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Seismic behaviour of concrete-filled steel tubular frame to RC shear wall high-rise mixed structures

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ABSTRACT

Composite frames consisting of concrete-filled steel tubular (CFST) columns and steel beam are being used more and more popularly in building structures. In China, the composite frame structures are often mixed with reinforced concrete shear walls to form a high-rise building system. However, there was seldom information on the seismic performance of this kind of mixed construction. Shaking table tests on two building models with 30 storeys consisting of composite frames and RC shear walls were thus presented in this paper. CFST columns with circular and square sections were used in the composite frames respectively. Three kinds of real earthquake records, including Taft (EW), El Centro (NS) and Tianjin waves with peak accelerations of $0.2g$, $0.4g$, $0.6g$, and $0.8g$, were applied respectively to simulate different levels of earthquakes in the tests. It was found that the composite frames cooperated well with the core RC shear wall structure under earthquakes, and the two building models exhibited excellent seismic performance.

1. Introduction

Concrete-filled steel tubular (CFST) columns had been widely used in civil engineering projects in the past decades, they have been proved to be inherently efficient in load carrying capacity, fire resistance, stiffness, ductility and energy absorption capacity, and fast in construction [1].

Composite frames consisting of concrete-filled steel tubular (CFST) columns and steel beams (named CFST frames in this paper) are being used more and more popularly in building structures. In China, CFST frame structures are often mixed with reinforced concrete (RC) shear walls to form a high-rise building system to resist both the vertical and lateral loads efficiently. However, there is still not sufficient information on the seismic design of this type of mixed structural system.

In the past, there have been a large number of research studies on the performance of CFST columns. These literatures had been reviewed by [2–4]. Several state of the art reports or papers were also published recently on CFST structures, such as [5–8]. There also had been some studies performed on the behaviour of CFST beam-to-column connections, such as [9,10]. But there is still very limited information on the CFST frames to RC shear wall mixed building systems under seismic loadings. This indicates a need for further research in this area.

Shaking table tests on two building models with 30 storeys consist of composite frames and RC shear walls were thus carried out and presented in this paper. The objectives of this research are fourfold. First, to evaluate the behaviour of mixed structures consisting of CFST columns under various real earthquake records. Second, to investigate the consistency of CFST frames with RC shear walls under earthquake. Third, to study the shear force distribution between the composite frames and shear walls, and thus to understand the effects of different CFST column sections (circular and square) on the seismic performance. Finally, to determine the damping ratio, which is necessary for the seismic analysis of a mixed structural system.

2. Experimental program

2.1. General descriptions

Two building models were tested. The models were designed based on a building structure in practice [11,12]. Each model has 30 storeys and with a similitude ratio of 1:20, i.e., a length ratio of 0.05. Each building model consists of 20 CFST columns and RC shear walls. The difference between the two models is only the cross-sectional type of the CFST columns, i.e. circular and square respectively. The two types of the composite columns were designed to have almost the same compressive capacity based on the code of DBJ13-51-2003 [13]. For convenience of the descriptions as follow, the models with circular columns and

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Table 1
Properties of steel.

No.	Type	t or d (mm)	f_y (N/mm^2)	f_u (N/mm^2)	E_s (N/mm^2)	μ	Elongation (%)
1	Tube with square section	1	378.6	468.3	1.85×10^5	0.291	14.6
2	Tube with circular section	1	312.3	374.8	1.70×10^5	0.258	13.3
3	Flange of steel beam	1.5	548.6	704.9	1.92×10^5	0.283	16.2
4	Web of steel beam	1	630.2	842.5	2.02×10^5	0.256	21.2
5	Steel bar in hidden RC column	2.2	319.6	401.2	1.72×10^5	–	35.2
6	Steel bar in RC shearing wall	0.7	295.1	394.4	1.66×10^5	–	–

Table 2
Mixtures and properties of concrete.

Type	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Fly ash (kg/m^3)	Steel slag powder (kg/m^3)	Water (kg/m^3)	HRWR[a] (kg/m^3)	f_{cu} (N/mm^2)	E_c (N/mm^2)
SCC	520	728	842	–	140	244	16	41.7	2.85×10^4
NC	470	724	836	141	–	221	11	47.5	3.14×10^4

[a] HRWR: Additional high-range water reducer.

square columns are denoted as "MCC" and "MSC" respectively in this paper.

Each model has 30 floors with a total structural height of 6.3 m. The outside dimension of the model is 2.2 × 2.2 m. The detail information of the building systems can be summarized as:

- Model weight: 7.3×10^3 kg (MSC) and 7.2×10^3 kg (MCC).
- Steel tube dimensions: $\square - 30 \times 30 \times 1$ mm (square column) and $\mathrm{O} - 30 \times 1$ mm (circular column).
- I-shape steel beams: $\mathrm{I} - 40 \times 15 \times 1 \times 1.5$ mm.
- Thickness of the shear wall: 25 mm (outer core); 20 mm (inner wall).

MSC is selected to show the scales of the model in Fig. 1. Some typical connections (No. 1– No. 5 in Fig. 1), such as the beam to column, beam to beam, beam to shear wall, as well as the hidden column (HC) and beams (B1 or B2) in RC core are also presented in this figure.

Artificial mass (including dead load and imposed load) of 9.6×10^3 kg was added uniformly on each floor of the model. The total weights of MSC and MCC are thus 1.69×10^4 kg and 1.68×10^4 kg, respectively.

2.2. *Material properties*

Tension tests were carried out to determine the material properties of steel sheets and rebars. Table 1 lists the measured average yield stress (f_y), tensile strength (f_u), modulus of elasticity (E_s), Poisson ratio (μ), and fracture elongation. t is the wall thickness of the steel tube or plate, and d is the diameter of the reinforced bar.

For convenience of pouring the concrete into the tube with a small section, a kind of self-consolidating concrete (SCC) was prepared, and the concrete was poured into the tubes without any vibration. The fresh properties of the SCC mixture used in CFST columns were: Slump flow: 270 mm; Unit weight: 2490 kg/m^3; Concrete temperature: 26 °C; Flow time: 8 s; Flow speed: 100 mm/s; Flow distance: 800 mm. A kind of normal concrete (NC) was used in RC shear walls. The mixtures and properties of the concrete are listed in Table 2.

2.3. *Fabrication of the mixed structures*

The procedure for the fabrication of building models can be generally summarized as:

(1) Frame components: The tubes and the beams were all manufactured from mild steel sheets. Plates were cut from the sheets, tack welded into a circular, square or I-shape and then welded together with single bevel butt welds.
(2) Frame: The steel frames consist of hollow steel tubes and beams was fabricated in the workshop and carried to the laboratory. A reinforced concrete raft base was specially designed to fit the column spacing on the shaking table. The column feet were inserted into the base and were attached firmly with the RC raft.
(3) Shear wall and RC floor: The EPP foam was used as the inner mold of the walls and floors in the construction. The concrete in the CFST column was poured from the top of the model.
(4) Setup and instruments: The model with the raft base was then placed on the shaking table by the crane. Twenty-four $\Phi 24$ high-strength bolts were used to make the model attached firmly to the shaking table. Strain gauges and acceleration sensors were then set on the model.

General views of the building models during construction are illustrated in Fig. 2. Some of the typical connections (corresponding to the joints, i.e. No. 1 to No. 4 as shown in Fig. 1) of the building models during construction are shown in Fig. 3. Fig. 4 shows the completed two models before testing.

2.4. *Testing program*

Three real earthquake records were used in the tests respectively, i.e.

- Taft (EW) wave;
- El Centro (NS) wave; and
- Tianjin wave.

Shaking table tests are conducted with 4 stages of increasing magnitude of earthquake excitations. The peak acceleration of each wave is adjusted as 0.2g, 0.4g, 0.6g and 0.8g respectively, to simulate the different level of the earthquakes. The procedure and the sequence of the shaking table tests are listed in Table 3.

2.5. *Instrumentation*

A total of twenty-eight displacement transducers were arranged for each of the model, to measure the displacements. Thirty accelerometers were used to measure the accelerations of the specified floor. Twenty-four strain gauges were installed to record the strain in the composite columns, steel beams and the shear walls, respectively.

Details of the locations of the measured points were shown in Fig. 1.

3. Test results and analysis

3.1. *Dynamic characteristics*

Tests were carried out to measure the dynamic characteristics of the models before and after the earthquake excitations. Each