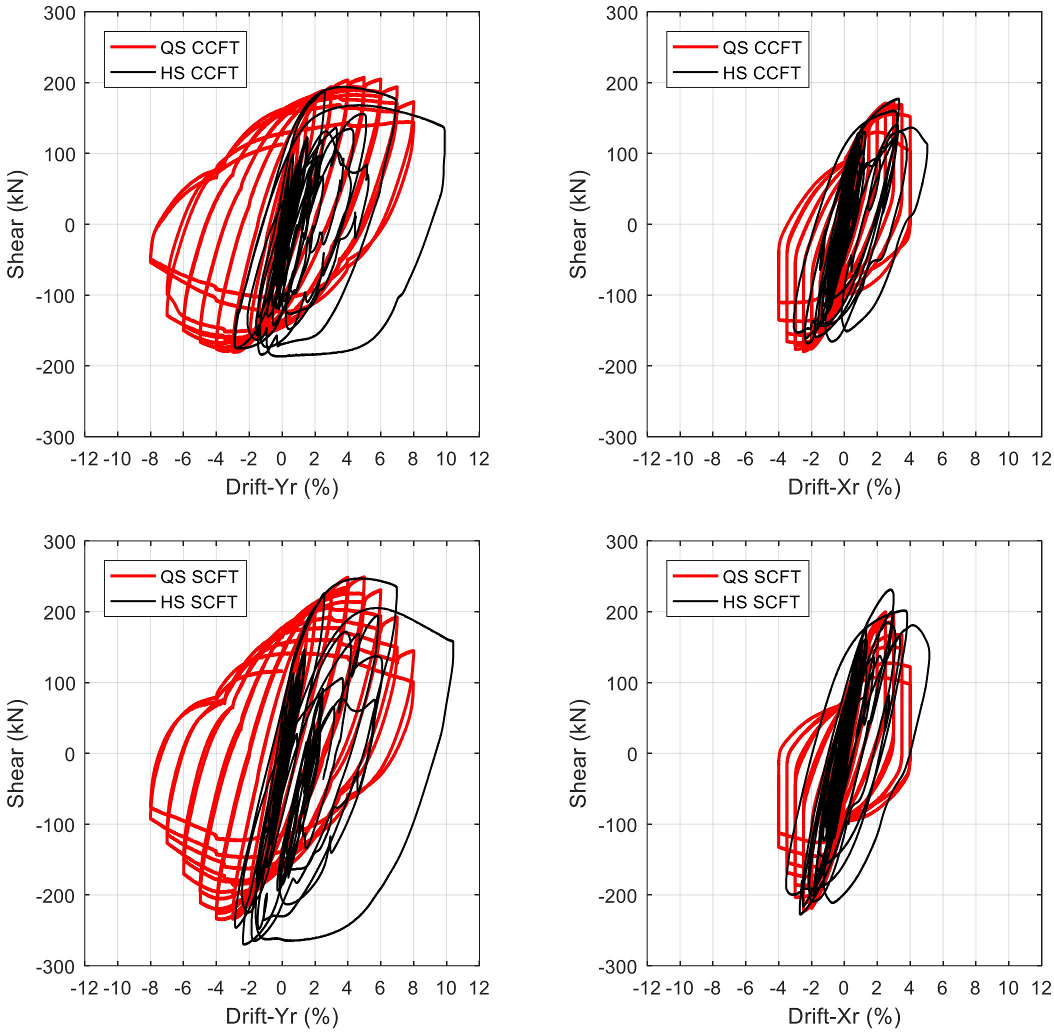

Figure 7. Comparison of the QS and HS response of columns in Yr- and Xr-directions

QS CCFT HS CCFT QS SCFT HS SCFT

Figure 8. Comparison of plastic hinges in QS and HS tests.

Conclusions

The key objective of this paper was to demonstrate the application of hybrid simulation (HS) as an alternative for the conventional quasi-static (QS) test in collapse assessment of CFT columns. Four experiments were conducted on identical large-scale, CCFT and SCFT columns by the respective testing methods using the state-of-the-art multi-axis substructure testing (MAST) system, which is capable of controlling all six-degrees-of-freedom (6-DOF) boundary conditions in mixed load and deformation modes. The CFT columns served as the first-story interior-column of a half-scale symmetrical 5×5 bay 5-story framed building structure. The load protocol in the QS test included variable axial load combined with bidirectional lateral deformation reversals, while in HS, more realistic boundary effects, including time-varying axial load and the ratcheting of structure’s lateral deformation, were simulated.

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