Survey on Seismic Damage Mechanism of Multi-story Masonry Structure with First Soft Floor

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Abstract. The multi-story masonry structure with first soft floor (MSMSFSS) is a special type of masonry structure, which is very popular in many towns and rural areas in the south of China. Large number of the MSMSFSSs locate in areas with high seismic intensity. In Wenchuan Earthquake, great casualties and huge economic losses were caused by the collapse and destruction of MSMSFSSs. It is an urgent task to find out the seismic damage mechanism of this structure, which is the foundation to develop seismic design theory and seismic reinforcement methods suitable for MSMSFSS. In this paper, we reviewed the main advances made in the research on seismic damage mechanism of MSMSFSS, including study results by field investigation, experiment and numerical analysis. Based on the discussion of some problems unsolved or to be improved, we proposed several suggestions to enhance the research of MSMSFSS in the future. The influence of the number of upper stories, the number of longitudinal walls, the location of openings, and the height-width ratio of inter-window walls should be taken into account. Comparative experimental study between MSMSFSS and ordinary multi-story masonry structure should be carried out. Quantitative research should be enhanced and simulation analysis methods should be widely utilized.

1. Introduction
The multi-story masonry structure with first soft floor [1] (MSMSFSS) emerged in many towns and rural areas of China during last 30 years. To use the first floor as shops or garages, some inner walls in the first floor were removed and the outer walls facing-street were replaced by RC plane frames. As shown in figure 1, this type of structure is exactly a combination structure, although it looks like an ordinary masonry structure. For this reason, MSMSFSS was also called as masonry structure with partial RC frame and partial masonry in bottom [2].

This kind of structure provides great convenience for families or individual merchants who prefer to work and live at the same place. It satisfies their multi-needs for residence, business, parking, social interaction and entertainment. Based on this background, numerous MSMSFSS buildings were built in towns and small cities of China, including earthquake prone areas. According to statistics, the stock of such houses has reached 2 million [3].

However, from the viewpoint of an anti-seismic engineer, MSMSFSS is a special masonry structure with some defects in the nature. As a combination structure, the RC frames in MSMSFSS can hardly deform synchronously with the rest masonry part under cyclic lateral force. Furthermore, the soft first floor is easy to collapse when it meets strong ground motion. Figure 2 shows the typical seismic damage mode for MSMSFSS buildings.
According to the field investigation results on Wenchuan Great Earthquake, multi-story masonry structure with first soft story buildings sustained serious damage in the whole disaster area [4]. In old Beichuan County, the collapsing ratio of MSMSFSS reached 85%, which was nearly twice of ordinary multi-story masonry structure (48%) [5]. Collapse and destruction of MSMSFSSs caused a large number of casualties and huge economic losses [6]. This indicates that the seismic capacity, especially the collapse resistance, of most MSMSFSSs is obviously insufficient.

Surprisingly, there were still some MSMSFSS buildings who kept standing after the great event, even in the meizoseismal areas. As shown in Figure 3, a MSMSFSS building of Ruyi Garden Residential Area in Jiangyou district with seismic fortification according to intensity IX kept intact after the Wenchuan Ms8.0 Earthquake [7]. As shown in Figure 4, a MSMSFSS apartment building (left building in the picture) in old Beichuan County with seismic fortification according to intensity VII suffered only medium damage [8].

These phenomena puzzled scholars and engineers, attracting them to find out the truth and the reason. It is necessary to investigate the seismic damage mechanism of multi-story masonry structure with first soft floor deeply and propose the anti-seismic design methods for them and the retrofitting design methods for the existing buildings.

In this paper, we reviewed the main advances in the research on seismic damage mechanism of MSMSFSS, including study results by field investigation, experiment and numerical analysis. We discussed some problems should be solved, then proposed several suggestions in the future study.
2. Main advances
Before Wenchuan Earthquake, there was almost no research on the seismic damage mechanism of MSMSFSS. After the Wenchuan earthquake, some scholars began to pay attention to the anti-seismic problems of such structures, and significant advances were made in the study of their seismic performance, including their failure mechanism.

2.1. Theoretical analysis based on field investigation
After Wenchuan earthquake, a group of scholars summarized and analyzed seismic damage phenomena of multi-story masonry structure with first soft floor based on the results from field investigation [1-11]. Generally speaking, the typical damage characteristics of MSMSFSS are as follows:

1) Longitudinal collapse usually happens in the first floor, which is the typical damage mode in this structure. 2) Inner longitudinal walls are usually damaged more heavily than outer longitudinal walls, and their failure patterns are affected by the location of openings. 3) If the height-width ratio of the wall between windows is high, cracks tend to happen in the spandrel panels. Otherwise, cracks usually generate in the walls under the windows. 4) MSMSFSSs with wing columns or/and wing walls are not easy to collapse. 5) MSMSFSSs with fewer stories are not easy to collapse. 6) MSMSFSSs with multi-longitudinal walls are not easy to collapse.

From different angles, scholars tried to explain the damage phenomena mentioned above and proposed some suggestions to enhance the anti-seismic ability of MSMSFSS. For example, Guo Xun pointed out that the large stiffness difference in longitudinal walls is the fundamental reason for the longitudinal collapse in the bottom floor [4]. Li Bixiong suggested to control the number of stories strictly, and design the masonry openings based on quantitative regulation [9]. Li Yingmin suggested strengthening the research of wall crack prevention [10]. Zhou Yun proposed that the failure mode in inter-window walls should be avoided by controlling the height-width ratio [11].

The work above confirmed the particularity of the multi-story masonry structure with first soft floor, and put forward some valuable scientific problems. At the same time, preliminary solutions to these problems were given, which laid a foundation for further in-depth study.

2.2. Experimental study
To deeply investigate the damage mechanism and seismic reinforcement of multi-story masonry structure with first soft floor, the research team led by Guo Xun carried out a series of experimental studies.

Liu Hongbiao reproduced the collapse process of two MSMSFSS buildings and analyzed their collapse mechanism by comparing the shaking table tests of two one story 1:5 scaled MSMSFSS models [12]. The results showed that the main reason for the failure or collapse of the bottom layer of this kind of structure is the great difference in the lateral stiffness of longitudinal walls. Seismic response of each wall was quite different from others with different stiffness, so that the walls were damaged one by one during an earthquake, leading to the final collapse of the building. Adding wing walls and establishing structural columns on both sides of the entrance are important measures to increase lateral stiffness of the weak walls. The test results suggested that the longitudinal walls in MSMSFSS should be designed with almost equal lateral stiffness, and explained why the MSMSFSS apartment building in old Beichuan County did not collapse in the Wenchuan Earthquake.

Liang Yongduo studied the failure mechanism of common MSMSFSS, MSMSFSS with wing columns and wing walls, MSMSFSS reinforced by rectangle steel pipes and profiled bars through a comparative seismic simulation experiment of three 1:5 scaled models [3]. Based on the test results, the damage mode of each longitudinal wall and the invalidate orders were obtained; the key function of winged walls and winged columns in earthquake resistance was validated; the feasibility and practicality of the reinforcement method through rectangle steel pipe was proved. Finally, the reinforcement concept of “balancing stiffness and increasing ductility” was put forward.
Zhou Yang furtherly investigated the influence of the stiffness difference in longitudinal walls on the collapse mode of MSMSFSS buildings through pseudo-static tests on longitudinal walls and shaking table tests of three 1:5 scaled models [1, 13-14]. Through the pseudo-static tests, the lateral stiffness of typical longitudinal walls were measured quantitatively. The test results verified that the stiffness values in longitudinal walls of common MSMSFSS were quite different and the wall with larger stiffness bore more lateral force. Model shaking table test illustrated that three longitudinal walls did not fail simultaneously during the collapse process of first floor in common MSMSFSS buildings. The internal longitudinal wall which had the maximum stiffness failed first and lost carrying capacity. Then the seismic and gravity loads were transferred to the two relatively weak longitudinal walls. Because their carrying capacity was obviously insufficient, the first floor collapsed at last. This work verified the inference that the large stiffness difference in longitudinal walls is the fundamental reason for the longitudinal collapse in first floor. The mechanism and key influencing factors of collapse mode of longitudinal wall were clearly understood. The necessity and feasibility of seismic and reinforcement design of this kind of structure by controlling the stiffness difference of longitudinal walls were confirmed.

Important progress has been made in the studies above. The fundamental cause of the longitudinal collapse mode of multi-story masonry structures with first soft floor has been identified, and the key influencing factors to the stiffness of longitudinal walls have been found. The principle for seismic design and reinforcement of such structures has been pointed out.

2.3. Numerical analysis
Zhan Xiaoping studied the seismic performance of MSMSFSS using numerical analysis method by comparing with ordinary multi-story masonry structure and multi-story masonry structure with bottom RC frame [2]. In this work, the elastic and elastic-plastic responses of the three kinds of structures were obtained base on finite element method. The results showed that the displacement, strain and energy dissipation characteristics of MSMSFSS are close to those of ordinary multi-story masonry structure. When meeting ground motions in seismic intensity VI or VII, this kind of structure will not collapse. The numerical results indicated that the plastic strain occurred in the inner longitudinal walls was larger than that in outer longitudinal walls, which verified that the distribution of seismic load is decided by stiffness. Limited by the applicability of FEM, the collapse responses of MSMSFSS were not obtained in this study.

Liu Hongbiao used the finite element method and Abaqus software to analyze the elastic-plastic seismic response of the apartment building of Beichuan Telecom Bureau under the action of Wolong wave [15]. In this work, frequency domain analysis was used to determine the damage status of the structure, and the failure process of the structure was not visually presented.

3. Problems to be solved
Although remarkable advances have been made in the research work for seismic damage mechanism of MSMSFSS, there are still some problems to be solved in the near future.

1) Research topics should be supplemented.

In the study of collapse mechanism, the influence of the number of upper stories and the number of longitudinal walls has not been considered. The actual earthquake damage showed that these two factors are also very important. Controlling the number of stories and increasing the number of longitudinal walls are also effective measures to control the collapse of such structures.

In the aspect of wall cracking mechanism, the generation process of different failure modes and their key influencing factors have not been studied in depth; the influence of opening location and the influence of height-width ratio of inter-window walls have not been taken into account. For a masonry structure, wall failure is the leading step of collapse. If the wall cracking can be controlled effectively, the building is difficult to collapse.

In the evaluation of aseismic capacity, the comparative experimental study between MSMSFSS and multi-story masonry structure has not been carried out. From a practical viewpoint, it is a feasible
strategy to measure the seismic capacity of multi-story masonry structures with first soft floor by taking the seismic capacity of ordinary multi-story masonry structures as a yardstick.

2) Quantitative research should be enhanced.

The existing research results mainly focused on qualitative studies, and the quantitative output was rare. This caused great difficulties for its practical application. For example, multi-story masonry structures with first soft floor are sensitive to the stiffness difference of longitudinal walls, and should be designed according to the principle of equal stiffness. In practice, this is difficult to be performed strictly. Therefore, the stiffness difference needs to be controlled within a reasonable range. This range should be written in the seismic code, to guide designers in their practical work. So what is the red line? Only quantitative research can give the definite answer. For another example, it has been proved that adding wing walls and wing columns in the front frame can significantly improve the seismic performance of multi-story masonry structures with first soft floor, but how should we set them in the practical engineering? What specific requirements should they meet at least in position, size, material and structure? If there is no specific provision in the seismic code, problems are also likely to arise in the implementation.

It can be seen that qualitative research results are not enough for this study, and more comprehensive quantitative analysis is needed urgently. Only in this way can we provide more effective technical guidance for specific seismic design of MSMSFSS.

3) More research means should be utilized.

The existing research work mainly focused on theoretical analysis and experimental study based on earthquake damage phenomena. The research based on numerical analysis was relatively rare and insufficient, which failed to give full play to the advantages of numerical simulation.

Theoretical analysis and experimental research have their advantages which are hard to be replaced, but they also have their limitations. For example, to study the influence of stiffness difference on structural failure mode, it is impractical to test dozens or dozens of models in turn on the shaking table. For another example, to simulate the collapse process of the same structure under different seismic waves, shaking table tests need multiple models, which will cost a lot of money and time. Fortunately, these problems can be easily solved by numerical simulation. Therefore, in order to promote the research on seismic damage mechanism of MSMSFSS from qualitative to quantitative level, it is necessary to fully utilize the power of numerical analysis methods and simulation analysis tools.

4. Conclusion

In summary, the multi-story masonry structure with first soft floor is a special type of masonry structure emerged for economic reason. It has particularities in structural composition and failure mode, which is the fundamental reason for its distinctive damage phenomena. To establish seismic design theory and seismic reinforcement methods suitable for MSMSFSS, it is an urgent task to study the typical failure modes and seismic damage mechanisms of MSMSFSS deeply.

At present, although some significant advances has been made in the existing research, there are still some deficiencies in depth and breadth. The knowledge acquired is mainly at qualitative level. Systematic theory for the seismic design and reinforcement of this kind of structure has not been built.

Therefore, the study of seismic damage mechanism of multi-story masonry structure with first soft floor needs to be further developed. The influence of the number of upper stories, the number of longitudinal walls, the location of openings, and the height-width ratio of inter-window walls should be taken into account. Comparative experimental study between MSMSFSS and ordinary multi-story masonry structure should be carried out. Quantitative research should be enhanced and simulation analysis methods should be widely utilized.

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References
[1] Zhou Y., Guo X., Sun L. (2014) Experimental study on seismic performance and collapse mechanism of multi-story masonry structure with first soft floor. Journal of Earthquake Engineering and Engineering Vibration, 34 (5): 118-128.
[2] Zhan X. (2011) Analysis on seismic performance of masonry structure with partial RC frame and partial masonry in bottom. Master's Thesis, Chongqing University, Chongqing.
[3] Liang Y. (2013) Damage mechanism and retrofitting method of multi-story masonry structure with first story used as shops against earthquake. Ph.D. Thesis, Institute of Engineering Mechanics, China Earthquake Administration, Harbin.
[4] Guo X. (2009) Characteristics and mechanism analysis of the great Wenchuan Earthquake. Journal of Earthquake Engineering and Engineering Vibration, 29 (6): 74-87.
[5] Guo X. (2010) New understanding on earthquake damage and collapse resistance from Wenchuan Earthquake. Journal of Civil Architecture and Environmental Engineering, 32 (s 2): 28-29.
[6] Chen Z., Qian M. (2008) Report on building damage survey in the Wenchuan Earthquake and post-disaster reconstruction analysis. China Construction Industry Press, Beijing.
[7] Yuan Y., Sun B. 2008 General introduction of engineering damage of Wenchuan Ms 8.0 Earthquake. Journal of Earthquake Engineering and Engineering Vibration, 28(s).
[8] Liu H. (2012) Collapse mechanism of multi-story masonry structure with first story used as shops. Ph.D. Thesis, Institute of Engineering Mechanics, China Earthquake Administration, Harbin.
[9] Li B., Xie P., Wang Z., etc. (2009) Wenchuan earthquake field reconnaissance and analysis on multi-story masonry structure buildings. Journal of Sichuan University (Engineering Science Edition), 41 (4): 19-25.
[10] Li Y., Han J., Liu L. (2009) Investigation and analysis of masonry building damage caused by the 5·12 Wenchuan earthquake, Sichuan Province. Journal of Xi'an University of Architectural Science and Technology (Natural Science Edition), 41 (5): 606-611.
[11] Zhou Y., Zou Z., Zhang C., etc. (2009) Study on the damages to masonry-building in Wenchuan Earthquake as well as the corresponding aseismic approach and methods. Journal of Disaster Prevention and Mitigation Engineering, 29(1):109-113.
[12] Liu H., Guo X. (2012) Study on shaking table collapse tests of typical masonry structure in meizoseismal area. Journal of Civil Engineering, 45 (12): 18-28.
[13] Zhou Y. (2014) Collapse mechanism and seismic retrofitting design of multi-story masonry structure with first weak story. Ph.D. Thesis, Institute of Engineering Mechanics, China Earthquake Administration, Harbin.
[14] Zhou Y., Guo X., Sun L., etc. (2014) Experimental investigation on seismic performance of confined masonry wall with reinforced tied columns. Journal of Earthquake Engineering and Engineering Vibration, 34(6):160-168.
[15] Liu H., Liu X., Zhang Q., etc. (2014) Calculation method of elasto-plastic seismic response of multi-story masonry structure with first floor used as shops. Building Structure, 44 (15): 83-87.