



Shaking Table Test Study on the Influence of Construction Procedure for Modular Precast Composite Shear Wall Structures

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Abstract. In this study, comparative shaking table tests were conducted on two 1/4-scaled concrete modular models to investigate the influence of construction process on the seismic performance. The test models included a modular precast model and a modular cast-on-site model. A series of shaking table tests were input with incremental intensities until the models failed. The test results showed that the bottom vertical joints were the most critical components in the modular models. The modular cast-on-site model failed with partial pull-out of the screws in the bottom vertical joints. The modular precast model failed with the nut slip and screw fracture in the bottom vertical joints, resulting in a little lower ultimate bearing capacity than the modular cast-on-site model. The small model size and assembly process decreased the fundamental frequency of the Y-directional translation mode for the modular precast model. The modular precast model had comparable displacement and acceleration responses to the modular cast-on-site model when the vertical joints were intact, but showed larger displacements with the vertical joints approaching failure. The test results demonstrate the significance of strengthening joint bolts and protecting bolt threads in the engineering applications.

Keywords: Modular building · Construction process · Seismic performance · Bolted joint · Shaking table test

1 Introduction

Modular buildings adopt precast volumetric modules as structural components to achieve a high prefabricating level [1]. Modular buildings outperform cast-in-place structures due to faster construction process, less resource consumption and fewer labor requirement [2]. The lateral load resisting ability of modular buildings are provided by assembled modules, which makes the seismic resistance mechanism different from that of cast-in-place structures.

The seismic performance of modular precast buildings is affected by the connecting joints, as the joints are critical components to transfer vertical and lateral loads. In practical engineering applications, the construction process may influence the actual

performance of precast structures due to size deviation and construction damage, such as grouting defects [3, 4], joint slip [5] and bolt looseness [6]. Wang et al. [7] conducted numerical studies on a concrete module wall-core system and found that the defects of vertical inter-module connections increased the moments and shear forces of core walls.

In this study, an innovative modular precast composite shear wall (MPCSW) structure is introduced [8, 9]. Comparative shaking table tests were conducted on a MPCSW model and a modular cast-on-site shear wall (MCOSW) model. Both the MPCSW model and MCOSW model were designed with the concept of modular building, but were built with different construction methods. The MPCSW model adopted fully modular assembly method, with all the concrete modules and joints prefabricated off-site and assembled on-site. For the MCOSW model, the concrete modules were cast-on-site.

Based on the test results, the failure pattern, dynamic characteristics, displacement and acceleration responses were comprehensively analyzed to investigate the influence of construction process on the seismic performance. The test and analysis results are helpful for the application of modular buildings in practical engineering.

2 Description of the MPCSW Structure

The MPCSW structure consists of concrete modules and connecting devices. Each concrete module is regarded as an individual room in the modular building. A concrete module includes the shear walls, coupling beams, cantilever beams and a slab, as shown in Fig. 1a. Groups of holes are reserved in the shear walls and beams for horizontal assembly between adjoining modules at the same floor. Steel sleeves are embedded at the top and bottom of the shear walls and are connected to the longitudinal rebars for vertical assembly between upper and lower modules. The MPCSW structure differs from existing concrete modular buildings in terms of fully modular construction without any on-site casting or grouting. The MPCSW structure entirely relies on concrete modules to resist lateral loads rather than cast-in-place cores.

Figure 1b plots the schematic diaphragm of the horizontal assembly method. The horizontal connecting devices include screws and nuts. The screws are passed through the reserved holes in walls and beams, and are tightened using nuts. The adjoining concrete modules can be assembled at the same floor, and the horizontal joints are formed. Figure 1c illustrates the method of vertical assembly. The vertical connecting devices consist of H-section beam connectors and bolts. The concrete modules can be fixed to the H-section beam connectors using bolts, with the bolts screwed into the sleeves embedded in the concrete modules.

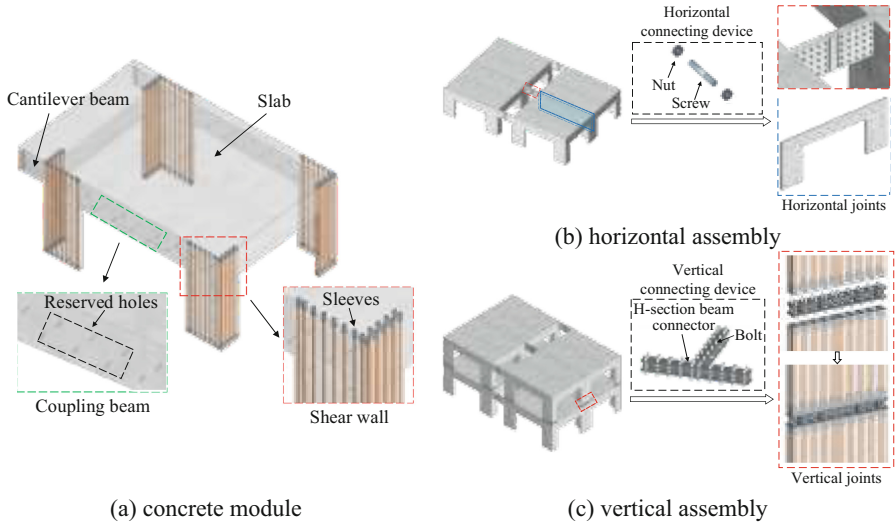


Fig. 1. Schematic diaphragm of the MPCSW structure.

3 Shaking Table Test Program

3.1 Test Model Design

The test models included a modular precast composite shear wall (MPCSW) model and a modular cast-on-site shear wall (MCOSW) model. The test models were 1/4 scaled in length, and other primary similarity ratios are listed in Table 1.

Table 1. Primary similarity ratios.

Physical quantity	Symbol	Similarity ratio	Physical quantity	Symbol	Similarity ratio
Length	S_l	1/4	Mass	S_m	0.035
Density	S_ρ	2.267	Damping	S_c	0.078
Elastic modulus	S_E	0.68	Time/Period	S_t	0.456
Strain	S_ε	1	Acceleration	S_a	1.200

The MPCSW model and MCOSW model had the same layout, dimension, material and reinforcement, but were built with different construction methods. The MPCSW model was fully assembled by concrete modules and bolted joints, whereas the MCOSW model was cast-on-site. Figure 2a plots the plane layout of the test models. Each test model mainly comprises two complete modules, and two partial modules were also constructed for boundary assembly. The coupling beams and shear walls perpendicular to the module assembly direction had half the standard thickness for horizontal assembly.

The reinforcements of the coupling beams and shear walls are shown in Fig. 2b. The longitudinal rebars in shear walls were replaced by M6 screws for the simplification of

vertical joints, because there was difficulty in manufacturing the bolts and sleeves in the 1/4-scaled models, as illustrated in Fig. 3. Figure 4 plots the elevation view of the test models. Each floor was 1.0 m in height, consisting of 0.95 m concrete modules and 0.05 m vertical joints. The screws in horizontal joints were staggered with the interval of 200 mm.

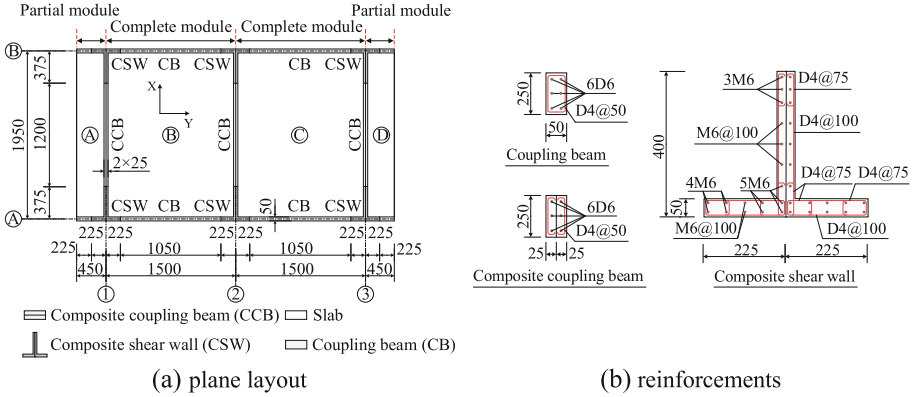


Fig. 2. Configuration of the test models.

Table 2. Material properties of the reinforcements in the test models.

Material	Diameter (mm)	Yielding strength (MPa)	Ultimate strength (MPa)
HRB400 rebar (D6)	6	461.0	591.0
Screw (M6)	6	484.8	580.1
Galvanized iron wire (D4)	4	326.9	432.7

The modules were cast using self-compacting concrete, with the 28-day cubic compressive strength of 55.16 MPa. The rebars and screws had similar diameters and strengths for equivalent replacement. Stirrups were made of galvanized iron wires. The detailed diameters and strengths of the reinforcements are listed in Table 2.

3.2 Construction Method

The MPCSW model followed the fully assembly method. The detailed construction process of the MPCSW model is illustrated in Fig. 5, and the steps are as follows: (a) The concrete modules and joints were prefabricated off-site, and the bottom modules were fixed to the foundation by vertical joints; (b) The upper modules were hoisted to the top of lower modules; (c) The upper modules were vertically fixed by vertical connecting devices; (d) The adjoining modules were assembled using horizontal connecting devices. The MPCSW model could be completed by repeating Steps from (b) to (d).

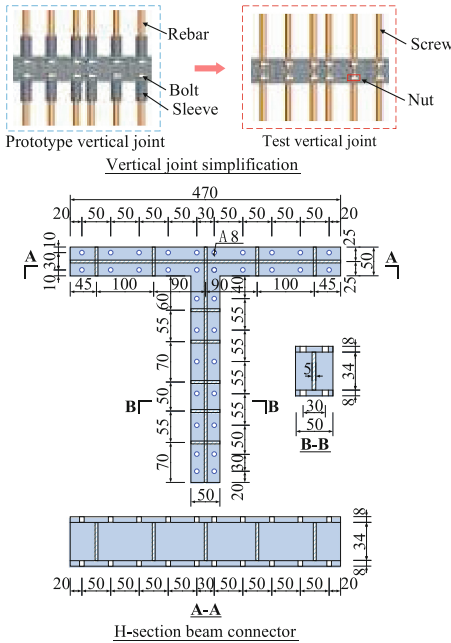


Fig. 3. Details of the vertical joints.

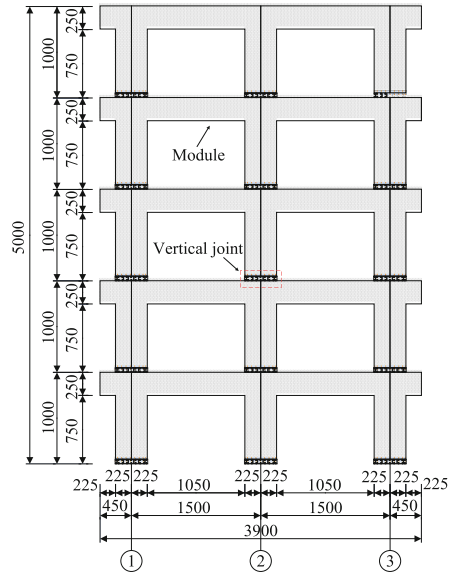


Fig. 4. Elevation view of test models.

The concrete modules in the MCOSW model were cast-on-site. Figure 6 shows the detailed construction steps: (a) The bottom H-section beam connectors were fixed to the model foundation; (b) The module reinforcements were constructed; (c) The module framework was set up, and the holes were reserved; (d) The adjoining module was constructed by the same method, and horizontal joints were installed; (e) Built the upper modules following Steps from (b) to (d), and the MCOSW model could be completed.



Fig. 5. Construction process of the MPCSW model.

3.3 Loading Sequence and Measurement

The earthquake inputs included El-Centro wave, Taft waves and SHW2 wave. The El-Centro wave and SHW2 wave were input along X-direction only, whereas the Taft waves were imposed in the X-, Y- and Z-directions. The acceleration spectra of the earthquake waves are plotted in Fig. 7, and fit well with the standard curve defined in Chinese code



Fig. 6. Construction process of the MCOSW model.

for seismic design of buildings [10]. The PGAs in the Y- and Z-directions were scaled to 0.85 and 0.65 times of that in the X-direction, respectively.

Table 3 lists all the loading cases. The seismic intensities increased from 0.04 g until the test models failed. The MPCSW model failed during the 1.20 g SHW2 wave, and the MCOSW model lost its capacity after the 1.60 g Taft-XY wave. For each intensity level, the earthquake waves were imposed in the sequence of El-Centro wave, Taft-X wave, Taft-XY wave, Taft-XYZ wave and SHW2 wave.

Figure 8 plots the arrangement of the transducers on a plane view of a typical floor. The displacement and acceleration responses were recorded during the tests. The accelerators at the model center could record the accelerations in all the three directions. The strain gauges were installed on the longitudinal screws near the shear wall edge at the first and second floors to record the local strain responses.

Table 3. Summary of loading cases.

Sequence	Earthquake wave	Direction	PGA
1	El-Centro	X	0.04 g (service level earthquake), 0.12 g (design based earthquake), 0.26 g (maximum considered earthquake), 0.48 g, 0.72 g, 0.90 g, 1.20 g, 1.60 g
2	Taft-X	X	
3	Taft-XY	X, Y	
4	Taft-XYZ	X, Y, Z	
5	SHW2	X	

4 Test Results and Analysis

4.1 Failure Pattern

The MPCSW model and MCOSW model showed no visible damage after 0.04 g and 0.12 g tests. The coupling beams cracked after 0.26 g tests and the shear walls cracked after 0.90 g tests for both the models.

The MPCSW model lost its capacity during the 1.20 g SHW2 wave. As shown in Fig. 9a, the nuts slipped from the screws at the upper flanges of the bottom H-section beam connectors, and a few screws fractured. Because the upper screws were weakened during the assembly process, resulting in the nut slip under high intensity excitations.

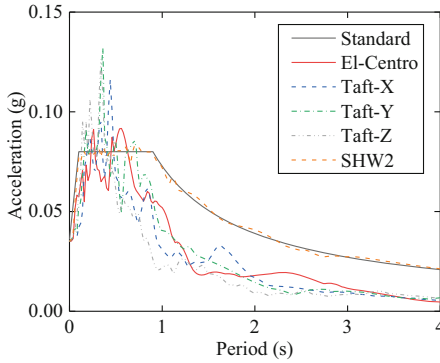


Fig. 7. Acceleration spectra.

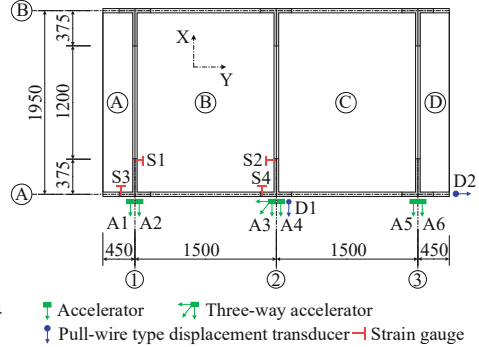


Fig. 8. Transducer arrangement.

Consequently, the tensile forces of other intact screws increased due to internal force redistribution and the screws fractured.

For the MCOSW model, during the 1.60 g Taft-XY wave, the nuts slipped from the screws at the lower flanges of the bottom H-section beam connectors, and the screws tended to be pulled out from the foundation, as shown in Fig. 9b. The concrete crushed at the model bottom, as shown in Fig. 10. The failure pattern indicated that the bottom vertical joints were the most critical components in the modular models. In engineering applications, the joint bolts should be strengthened and the bolt threads should be carefully protected to avoid premature failure.

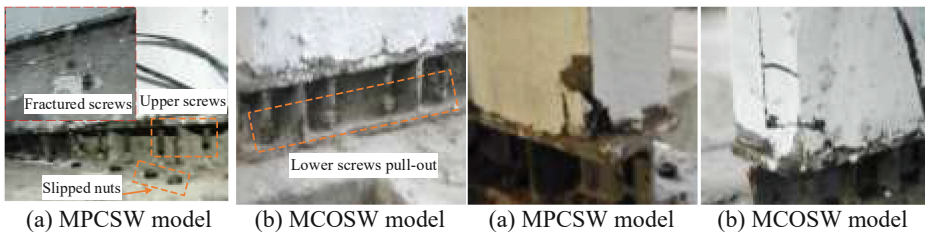


Fig. 9. Vertical joints failure.

Fig. 10. Bottom concrete crushing.

4.2 Dynamic Characteristic

Figure 11 plots the first three orders frequencies of the test models. The MPCSW model had lower fundamental frequency in the Y-direction than the MCOSW model. With the increasing PGA, the MPCSW model exhibited lower frequencies in the Y-direction, but performed similar frequencies for the X-translation and torsion modes. It indicated that the influence of screw weakening varied for different modes, which might be affected by the distribution of the damaged screws.

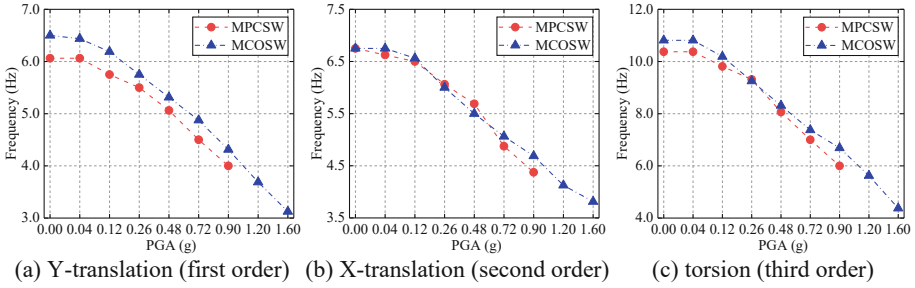


Fig. 11. First three orders frequencies.

4.3 Dynamic Responses

Figure 12 compares the X-directional lateral displacement envelopes for the test models. The displacements were generally similar from 0.04 g to 0.90 g tests, whereas the MPCSW model performed larger displacements under 1.20 g tests, especially for the Taft-XY and Taft-XYZ waves. It indicated that the assembly process had no obvious influence on the displacement responses before 1.20 g tests when the joints were intact. Nevertheless, the small model size and assembly process caused initial defects to the screw threads in the MPCSW model. The vertical joints were approaching failure during the 1.20 g tests and induced larger displacements.

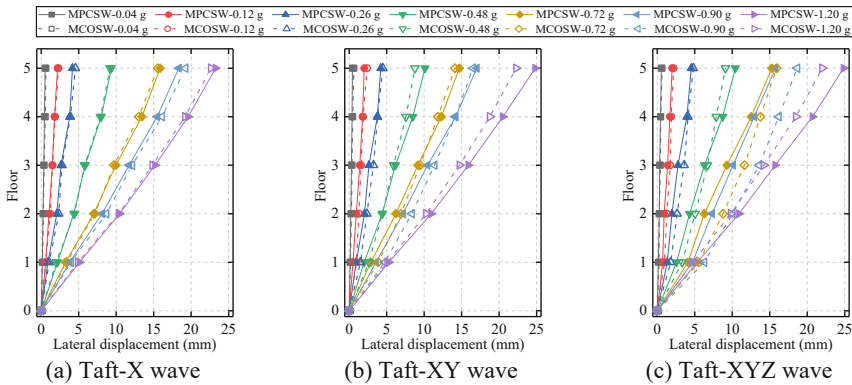


Fig. 12. X-directional displacement envelopes under Taft waves.

Figure 13 compares the X-directional floor acceleration envelopes between the test models from 0.04 g to 1.20 g tests. The MPCSW model showed comparable acceleration responses to the MCOSW model. It indicated that the construction process had no obvious influence on the acceleration before vertical joints failure.

Figure 14a plots the top displacement time histories under the ultimate loading case for the test models. The displacements of the MPCSW model exhibited obvious rocking mechanism and reached up to 207.6 mm due to the failure of vertical joints. For the MCOSW model, the displacement responses showed cyclic vibration mode, indicating

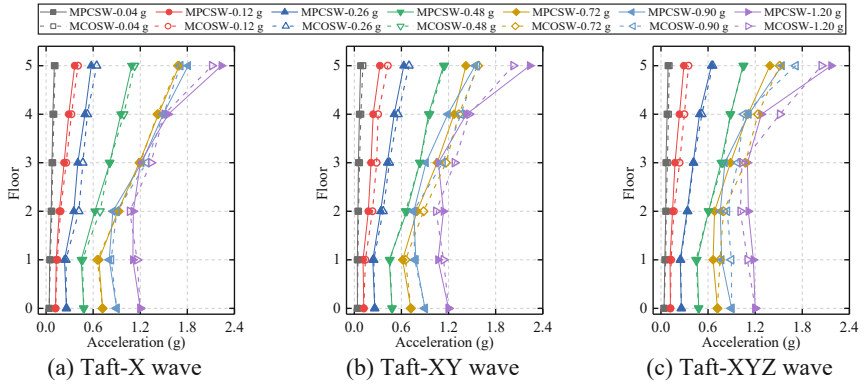


Fig. 13. X-directional acceleration envelopes under Taft waves

that the displacements were dominated by structural deformation. Figure 14b plots the top acceleration time histories under the ultimate loading case. The MPCSW model showed no obvious acceleration amplification compared to the MCOSW model.

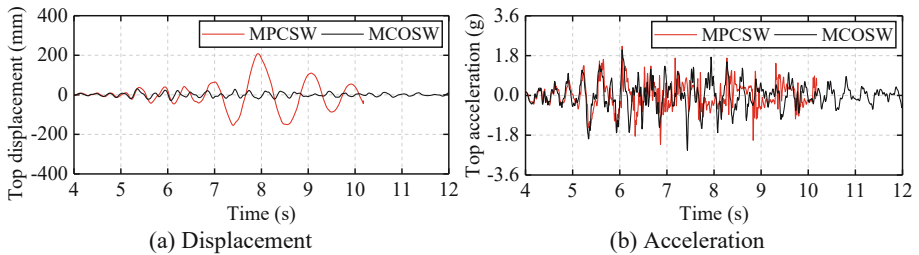


Fig. 14. Displacement and acceleration time histories under the ultimate loading case.

5 Conclusions

In this study, comparative shaking table tests were conducted on two 1/4-scaled modular models to investigate the influence of construction process on the seismic performance. The following conclusions can be drawn:

- (1) Both the modular models suffered from bottom vertical joints failure. The MCOSW model failed with nut slip and partial screw disconnection from the foundation under 1.60 g test. The MPCSW model showed premature bottom vertical joints failure under 1.20 g test due to nut slip and screw fracture.
- (2) The MPCSW model had lower fundamental frequency than the MCOSW model in the Y-directional translation mode, but showed comparable frequencies for other modes.

- (3) The assembly process showed no obvious influence on the displacement and acceleration when the joints were intact, but significantly increased the displacements with the vertical joints approaching failure.
- (4) The small model size and assembly process of the MPCSW model caused initial defects to the screws in the vertical joints, and led to premature failure of the MPCSW model. The joint bolts should be strengthened and the bolt threads should be carefully protected in practical engineering applications.

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