Seismic Performance Evaluation of Masonry Buildings Retrofitted by Pre-Cast RC Walls

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SUMMARY:
A retrofitting technology using pre-cast reinforced concrete (RC) panels is developed to improve the seismic performance of old masonry buildings. The pre-cast RC panels constitute an external RC wall system surrounding the existing masonry building. The RC walls are well connected to the existing masonry building, which provides enough confinement to effectively improve the ductility, strength, and stiffenss of old masonry structures. The RC panels are fabricated in factory, significantly reducing the situ work and associated construction time. To demonstrate the design theory and the construction procedure, a full-scale five-story specimen was constructed. The retrofitting process is completed within five weeks with very limited indoor operation. The specimen was then tested in both lateral and longitudinal direction. The seismic performance was fully exmained by quasi-static cyclic tests and pseudo-dynamic tests. The results indicate that the strength increases 3-5 times, and the stiffness 2-3 times of the original structure.

Keywords: Masonry buildings, Pre-cast RC panel, Pseudo-dynamic testing, Seismic performance

1. INTRODUCTION

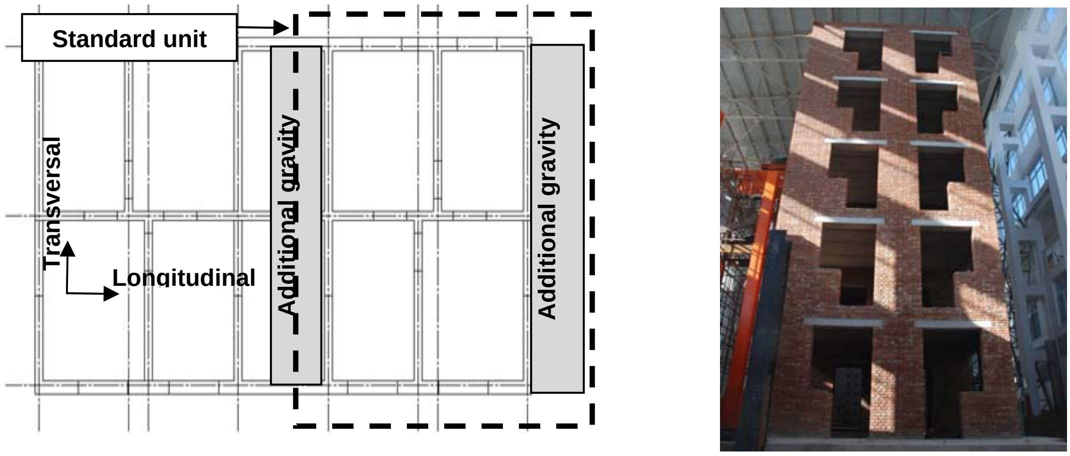
Recent earthquakes imposed significant damage on masonry buildings, particularly those without any seismic specification. The failure of masonry buildings consequently causes massive casualties as what happened during Tangshan earthquake (Cai, 1984) and Wenchuan earthquake (Chen, 2009). In China, a lot of investigations and researches have been conducted extensively after 1976 Tangshan earthquake. Many ideas and technologies were proposed to improve the seismic performance of masonry buildings (Liu, 1985). One of the most important findings is that the composite masonry structure with constructional reinforced concrete columns and beams presents drastically-improved behaviour. Nonetheless, there still exist many old masonry buildings constructed during 1970's. They were designed without any seismic detailing. More seriously, some were constructed in the seismic-prone area and are threatened from potential huge earthquakes. Most of these buildings were built in downtown areas. To demolish and rebuild is not quite possible because of the large demand of fundings and evacuation houses. This has been a weak point of the capital disaster mitigation system that to be solved urgently.

Some seismic retrofitting technologies have been developed and applied in the past several decades, such as the additional buttress column to enhance the stability, and the external pre-stressed steel bars or steel frame to improve the integrity (El Gawady et al, 2004). One of the most widely applied technologies in China is to sandwich masonry walls with reinforced concrete on both sides (Deng, 2008). This method is able to improve the strength and stiffness effectively, and can be implemented easily. However, it takes a longer period than six months, and has to be implemented in door, thus disrupting the routine life of residents seriously. The concrete has to be casted in site which has adverse influence on the residential environment. More seriously, the effectiveness is determined by the construction quality. To this end, a novel retrofitting technology is developed, which adopts pre-cast reinforced concrete panels to enlarge the section of masonry walls, thus improving both strength and stiffness simultaneously. The panel is fabricated in factory. Both situ work and construction time are reduced, and the quality can be easily controlled, making the seismic performance predictable.

Different strategies are adopted for the longitudinal and transversal masonry walls. In the longitudinal direction, a pre-cast reinforced concrete panel (PRCP) is pasted on the exterior surface of the external walls, while in the transversal direction, a pre-cast steel reinforced concrete panel (PSRCP) is adopted to extend the section area of the transversal interior masonry wall. The key of the proposed retrofitting technology are the connections between the RC members and the existing masonry building. In this regards, a full-scale five-story masonry building was reproduced in the structural lab of Institute of Engineering Mechanics, China Earthquake Administration, and was further retrofitted by means of the proposed method. The design, fabrication, construction procedures were examined extensively, and the seismic performance was investigated through quasi-static tests and pseudo-dynamic tests.

2. PROTOTYPE TO BE RETROFITTED

The old masonry buildings were typically five- to six-story high, with several standard units along the longitudinal direction, as shown in Fig.2.1 (a), which follows the specifications regulated in the Residential Standard of Masonry Structures (2nd edition, 1973) edited by Beijing Institute of Architectural Design (BIAD, 1973). One of the standard units was taken as the specimen to be constructed in the laboratory. It is a two-span by two-span five-story full-scale building with the width of 6.2m, the length of 9.5 m, and the height of 14.2 m, as shown in Fig.2.1 (b). Total weight is about 400 ton. Additional 20 ton sands were distributed on each floor along the external transversal walls to represent the gravity load in the additional floor area which is not physically constructed. The thickness of the exterior wall is 370 mm, and the interior wall is typically 240 mm. The floor load is sustained by transversal walls through pre-fabricated slabs. To represent the behaviour of the old building, the strength of mortar was measured from real buildings and reproduced in the laboratory. The strengths of mortar are 2.5, 2.0, 2.0, 1.0 and 1.0 MPa for the first to five stories, respectively. The clay bricks with the lowest strength grade, MU10, allowed by the current code were used.



(a) (b)

Figure 2.1. Standard building to be tested

3. RETROFITTING PROCEDURES

The building was further retrofitted by the proposed technology to examine the construction organization and the seismic performance. Different strategies were adopted for the longitudinal and the transversal directions, as shown in Fig.3.1 In the longitudinal direction, a pre-cast reinforced concrete panel (PRCP) is pasted on the exterior surface of the external walls, while in the transversal direction, a pre-cast steel reinforced concrete panel (PSRCP) is adopted to extend the section area of the transversal interior masonry wall. The key of the proposed retrofitting technology is to guarantee the connection between the panels and the existing masonry building. Three techniques were developed to connect the RC panels tightly with the existing masonry walls, namely "reinforced concrete (RC) keys", "implanted reinforcement" and "CSV cement". Detail procedures are given as follows.

Step1, surface treatment of masonry walls: For the convenience of transportation and installation, the pre-cast RC member is divided into many pieces which are connected by cast-in-site concrete after installation. Within the region of post-cast concrete, some holes are chiselled on the masonry wall along the edge of the pre-cast RC panels, as shown in Fig.3.2 (a). The dimensions of these holes are 180 mm in length, 180 mm in height, and 120 mm in depth. Steel rebars are then put into the hole, and are hooked together with the rebars extended from inside of pre-cast RC panels. In the area without RC keys, steel rebars are implanted into the masonry wall, and also hooked at one end with the rebars of pre-cast RC panels, as shown in Fig.3.2 (b). Once concrete is casted, the pre-cast RC panels would connect securely with the existing masonry walls.

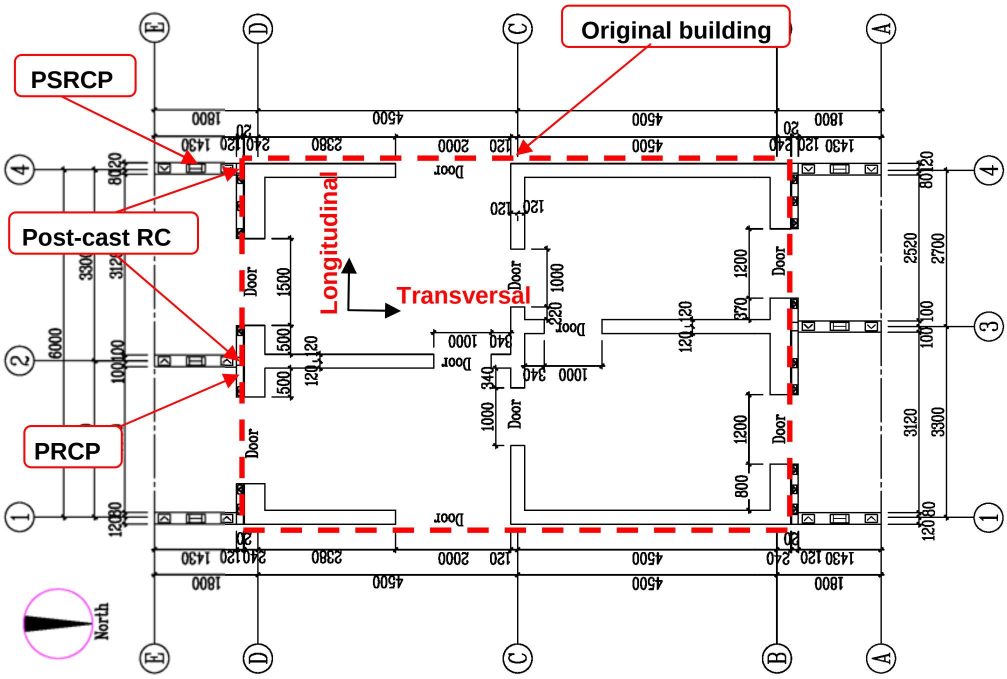


Figure 3.1 Different retrofitting techniques in two directions

(a) (b)

Figure 3.2 Surface treatment on masonry wall: (a) RC keys; (b) Implanted reinforcement

Step2, installation of pre-cast RC panels: Each pre-cast RC panel has hot-roll steel at both bottom and top surfaces. These steels are designed for the connection to the top and the bottom pre-cast RC panels, so that they constitute an entire piece of shear wall. The panel used for the transversal retrofitting contains three steels: two angles and one I-shaped steel. The I-shaped steel, totally half meter high, 200 mm extended from the bottom surface of the panel, is used to transfer shear force at the panel connecting surface, while the two angles have the same length as the height of the wall, which serve as the edge-constraint members to pass moment. With these two steel angles inside, the panel used in the transversal direction is also named after pre-cast steel reinforced concrete panel (PSRCP). PRCP is first installed along the surface of the longitudinal exterior masonry wall, as shown in Fig.3.3 (a). When positioning, there is a 20 mm gap left between the panel and the masonry wall. After that, the steel is welded to the top surface of the panel at the next story, as shown in Fig.3.3 (b). Once the PRCPs are positioned, the PSRCP is hoisted, positioned and connected similarly, as shown in Fig.3.3 (c). A precast reinforced concrete slab is then put on the top of the panels. The pre-cast members then form a balcony as shown in Fig.3.3 (d). The edges shared by these members need to cast concrete in site, as shown in Fig.3.3 (e). Before the concrete is casted, temporary supporters are needed to maintain the stability. After the pre-cast members are installed for one story, six steel rods are installed to connect the pre-cast members at both sides of the masonry building. This is the only task that has to be completed in door, as shown in Fig.3.3 (f). Once all of these tasks are completed, the post-cast concrete is poured into the post-cast band. And CSV cement is filled into the gap between the PRCP panel and the masonry wall to integrate the two components as one piece, which is taken as the third measure to guarantee the connection between the new structure with the old one.

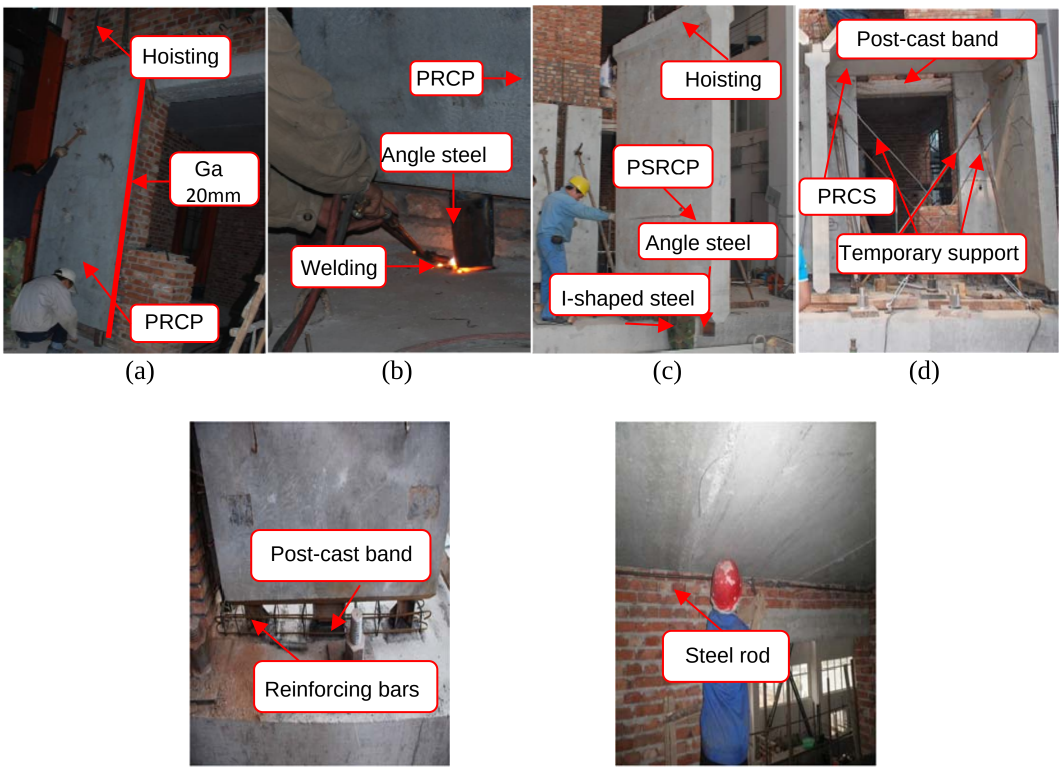
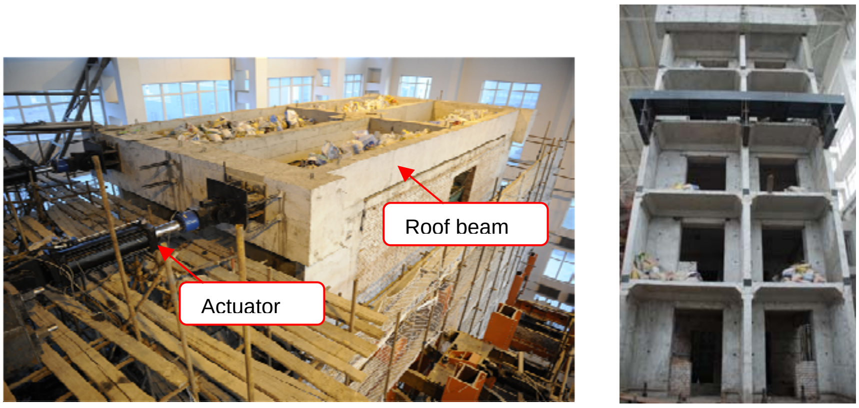


Figure 3.3 Installation of pre-cast RC panels: (a) Positioning of PRCP; (b) Weld connection of PRCPs; (c) Positioning of PSRCP; (d) Pre-cast balcony; (e) Post-cast connection; (f) Steel rods

Step 3, roof beam to connect pre-cast RC systems: Up to now, the pre-cast RC panels constitute two independent RC shear wall systems on both sides of the masonry building. Finally, the two systems are connected on the roof by RC beams, as shown in Fig.3.4 (a). The RC beams are supported directly by the RC panels, while the existing masonry building is not touched. It is also possible to construct additional stories based on the RC beams to further extend the living area. The overview of the entire retrofitted building is shown in Fig.3.4 (b), where the steel beam at the third floor is particularly used for the experiment.

The retrofitting process has lasted for five weeks, much less than traditional technologies. This method also provides extended living area, significantly improves the living condition.



(a) (b)

Figure 3.4 Roof RC beam to connect RC panels: (a) Roof RC beam; (b) Overview of retrofitted building

4. EXPERIMENT

The RC panels and RC beams form a huge RC frame which surrounds the existing masonry building, providing additional confinement on the masonry structure. The deformation of RC frame is flexible-dominated, while the deformation of masonry structure is a typical shear type. When the two types of structure work together, the damage of masonry building will be redistributed to the upper stories. In order to extensively examine the seismic performance of the retrofitted building, physical experiments were conducted. It was first loaded in the transversal direction, and then followed by the loading in the longitudinal direction. In each direction, quasi-static tests were first conducted to introduce slight damage in the structure. Then four rounds of pseudo-dynamic testing were conducted, each corresponding to the small, medium, rare, and very rare earthquakes. Only those results of pseudo-dynamic tests are discussed in this paper.

5. EXPERIMENTAL SCHEME

Considering the facility limitation in the structural laboratory, the full-scale structure is loaded at two stories in the transversal direction: the roof and the third story, each controlled by two 100-ton servo-hydraulic actuators, as shown in Fig.5.1 (a). The dynamics of the structure is thus simplified as a two-degree-of-freedom system. The two actuators at the roof are displacement-controlled during quasi-static tests, and the two at the third story are force-controlled with the force target as 60% of the reaction force obtained from the roof actuators. The two-DOF model maintains similarity of base shear force and overturning moment as the original model. In the longitudinal direction, the structure is simplified as a single-degree-of-freedom model, and loaded at the third story by three actuators, as shown in Fig.5.1 (b). The reason is that the aspect ratio is much different from the original structure if loaded at the roof, since only one standard unit is taken as the specimen. A typical method to simplify an equivalent SDOF model was employed, and the equivalent height is approximately at the fourth floor. To comply with the height, the target displacement is 75% of the calculated target.

A typical Operator-splitting (OS) algorithm [6] is adopted to solve the equation of motion. In this study, the El-Centro ground motion is taken as the seismic input. The design lifetime of the retrofitted building is 30 years. The peak acceleration is about 75% of the corresponding intensity level.

Specifically, for the VIII fortification area stipulated in Chinese seismic design code, the small, medium, and rare earthquakes have the peak ground acceleration (PGA) of 0.0525g, 0.15g, and 0.3g, respectively. Another round testing is appended using the ground motion with PGA of 0.4g to represent very rare earthquake.

(a) (b)

Figure 5.1 Loading scheme: (a) Transversal direction; (b) Longitudinal direction

6. EXPERIMENTAL RESULTS

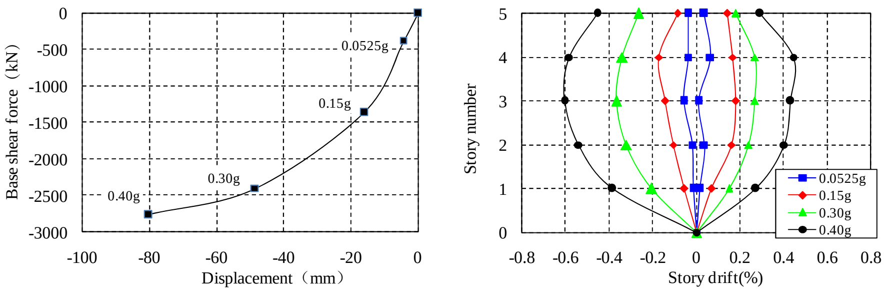
The maximum base shear forces vs. roof displacements at different PGAs are plotted in Fig.6.1 (a) for the transversal loading. When sustaining the very rare earthquake, the displacement is approximately 80 mm, and the base shear force is about 2764 kN, as listed in Table 6.1. The story deformation is plotted in Fig.6.1 (b). When sustaining the small earthquake, it deforms as a shear mode. With the increase of seismic intensity, the deformation becomes a flexible-and-shear mixed mode. Fig.6.2 shows the base shear force vs. roof displacement hysteretic curves under different seismic intensities. Significant nonlinearity can be observed under the rare and very rare earthquake. In the longitudinal direction, the maximum displacement is about 37 mm, and the maximum base shear force is about 1525 kN. Although significant nonlinearity can be observed after the very rare earthquake, the base shear force does not decrease, implying enough margins to prevent the structure from collapse.

7. CONCLUSIONS

This study proposes a technology using pre-cast reinforced concrete panels to retrofit existing masonry buildings. The pre-cast members constitute a frame wrapping the existing building. The confinement effectively improves the ductility, strength, and stiffness of masonry structures. Moreover, the panels are fabricated in factory, significantly reducing the situ construction work. A full-scale experiment validates the design theory. The connection works well and the seismic performance is well improved.

Table 6.1 Seismic responses of pseudo-dynamic testing

Input PGA (g)	Transversal direction				Longitudinal direction			
	Roof displacement (mm)		Base shear force (kN)		Roof displacement (mm)		Base shear force (kN)	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
0.0525	4.86	-4.31	449.6	-385.9	2.86	-3.63	214.9	-281.6
0.15	22.54	-16.09	1436.8	-1360.9	7.85	-10.93	643.9	-794.5
0.30	35.01	-48.67	2095.7	-2409.6	16.09	-24.63	1135.7	-1219.0
0.40	57.74	-80.51	2603.4	-2763.9	23.23	-36.64	1326.9	-1524.9



(a) (b)

Figure 6.1 Displacement responses: (a) Roof displacement vs. seismic intensity; (b) Story drift distribution

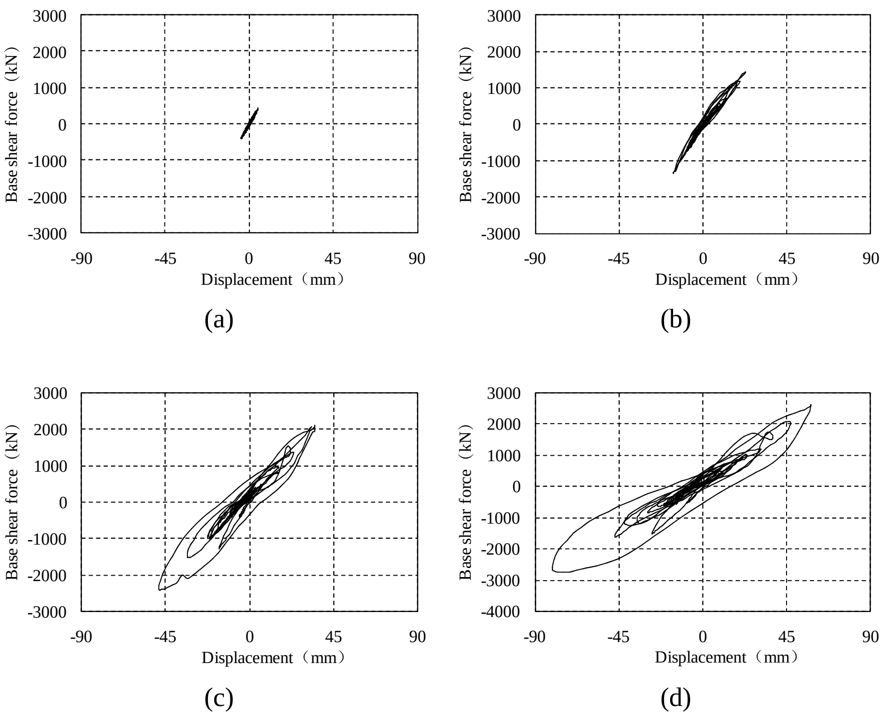


Figure 6.2 Hysteretic curves: (a) 0.0525g; (b) 0.15g; (c) 0.3g; (d) 0.4g

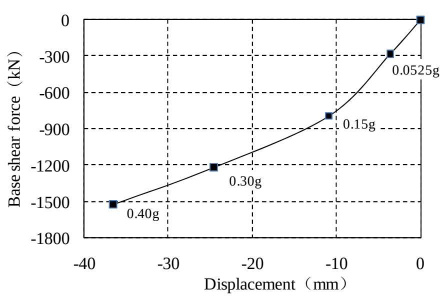


Figure 6.3 Displacement responses

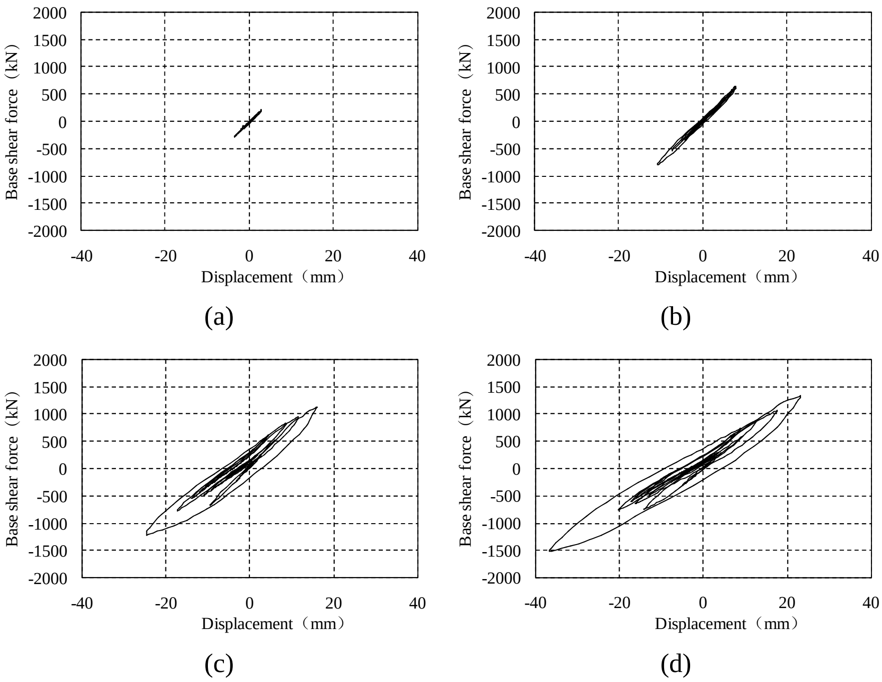


Figure 6.4 Hysteretic curves: (a) 0.0525g; (b) 0.15g; (c) 0.3g; (d) 0.4g

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