Performance of a seismically repaired masonry building

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Abstract

WenChuan and Lushan earthquakes in China caused significant damages of many masonry buildings. Most may not collapse, however, not be suitable for continuous living. Based on the seismic assessment, these seriously damaged masonry buildings have to be demolished. But it will take very long time and would cost a lot for a low-salary family to rebuild a new one. Chinese code for field survey stipulates that a crack wider than 3.0mm is a serious damage. And if the number of the walls with such cracks is over 50% of all of the walls, the building is deemed irreparable. This may be too strict since most masonry buildings with even much larger damages still stood right there. Plenty of techniques have been developed to enhance old masonry buildings without damage but lack of aseismic measures. However, their effectiveness to repair seismically damaged buildings remains unknown. This study conducted a series of test on a two-story full scale masonry building. The test was first conducted quasi-statically in both separate horizontal directions to reproduce the seismic damage. Then the damage assessment was carried out, based on which a repairing method employing steel-reinforced mortar layers was selected according to the cost, construction period and bearing load. Similar quasi-static test on the repaired building demonstrates that the strength after repair is about 2.84 times of the original building, and compared with the demolishing and reconstruction, the period reduced to 50%, and the cost reduced to 40%.

Keywords: masonry structures, reparability, supplement constructional column, cement mortar with steel meshes reinforcement.

1. Introduction

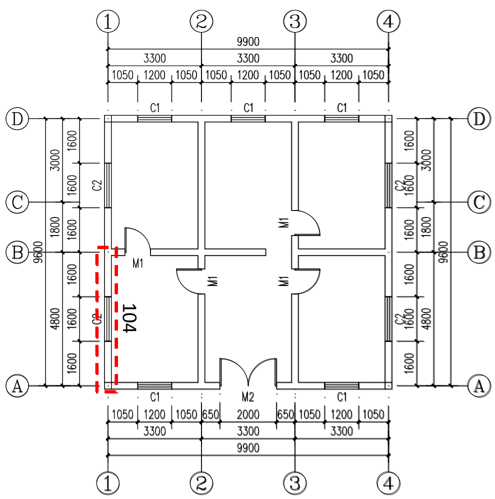
Significant damages and collapses of masonry structures were observed during WenChuan and Lushan earthquakes, which caused massive loss of human lives. People have to move into tentative camps until their houses were demolished and reconstructed. Chinese code [1] for field survey stipulates a crack wider than 3.0mm is taken as the serious damage. And if the number of the walls with such cracks is over 50% of all of the walls, the building is deemed irreparable. However, the field survey [2] indicated that most masonry buildings with such damages or even more serious still have enough capacity to resist aftershocks. Although may not be sufficient, this at least proves there's might be a chance to repair such buildings rather than demolish it directly. Further, if it can be repaired with a less cost than reconstruction, it can save money not only for the government but also for the residents.

Plenty of techniques to retrofit old masonry buildings exist. Dizhur [3] applied fiber-reinforced polymer (GFRP) fabric to two unreinforced masonry buildings which experienced strong earthquake shaking. It is found GFRP retrofits successfully preserve architectural features within the buildings as well as maintaining the structural integrity of the URM walls. The steel fiber reinforced mortar layers were also used in repairing masonry structures, as studied by Facconi et al [4]. Taghdi [5] retrofitted walls using a steel strip system consisting of diagonal and vertical strips. All walls were tested in-plane by lateral deformation reversals. It showed that the complete steel-strip system was effective in significantly increasing the in-plane strength and ductility of low-rise unreinforced and partially reinforced masonry walls. To investigate the effectiveness of several seismic strengthening techniques, Moon [6] conducted a full-scale quasi-static test on an unreinforced masonry (URM) structure. The retrofitting measures include fiber reinforced plastic overlays, near surface mounted rods, and vertical posttensioning. Results show that each system either increased the lateral in-plane strength and/or provided continuity of pier and spandrel elements over increased lateral displacements. At the same time, vertical unbonded posttensioning tends to alter pier failure modes from ductile rocking/sliding to more brittle diagonal tension. Ma [7] also adopted the external prestressing technique to improve seismic performance of masonry structures, and conducted shaking table tests. The failure mode of the tested masonry structures was influenced. Furthermore, the prestressing also improved the energy dissipation capacity of the walls and enhanced the overall stiffness of the masonry structure. Costa [8] studied some mainly used reinforcing schemes, and assessed their effectiveness by means of time history analyses. Results show that the application of reinforced plaster as a strengthening technique for masonry walls proved to be beneficial in terms of the improvement of the seismic response, resulting in an overall stress minimization. Shrestha [9] performed shaking table tests of half-scale brick walls to investigate the effectiveness of super elastic alloy (SEA) bars in retrofitting of historical masonry constructions. Corresponding nonlinear finite element (FE) models are developed to simulate the experimental observations. Both results demonstrate the effectiveness of SEA bars to provide the tested structure with strong re-centering capability and increased safety at relatively large excitation levels. Branco [10] conducted a comparative study of the performance of different seismic retrofitting techniques: the floor strengthening, insertion of concrete walls, the use of a base isolation solution, and the implementation of viscous dampers. These techniques were implemented in a model of an existing masonry building. It turns out that the solution of inclusion of concrete walls is the one that creates the most seismic strengthening. Nevertheless, using viscous dampers is the solution that maximizes the seismic strengthening, has ease of installation.

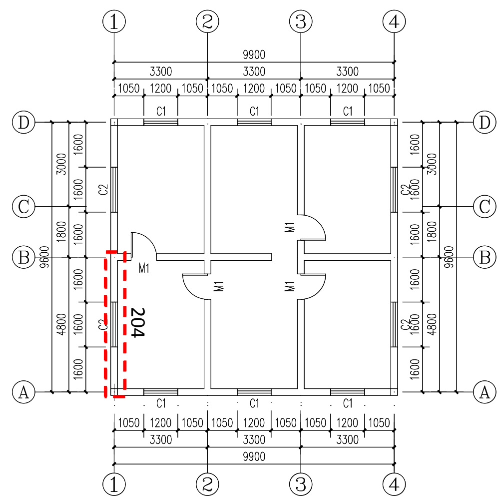
These techniques mostly applied to an old building lack of aseismic measures but without any damage. Their effectiveness to repair seismically damaged buildings remains unknown. Particularly, can the mechanical performance of a damaged building be recovered to satisfy all requirements of current seismic code, or are the period and cost taken for the repairing longer and larger than reconstruction? To answer these questions, a series of test on a two-story full scale masonry building were conducted. The test was first conducted quasi-statically in both separate horizontal directions to reproduce the seismic damage. Then the damage assessment following the Chinese code was carried out, based on which the repairing method with dual-surface reinforced mortar was adopted considering the repairing costs, construction period, bearing load, and material availability in countryside. Finally, another round of quasi-static test was conducted to evaluate the seismic performance after repairing.

2. Typical masonry residential building in high-seismicity region of China

The two story masonry building was architecturally designed following the Standard Constructional Details for Earthquake of Residential Buildings in Chinese Countryside (SG618-1~4) [11], but with some simplifications, such as the reduced number of constructional columns. It is supposed that the residential building in the countryside would not completely follow the Standard because of the cost. Therefore, the constructional columns were only built at the four corners, but not at all intersection points of walls as stipulated by Chinese Code for Design of Masonry Structures (GB50003-2011)[12]. The plan of the building is 9.9 m by 9.6 m, with the height of 6.6 meter, as shown in Fig.1. Total floor area is 190 m^2. In order to focus on the seismic performance of walls, the staircases were not constructed in the specimen. Each constructional column has a section of 230 x 230 mm with four longitudinal rebars with the diameter of 14mm. The reinforcement hoops were 8mm in diameter, arranged along the height for every 200mm, and densified for every 100mm in the range of 500mm close to both ends. It was the walls beside the constructional columns were first built, and then followed by the concrete cast-in-situ to make the constructional column, as shown in Fig.2 (a). All masonry walls are 240mm thick and built in a clockwise pattern. And the mortar with very low compressive strength (less than 5.0MPa) was adopted to simulate the old masonry buildings. Both head joints and bed joint were filled with mortar to securely connect the bricks. Above the openings of windows or doors, there were lintels with section of 230 x 230mm to sustain the gravity passed from the above stories. The thickness of the slabs was 250mm, which was designed to accommodate the embedded rebars connected to the loading devices. The thick slab guarantees uniform distribution of actuator loads into the structure. The building after construction is shown in Fig.2 (b). Generally, the specimen represents the old masonry residential buildings built thirty years ago in high seismicity regions of Chinese countryside.



a. First story



b. Second story

Fig. 1 – Plan view of the typical masonry building

a. Constructional column and walls

b. South elevation of overall building

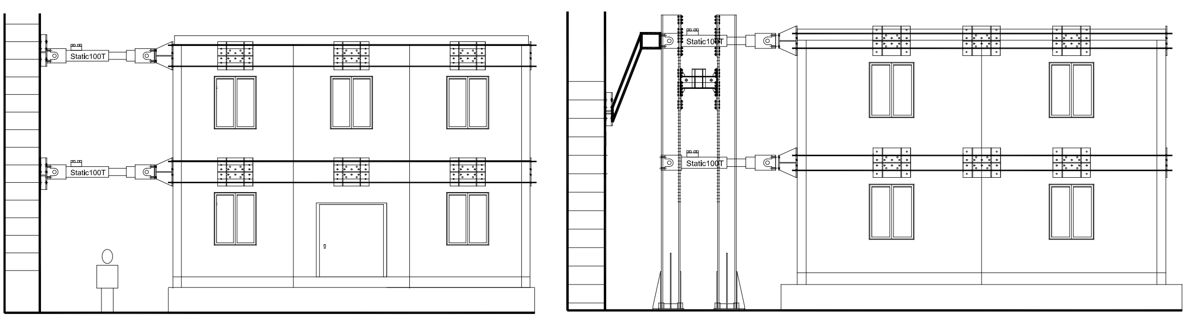
Fig. 2 – Construction of the masonry building

The grade of the clay bricks is MU10, and the mortar is M2.5 with the averaged strength measured from the standard samples of 4.7MPa. The concrete in slabs and foundation beams is C40 with the measured compressive strength of 35.8MPa from cubic samples. The concrete in constructional columns is C20 with the measured compressive strength of 15.9MPa. HRB-335 rebars are used as the longitudinal rebars of constructional columns, with the yielding strength of 402MPa, while the hoops are HPB-300 with the measured yielding strength of 270MPa.

3. First experiment on the old building

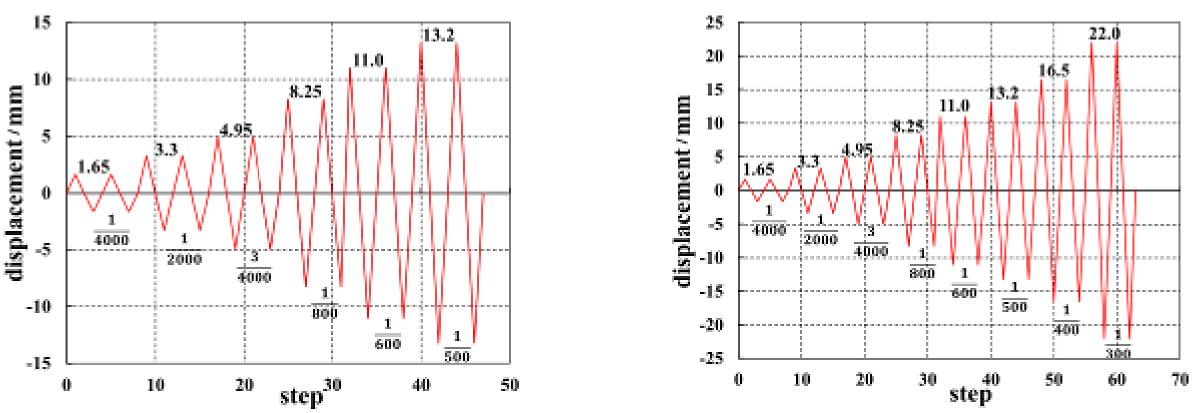
3.1 Loading and measuring scheme

Quasi-static tests are conducted in the two lateral directions separately because of the device limitation. The strong axis contains four pieces of masonry walls and denoted as the east-west direction (EW), while the weak axis has three pieces of walls, and named as the north-south direction (NS). Four 1000kN actuators are used for the cyclic loading. Each slab is connected with two 1000 kN servo-hydraulic actuators. The reaction wall is used in the NS loading, while a frame is designed for the reaction in the EW loading, as shown in Fig.3. The actuators at the roof level are controlled in displacement, following a prescribed cyclic loading pattern, while those at the first floor level are controlled in force, following 1/2 of the reaction force from the actuators at the roof. Two cycles are loaded at each amplitude value, and steadily increased until the bottom shear force decreased below 85% of the peak value. The loading protocols of the two directions are shown in Fig.4 in terms of the roof displacement and roof drift ratio. The loading displacement is controlled by the averaged feedback values of two displacements transducers attached at the roof. There are another two transducers located at the first floor, which are used to calculate the story drifts.



a. Loading in the weak axis b. Loading in the strong axis

Fig. 3 – Loading scheme



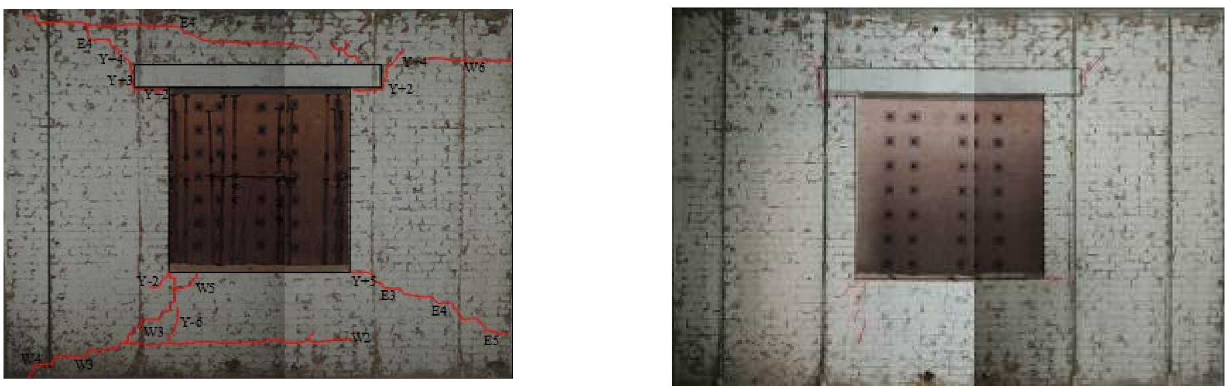
a. in the weak axis b. in the strong axis

Fig. 4 – Loading protocol

3.2 Damages observed from experiment

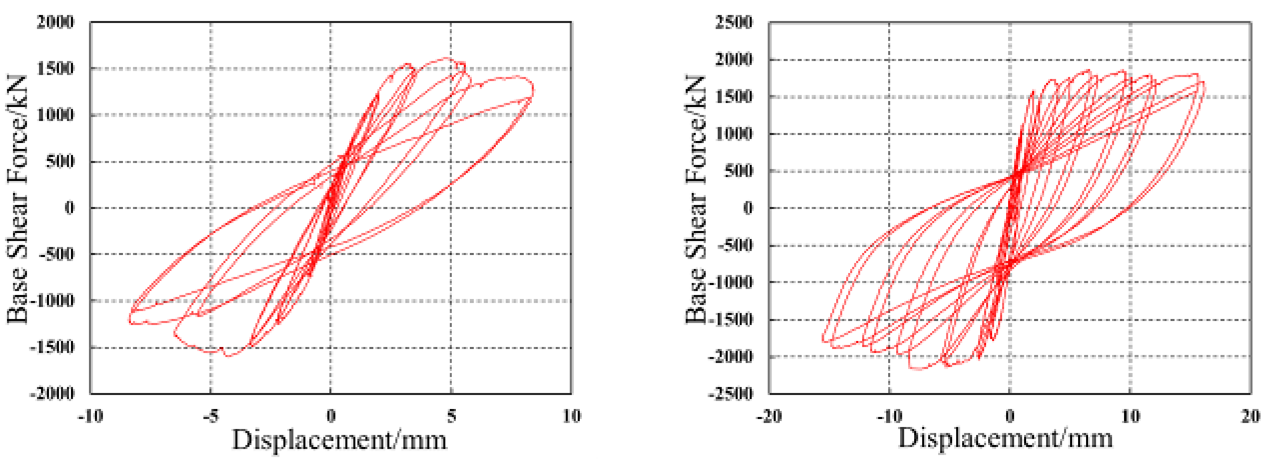
Because of the length limitation, only the damages on the walls in the strong axis are discussed. Generally, the damages were concentrated in the first story. When the roof displacement reached 3.3mm, most walls in the first story cracked. At this moment, the story drift of the first story is 2.08 mm, and the drift ratio is 1/1587. The cracks initiated from the corners of window or door openings, along the bed joints or the head joints. The walls with similar opening ratios (opening area over the wall area) cracked almost simultaneously. With the increase of loading, the cracks developed along 45 degrees and became wider. When the roof displacement reached 13.2mm, X-type cracks were observed in most walls in the first story. Continuously to 22mm, almost all walls were damaged seriously accompanied with brick crush, out-of-plane deformation, and cracks wider than 20mm. Typical damages on the wall 104 and 204 as shadowed in Fig.1 are plotted in Fig.5. During the whole loading process, the damages on the constructional columns were very slight, with the maximum crack width less than 0.2mm.

Fig.6 shows the hysteretic curves of the first story in the weak and strong axes. In the weak direction, maximum loading is 1558.9kN in the positive loading direction, corresponding to the story displacement of 5.5mm, and in the negative loading direction, it is 1457.7kN. In the strong axis, when the story displacement reached 8.8mm, it got to the peak value of 1861.2kN in the positive loading direction and 2165.9kN in the negative loading direction.



a. 104 b. 204

Fig. 5 – Damages of typical walls



a. in the weak axis b. in the strong axis

Fig. 6 – Hysteretic curves in the first story

4. Damage assessment and design for repairing

4.1 Damage assessment using Chinese code

With all of these observations, the Chinese code [1] for field survey was adopted to evaluate the damage state of the masonry building. The damage levels are described in Table 1, and the definition of the structural damage level is given in Table 2 where, the ratio is the number of damaged walls over the total number of the walls. Note that all damage descriptions in both Tables are the residual cracks after one earthquake.

From the observation after the experiment, it is obtained according to the Code method that, the percentage of walls with obvious cracks is 26.5%, those with severe damages is 50%, and those near collapse is 23.5%. Therefore, the overall structure is judged as a severe damaged building, difficult to repair or economically inefficient if repaired.

Table 1 – Damage levels and description of masonry structural members [1]

Damage level	*Negligible*	*Slight*	*Obvious*	*Severe*	*Near collapse*
Description	Cracks observed	Crack width <1.5mm	Crack width≥1.5mm, cracks almost penetrate wall	Crack width≥ 3.0mm, crack penetrates wall	Multiple penetrating cracks, brick crushed and falling down

Table 2 – Damage levels of masonry structure [1]

Damage level	*Negligible*	*Slight*	*Obvious*	*Severe*	*Near collapse*
Operational	<10%				
Slight damage		<10%			
Moderate damage		>50%	10%~50%	<10%	
Severe damage			>50%	10%~50%	Local collapse
Collapse				>50%	Collapse

4.2 Design for repairing

In order to examine the economic efficacy and the mechanical efficiency of repairing techniques, the damaged building was decided to be repaired regardless of the conclusion obtained from the reconnaissance based on the Code. The repairing targets are: (1) repaired building shall perform much better than the original building by at least one damage level under the same deformation; and (2) repairing cost shall be less than reconstruction cost.

Considering the cost and material availability, the meshed reinforcement mortar was selected to repair the building, combined with the grout to fill the cracks and the additional constructional columns at the intersections of any two or more pieces of walls. HPB-300 rebars with the diameter of 6mm were used to make the steel mesh with spaces of 300mm in both horizontal and vertical directions. Two pieces of meshes were placed on the both surfaces of a wall, and hooked together by steel rebars through the wall. The M10 mortar was selected for the retrofitting with the thickness of 35mm considering the covering clearance of steel meshes.

4.3 Repairing process and cost

The repairing process includes repositioning of damaged walls with out-of-plane deformation, replacement of lintels falling during previous tests, filling the cracks wider than 1.0mm, clearing both surfaces to be covered by reinforced mortar, meshing and mortar plastering, and casting concrete to make additional constructional columns. Parts of the working procedures are shown in Fig.7, and the completely repaired building is shown in Fig.8. The repairing process has lasted for 23 days, while the build of the original building took 39 days. The cost of repairing is about 100,000RMB, while the construction of the original building spent 200,000RMB. If it has to be demolished and reconstruct, the demolishing would take another 10 days and cost another 30,000RMB. Therefore, the selected repairing technique saved more than half cost and working time than reconstruction.

a. repositioning b. Meshing c. Plastering d. polishing

Fig. 7 – Primary reparing processes

Fig. 8 – Repaired monsry building

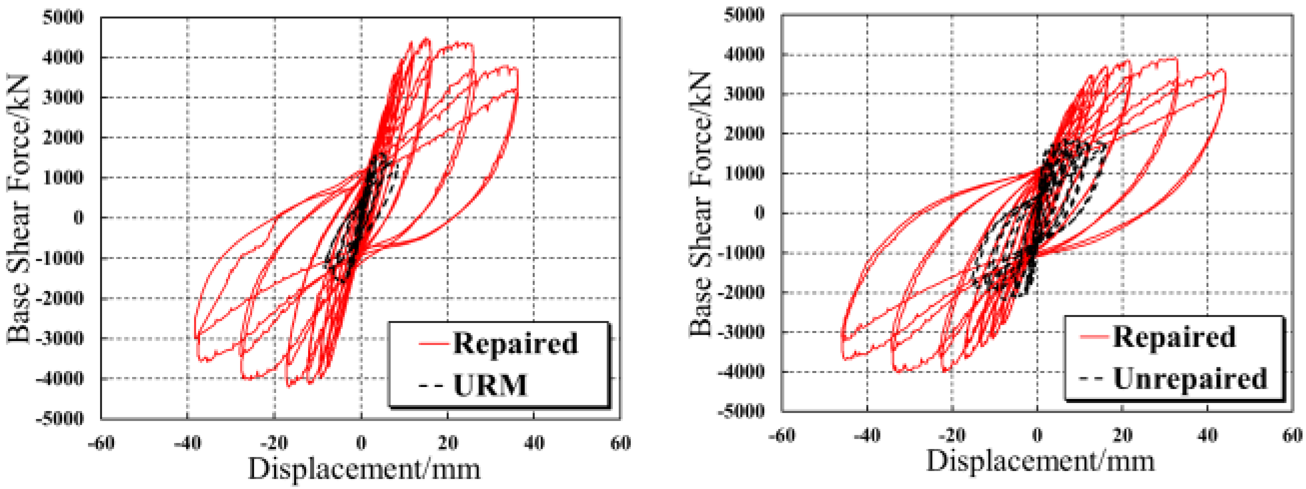
5. Experiment on the repaired building

The loading protocol of the repaired building is identical as the original building, but appended by two amplitudes of 33mm and 44 mm to achieve the expected failure mode. Similarly, the damages were concentrated in the first story, such as mortar spalling, rebar buckling in the constructional column, brick crush, and so on. However, the damage in the second story was relatively slight. No falling of mortar surface was observed. Cracks initiated from the opening corners. When being loaded to 11mm, the largest width of the crack was 3mm. The mortar started to spall when loaded to 16.5mm. The width expanded to 8mm at the amplitude of 33mm accompanied with brick crush. The deformation capacity of the repaired building is as twice as the original one. Damages of typical walls are shown in Fig.9 which can be compared with Fig.5 without repairing.

Compared in Fig.10 are the hysteretic curves in both lateral directions. The bearing capacity of the repaired building is as twice as the original one. From Table 3 where the peak loads are compared, the peak force of the retrofitted building is 2.84 times that of URM in the weak direction, and 1.85 times in the strong axis. The retrofitting targets are achieved. Note from Table 3 that the strength of the strong axis is smaller than that of the weak axis. The reason is that the two directions were loaded separately. The load was first conducted in the weak direction to a large deformation to 33mm at the roof. At this moment, the walls in both directions were damaged seriously because of the strong coupling or flange effect of the walls in the strong axis. Therefore, before the test in the strong axis, there have existed extensive damages in the walls in this direction.

a. 104 b. 204

Fig. 9 – Damaged pattern of repaired masonry building



a. in the weak axis b. in the strong axis

Fig. 10– Hysteretic curves in the first story compared with unreinforced masonry building (URM)

Table 3 – Comparison of peak loads (Unit: kN)

Structure type	URM	Repaired masonry
Weak axis	1558.96	4431.71
Strong axis	2159.87	3985.3

6. Summary and conclusions

In this research, a typical masonry structure in Chinese rural area was experimentally studied to examine its recoverability. Comparing the test results of the original structure and the repaired structure, the following conclusions might be drawn:

(1) Reinforced mortar plaster method is an effective rehabilitation scheme to the earthquake damaged masonry structure in rural area. Because of the conventional construction materials and the simple construction process, it is highly feasible to be applied in the rural area of China. On the aspect of the repair effect, it can meet the demands such as: the strength increased by 2 times, time and cost reduced to half of the reconstruction activity.

(2) Repaired building ability to slow the cracking process is improved, and the degree of damage is much slighter. Furthermore, the reparation also increases the structure ductility by 200%.

(3) Chinese code for the determination of structure damage degree is relatively conservative, buildings that were estimated as severe damaged still worth a reparation.

7. Acknowledgements

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