Seismic Behavior of a Novel Prefabricated Concrete Sandwich Panel System

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Abstract. An innovative sandwich wall panels as structural load-bearing elements have been presented. Besides the conventional configuration of sandwich panel, this new panel system has some distinctive characteristics including core column reinforced by spiral stirrup along the panel cross-section with spacing 650mm, foamed concrete as insulation layer, self-compacting concrete used in external layers. Furthermore, to improve the global strength and stiffness of panel, 3D steel wire system which is composed by two vertical steel wire meshes connected by horizontally short steel bar has been uniquely employed in concrete layer. An experimental campaign has been carried out to investigate the seismic behavior of this new panel system. According to the analysis of load-bearing capacity, hysteretic behavior, skeleton curves and stiffness degradation, conclusions could be drawn that the new prefabricated concrete sandwich wall system has comparable performance with traditional concrete solid wall.

1. Introduction
In order to improve the mechanical properties of sandwich walls, new material and new structure configuration have been adopted in sandwich walls in recent years. Fernando [1] developed a foamed concrete slabs using recycled expanded polystyrene (EPS) which had the advantages of energy saving and weight reduction. S. A. Taghizadeh [2] studied the damage mechanism of sandwich wall panels by testing three different quasi-static compression loading conditions for rectangular sandwich, trapezoidal and triangular composite sandwich panels with the same thickness. Wang Zhong-gang [3] discussed the differences between existing ceramic sandwiches and traditional ceramic sandwiches through a three-point bending experiment on ceramic sandwich panels of tile panels. Hou He-tao [4] provided a new type of prefabricated sandwich wall panel whose concrete layers were connected by diagonal steel bars and the insulation layer was made of EPS. Based on test data and simplified strain/stress diagram, an analytical model was developed to analyze the flexure performance of the proposed sandwich wall panel. Won-chang Choi [5] showed the experimental results of push-out tests of concrete sandwich panels that used a grid type of glass fiber-reinforced polymer shear connector and then compared these results with previous research results that were based on corrugated shear connectors. James S. Davidson [6] focused on analytical methods for foam-insulated concrete sandwich panels (ICSP). However, from a structural point of view the main drawback of sandwich panel system is the application limitation only in low-rise (generally less than three stories) buildings and it is not suitable for high-rise buildings as a load-bearing system due to relatively low strength and stiffness. What’s more, the heat-bridge effect is another main problem hardly to solve in the design of sandwich wall system since the existence of steel shear connector. To overcome those drawbacks mentioned above, an innovative concrete sandwich panel structural system is introduced in this work. Compared with the common sandwich panels, there are
several typical characteristics for this panel which includes reinforced core columns confined by spiral stirrup along panel cross-section with spacing 650mm, foamed concrete as insulation layer between external layers, and self-compacting concrete applied in structural layers with high flow ability. To meet the strength and stiffness requirement in the application of multi-story and high-rise building, a 3D steel wire system in each concrete layer which is composed of two vertical steel wire mesh connected by horizontal steel bar has been employed. A typical panel diagraph has been shown in Figure 1.

![Figure 1. Prefabricated sandwich panel](image)

2. Specimen Information
Two full-scale sandwich panel wall specimens have been designed and constructed. One specimen has planar steel wire mesh in the structural layer and the other has three-dimensional steel mesh. The planar mesh is consisted of steel wire in two orthogonal directions with same spacing 50mm and the diameter of steel wire is 3mm. While in the 3D steel wire system two planar steel meshes are linked together by automatically electro-welded steel bar with diameter of 2 mm orthogonally to steel meshes. The fine-aggregate concrete has been adopted in specimen construction and the actual compressive strength after 28 days curing is 45.6MPa. The yield strength and ultimate tensile strength of steel wire is 550MPa and 670MPa and the yield strength of the steel bar is 570 MPa. The detailed information of specimens has been shown in Table. 1 and Figure. 2-3.

| No. | Wall height | layer thickness | Insulation thickness | Steel wire mesh type | wire diameter | Diameter of spiral stirrup | Diameter of column rebar |
|-----|-------------|-----------------|---------------------|---------------------|--------------|--------------------------|--------------------------|
| Y1  | 2.4m        | 25 mm           | 60 mm               | planar              | 3 mm         | 4 mm                      | 8 mm                      |
| Y2  | 2.4m        | 40 mm           | 60 mm               | 3D                  | 2 mm         | 4 mm                      | 8 mm                      |

![Figure 2. Cross-section of panel with planar steel wire mesh](image)

![Figure 3. Cross-section of panel with 3D steel wire system](image)

The specimen is vertically secured to a reaction steel frame and therefore an ideal cantilever behavior of specimen could be obtained. Using a displacement-controlled cyclic loading system, one loading
cycle is applied before the steel bar yields; three loading cycles are applied after the steel bar has yielded. The test setup is shown in Figure 4.

![Test setup](image)

Figure 4. Test setup

3. Experiment results

3.1. Failure modes

Specimen Y1 behaves in a linear manner at the initial stage of loading and there is no visible crack in specimen surface. The first horizontal crack appears at the base corner of panel at the displacement cycles of 4.3mm and the crack closes after the displacement has unloaded to zero. In the displacement cycle of 16.3mm, severe crack is seen in bottom corner with concrete spalling, meanwhile the specimen reaches ultimate strength of 246kN and 237kN for the positive and negative loading direction respectively.

Similar structural performance has been found in specimen Y2 during the process of cyclic loading, the first crack horizontally appears at the base corner of specimen in the cycle of displacement amplitude 3mm and extends diagonally in the subsequent cycles. Compared with Y1, the specimen Y2 has 5% increase of ultimate strength with almost equal deformation capability. The failure modes of specimen Y1 and Y2 have been shown in Figure 5 and Figure 6 respectively, and the main results are listed in Table 2. The significant difference in failure modes is that for Y2 the cracks mainly occur in the surface of one-third panel height and the amount of cracks in the ultimate failure is greatly less than that of Y1, meanwhile the crack width of Y2 is generally smaller than that of Y1 under the same lateral displacement. The comparison indicates that the employment of three-dimension steel wire system has greatly improved the crack resistance of panels.

| Specimen ID | load  | displacement | Ultimate load | Peak displacement | steel ratio |
|-------------|-------|--------------|---------------|------------------|-------------|
| Y-1 Positive | 140 kN | 4.3mm | 246 kN | 23.0mm | 0.68% |
| Y-1 Negative | -138kN | -4.1mm | -237 kN | -22.3mm |  |
| Y-2 Positive | 143kN | 3.0mm | 256 kN | 22.1mm | 0.51% |
| Y-2 Negative | -140kN | -3.2mm | -248 kN | -22.0mm |  |

![Y1 Failure pictures](image)

Figure 5. Y1 Failure pictures

![Y2 Failure pictures](image)

Figure 6. Y2 Failure pictures
3.2. Hysteresis curves

The hysteresis curves (lateral forces versus displacements) have been displayed in Figure 7 and 8. The initial stiffness before cracking is equal to approximately 40kN/mm. After the first visible crack appears under the load 140kN, corresponding to the lateral displacement of 4.3mm, the larger hysteresis loops can be observed and the shape change of hysteresis loops indicates that the appearance of pinching. The specimen Y1 reaches peak strength at the displacement cycle of 17.6mm and in the subsequent cycles the strength has a significant drop, for a targeted drift the strength at the third cycle there is approximately 20% reduction compared to the strength at the first cycle. As far as specimen Y1 is concerned, a significant strength and stiffness degradation has been seen after the peak strength and the residual strength at ultimate state has dropped to about 20% of maximum strength. The curve of specimen Y2 exhibits a small hysteresis loop and no visible damage is found in the elastic stage. Specimen Y2 reaches its ultimate strength at the lateral displacement of 8.6mm and the maximum load-bearing capacity is 256kN which is slightly higher than that of Y1, while after peak load Y2 still remains a relatively high residual strength and there is only 20% strength reduction even in the ultimate failure.

![Figure 7. Hysteretic curve of Y1](image1)

![Figure 8. Hysteretic curve of Y2](image2)

3.3. Skeleton curves

The skeleton curves for two specimens have been compared in Figure 9. It can be seen that the slope of Y2 skeleton curve in the elastic phase is larger than that of Y1, which indicates that the Y2 has larger stiffness than Y1. Although the two specimens have almost the same peak strength, the lateral displacement of Y2 at the peak load is 20.19mm while the peak displacement of Y1 is 23mm. What’s more, the load-bearing capacity of Y1 has a significant reduction while the residual strength of Y2 decreases slowly. The comparison of skeleton curves indicates that the seismic performance of Y2 is better than Y1 with the reason that three-dimensional steel wire system could provide effective reinforcement to concrete layer with stiffness enhancement and crack resistance.
4. Conclusions
A novel prefabricated sandwich wall panel system has been presented in this work and the seismic behavior for different cross-section types of wall panels was experimentally studied. The structural layer of sandwich panel could be reinforced by either planar steel wire mesh or 3D steel wire system according to the requirement of structural load-bearing. The reinforced core column confined by spiral stirrup was proved its function to improve the stiffness and stability. In the ultimate failure the cracks of specimen Y2 mainly distributed along the surface of 1/3 specimen height while the crack pattern of specimen Y1 has fully developed throughout the whole surface which indicated that three dimensional steel wire skeleton could be effective to enhance crack resistance of panel. Compared with Y1, specimen Y2 exhibited more economical characteristic with smaller wire diameter and less reinforcement ratio. The analysis results of skeleton curves indicated that Y2 could keep a higher residual strength after peak load while there was an obvious strength decrease for Y1. The ductility coefficients of two specimens were larger than the required value for ductile performance in earthquake action. Compared with Y1, the specimen Y2 had much slower stiffness degradation.

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