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SEISMIC PERFORMANCE EVALUATION OF ASSEMBLED O-STABLE PANEL WALLS

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O-Stable Panel is a new type of assembled structural wall. To evaluate the performance properties of the O-Stable Panel system, three integral prefabricated panel specimens with different vertical connections at the bottom and one full cast-in-place panel specimen were designed and tested under the low cycle lateral reciprocating loading. The performance of the prefabricated O-Stable Panel systems with different vertical connection configurations was compared with those of the full cast-in-place panel. The investigation reveals that all prefabricated O-Stable panel specimens developed vertical cracks penetrating through thickness of the panels at the panel joint and at the positions where panel thickness variation occurs at the ultimate failure state. The O-Stable panels possess the likely symmetric and stable hysteretic curves and no pinching appearance in shape of the curves. The panel with grouting sleeve in vertical joint for steel rebar appears sharp degrading in seismic index as the lateral drift of the wall increases beyond yield of the panel. For the assembled panel with preinstalled rebar stretched into the foundation beam for the vertical rebar joints, it has very close values in the hysteretic energy dissipation as that in the full cast-in-place panels.

Keywords: Prefabricated O-Stable panel, Low cyclic reciprocating loading, Hysteresis curve, Skeleton curve, Seismic performance, Vertical joint.

1 INTRODUCTION

An Assembled building structural system has shown the advantages of fast construction speed, energy conservation, and environmental protection etc. It meets the major requirements of housing industrialization. The key issues utilizing this construction technology are to ensure the effective horizontal and vertical joints of the assembled structural members.

O-Stable panel is a prefabricated integral building wall technology patented in Malaysia. The concrete panels can be tailored to meet any size or into any design as demanded by the architect. With standard vertical and one standard horizontal joint, it has enabled the structure to achieve refinement, while maintaining its simplicity and unparalleled quality. The wall then consists of prefabricated panels and cast-in-place column joints. The horizontal joints that connect the adjacent panels are provided by the cast-in-place concrete. The vertical joints between the adjacent upper and lower storey are via the cast-in-place columns and as well as the preinstalled steel bars of the panels stretching into the cast-in-place concrete floor. These joints enable an efficient force transfer to both the vertical and the horizontal loading of the building. This prefabricated O-Stable panel system has been successively used in multi-storey building construction in Malaysia. Since there are no specific design requirements for the seismic fortification in the Malaysia building codes, questions arise what likely seismic performances the panel system would possess, and whether this innovative panel system can be used in the buildings in the seismic areas, and capable of enduring the major earthquakes or not.

A research program is conducted to investigate the seismic behavior of the O-Stable panel system. Tests of four O-Stable panel specimens are reported, among which three specimens are integral prefabricated concrete panel specimens with different configurations in the vertical connections at the bottom of the panels and one specimen is a full cast-in-place concrete panel.

2 SPECIMENS AND TEST SETUP

The scale of the four specimens is 1:2 to the prototype structure, and the overall sizes of the panels after assemblage are 2100mm×1300mm×125mm. Figure 1 shows the facades for each specimen and the cross section for a single piece of the prefabricated O-Stable panel. The 300mm wide horizontal joint, shaded area in Figure 1 connecting to the two prefabricated panel segments, is cast-in-place concrete, and the main longitudinal steel reinforcements are anchored into the support beam. The outstretched transverse steel bars of the prefabricated O-Stable panels are anchored with the bent ends into the horizontal cast-in-place concrete joint. Specimen O-I-1 is a whole cast-in-place concrete wall specimen, and the vertical reinforcements of the panel are anchored into the stiff foundation beam. Specimen O-I-2 is an assembled wall consisting of two prefabricated panel segments and a cast-in-situ concrete joint. To connect the vertical rebars of the upper prefabricated panel and the bottom beam, the grouting sleeves are used.

Specimens O-I-3 and O-I-4 are also assembled wall units composted of the prefabricated panels and the cast-in-situ concrete joint, but with different in vertical anchor joints connecting the upper panels to the foundation beam, and vertical joints is formed by the out stretched steel bars of the upper prefabricated panel embedding in the concrete layer of 75 mm thick above the bottom beam. Specimen O-I-3 does not anchor the vertical reinforcements of the prefabricated panel into the bottom beam except at the edge part of the cross section. Specimen O-I-4 has all vertical reinforcements of the prefabricated panel into the bottom beam. The configurations of vertical joints of the tested specimens are shown in Figure 2. Details of the reinforcements in panel and the horizontal cast in place joints are shown in Table 1.

Low cyclic reciprocating lateral loading were exerted on the four specimens, and the test loading rig is shown in Figure 3. A constant axial compression force 530 kN was applied to each specimen, maintaining an axial compression ratio of 0.25 in the wall panel for each specimen. The horizontal loading to the wall specimens was exerted on the loading beam above the wall panel through a push-pull electro-hydraulic servo actuator 650kN in capacity. A force-displacement loading protocol was adopted in application of the reciprocating lateral loading for each specimen. Before the wall yielded, the lateral force was applied one cycle for each load step to the panel with a force increment of 10kN. After the wall yielded, the lateral loading was applied to the wall specimen in a displacement control mode three cycles per load step, with a lateral increment of the half yield displacement occurring on the top of the wall panel, where the yield displacement is notated as displacement of the loading beam when initial yield occurs in the wall panel. The test was terminated when the lateral force dropped to 85% of the peak load. Lateral forces and the corresponding displacements in the midpoint of loading beam were all recorded by a data Log system through sensors monitoring in the electro-hydraulic servo loading system. Strains of the longitudinal reinforcements, the sleeve connection were also gauged, and the measuring points are shown in Figure 4. The lateral displacements of the walls and the supports were also measured.

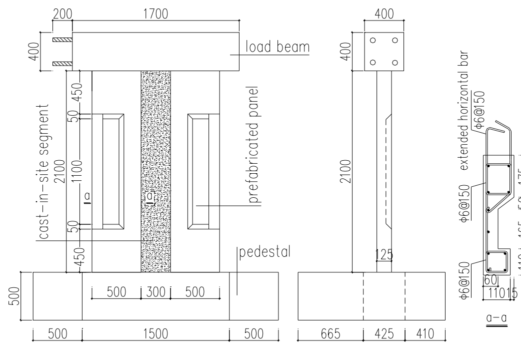


Figure 1. Layout and dimensions of test specimens and cross section.

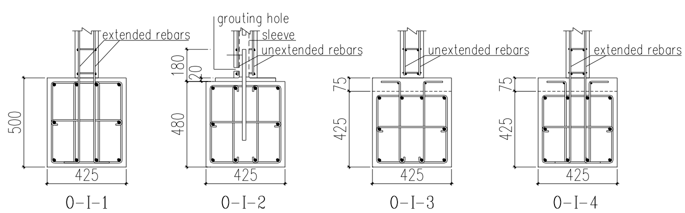


Figure 2. Connection configuration of panel and base.

Table 1. Steel reinforcement for major parts of specimens.

Thick boards		Thin boards	Edge members	
Vertical reinforcement	Horizontal reinforcement	Two directions	Longitudinal reinforcement	Stirrup
ϕ8@150	ϕ6@150	ϕ6@150	4 ϕ 8	ϕ6@150

3 TEST PROCESS AND FAILURE PATTERNS

Initial cracks occurred at the bottom of the edge components for each specimen. As the load increased, more fine horizontal cracks appeared immediately close to the initial crack and extended to the cast-in-situ segment.

After yielding in the specimens, the lateral loading was applied in a displacement mode. The horizontal cracks developed and the length and width of the cracks increased. Vertical cracks also appeared and developed through the full depth of the panels at the interface between the prefabricate panels and the cast-in-place column joints. Vertical cracks also occurred at the positions where the wall thickness changed from thick panel to thin panel. For all O-Stable panel specimens, the ultimate failure occurred when the vertical cracks penetrated the full depth and full thickness of the wall panels. Concrete crush and reinforcements yielding were observed at the bottom of the edge members of the specimens as shown in Figure 5. The lateral reciprocating loading also dropped down to 85% of the peak force values for all specimens when the tests were terminated.

Figure 3. Loading device.

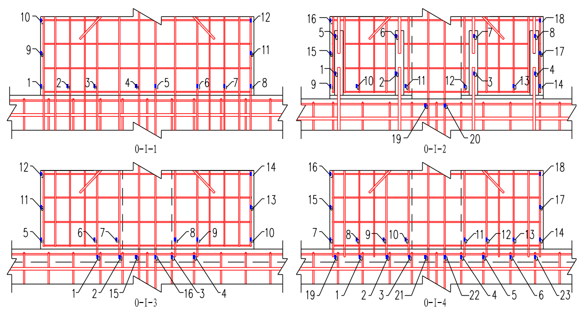


Figure 4. Arrangement of measuring points in strain.

(a) O-I-1 (b) O-I-2 (c) O-I-3 (d) O-I-4

Figure 5. Failure patterns of the test specimens.

4 SHEAR RESISTANCE OF THE SHEAR CONNECTION

Hysteresis curves: The load-displacement hysteresis curves of the specimens are shown in Figures 6(a) to 6(d), and the skeleton curve extracted from the hysteretic curves are shown in Figure 6(e). The hysteresis curves of panels show different extents of spindle shape. The skeleton curve of O-I-1 shows a better seismic behavior and the lateral load decreases at the late stage of loading. With a good ductility, O-I-1 can satisfy the requirements of the seismic design code in China (GB50011-2010). For assembled specimens, O-I-2 possess a relatively poor ductility, and does not meet the specification requirements in ductility, Specimen O-I-3 has a similar magnitude of the ultimate bearing capacity as specimen O-I-2, but an even lower ductility. Specimen O-I-4 has the largest ductility among the four specimens, but a slight low lateral bearing capacity.

Displacement ductility: A displacement ductility coefficient is defined as the ratio of ultimate displacement and yield displacement. The coefficients for four specimens are shown in Table 2. The ductility coefficient of O-I-4 is larger than that of the whole cast-in-place specimen (O-I-1). O-I-3 possesses the largest yield displacement, and the lowest mean displacement ductility coefficient. If concrete is constrained effectively in the edge member to the foundation beam, it will in turn improve the displacement ductility of the assembled panel wall.

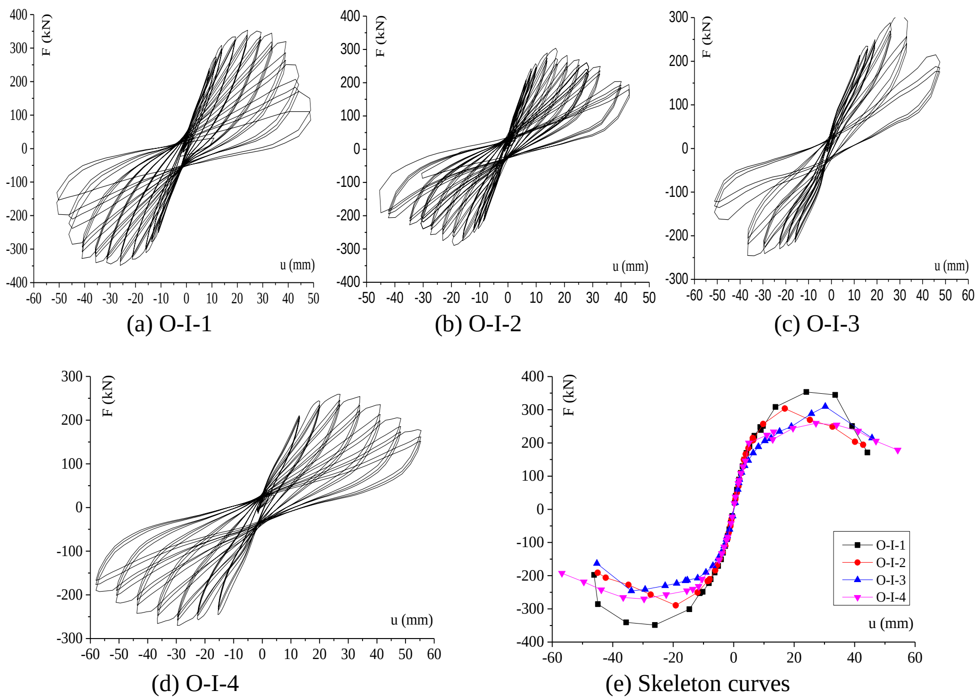


Figure 6. Horizontal load - vertex displacement hysteresis curves.

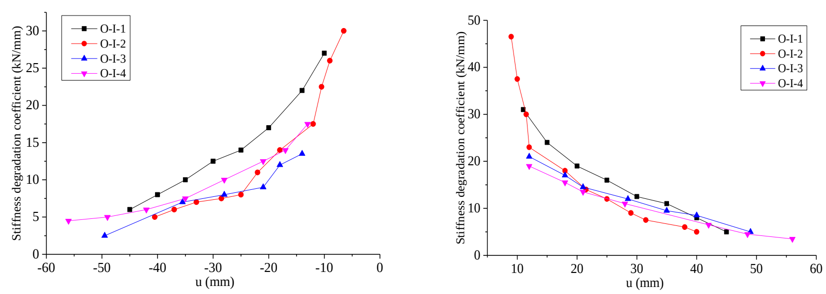
Table 2. Yield displacement and displacement ductility of specimens.

Specimens	Δ_y/mm		Δ_u/mm		M		μ_{ave}
	Positive	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**	
O-I-1	13.13	11.64	39.68	41.23	3.02	3.54	3.28
O-I-2	7.93	7.98	28.46	26.20	3.59	3.28	3.44
O-I-3	13.72	11.77	34.06	40.34	2.48	3.43	2.95
O-I-4	7.85	9.39	40.37	48.40	5.15	5.16	5.15

Stiffness degradation: Stiffness degradation of the structural panel wall reflects the degrading stiffness of the wall in resisting the lateral loading in term of increase of cycles of the reciprocating force, and can be expressed by equation (1), in which K_j is a loop stiffness degradation coefficient under j^{th} loading level; Q_j^i and u_j^i are the peak force and displacement under number *i* cycle of the j^{th} loading level respectively. Figure 7 shows that the loop stiffness degradation coefficient decreases with displacement, both in positive and negative loadings

Energy dissipation: Accumulated energy dissipations of different specimens in the first cycle of various displacements loading level show that in the early loading, each specimen works in the elastic region and the accumulated energy dissipation is very small. With increase of displacement and loading cycle numbers, the panel walls undergo the elastic-plastic stage. When decline of the loading occurs, the accumulated energy dissipation will still increase. At the ultimate failure state, energy dissipation in specimen O-I-3 is fairly close to that of specimen O-I-4, but the both are lower than that of specimen O-I-1. Specimen O-I-2 has the lowest energy dissipation, and it suggests that the grouting sleeves configuration in connecting the vertical rebars between the prefabricated panel and the support beam is not efficient in energy dissipation.

$$K_j = \sum_{i=1}^{n} Q_j^i / \sum_{i=1}^{n} u_j^i \tag{1}$$



(a) Negative loading (b) Positive loading

Figure 7. Stiffness degradation coefficient.

5 CONCLUSION

Under low cyclic reciprocating loading, flexural and shear failure occurred in the full cast-in-place concrete specimen. At the ultimate failure state, damages of the prefabricated panels were concentrated in the lower part of the wall, and vertical cracks penetrated through the thickness of the panels at the panel joint and at the positions where the panel thickness varied.

O-Stable panels possess the likely symmetric and stable hysteretic curves and no pinching appearance in the shape of the hysteretic curves. Grouting sleeve in connection of the vertical rebars has a higher bearing capacity, but smaller deformation ductility. The prefabricated O-Stable panels with the vertical reinforcements anchored into the foundation beam demonstrated higher efficiency than that of the cast-in-place panel regarding the energy dissipation.

Reference

GB50011-2010, Code for seismic design of buildings, Beijing: China Building Industry Press，2010 (in Chinese).