The Research on Storey Rigidity Ratio Control of Masonry Structure with Framework at the Bottom

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SUMMARY:
Masonry structures with concrete framework at the bottom are widely used but a large number were heavily damaged in earthquake. The difference of seismic performance between brittle part of masonry and ductile part of framework is the main reason of poor seismic performance and different failure modes of overall structure. Thus it is significant that controlling the value of rigidity ratio of the adjacent masonry storey, as transitional storey, and the bottom of framework storey in order to prevent the structure from causing larger inter layer displacement, or even collapsing. This paper establishes finite element model to analyze by using pushover analysis method. The failure modes of analysis models with different storey rigidity ratio are compared, which show a great different seismic performance especially when structures come into inelastic state under strong earthquake. Finally the reasonable value of storey rigidity ratio is proposed to help achieve good seismic performance.

Keywords: seismic performance, storey rigidity ratio, pushover analysis, masonry structure

1. INSTRUCTIONS

A large number of masonry structures with concrete framework at the bottom were heavily damaged in Wenchuan earthquake occurred in 2008 in Sichuan province of China, repeating again similar earthquake damage happened during the past in the whole world. As one kind of practical structural forms, they are widely used in the vast number of underdeveloped regions in China, even in the worldwide area. Generally, in this kind of structures, the bottom storey is made of reinforced concrete frame structure with a certain amount of shear walls, which forms a large hall to meet the commercial use requirements, and the upper storeys are made of masonry structures which are benefit to reducing the economic costs. For the whole structures, the different combination of masonry structure and reinforce concrete frame leads to different seismic performance and failure modes.

Zheng et al. (1998) finished the shaking table test on 1/6 scale models of five-storey masonry buildings with framework at the bottom. The result suggests that the concrete frame storey is the weak layer of the structure, and especially the column foot is easy to fall into destruction. This kind of failure mode is better because of having more energy consumption under earthquake. Zheng et al. (1999) did the further study on the theoretical calculation and the seismic design method of structures and proposed that in the zones with seismic design intensity of 7 and 8 degree, the reasonable storey rigidity ratio of second storey to first storey ranges between 1.2~2.0 and 1.2~1.6. Chinese code for seismic design of buildings (GB5011-2010) provides that the in the zones with seismic design intensity of 6, 7 and 8 degree, the storey rigidity ratio of second masonry-storey to first reinforced concrete-storey should not be greater than 2.5, 2.5 and 2.0, and should not be less than 1.0. The upper limit of storey rigidity ratio aims to prevent the lower framework from being too soft, and the lower limit aims to prevent the upper masonry storey from becoming weak layer.

According to reports on the damages of masonry structures with framework at the bottom in new county seat in Beichuan in Wenchuan earthquake (Jia et al. 2008), 19.1 percent of buildings were intact or minor damaged, 61.9 percent of buildings were severely damaged with bottom frame having large lateral displacement or even collapsing, and 19.0 percent of buildings were heavily damaged with masonry layers destroyed. Thus, the actual earthquake damage occurred as the slope or collapse of the bottom frame. This failure mode neither achieves the structural design concept of strong column-weak beam, nor realizes the seismic design principles of ensuring buildings not falling under strong earthquake.

This paper establishes finite element model to analyze by using pushover analysis method, which is easy to get the performance of structures in the whole process of imposing static loads simulating earthquake. The failure modes of analysis models with different storey rigidity ratio are compared. The result shows a great difference especially when structures come into inelastic state. Finally the reasonable value of storey rigidity ratio is proposed.

2. ELEMENT MODEL AND MATERIAL MODEL

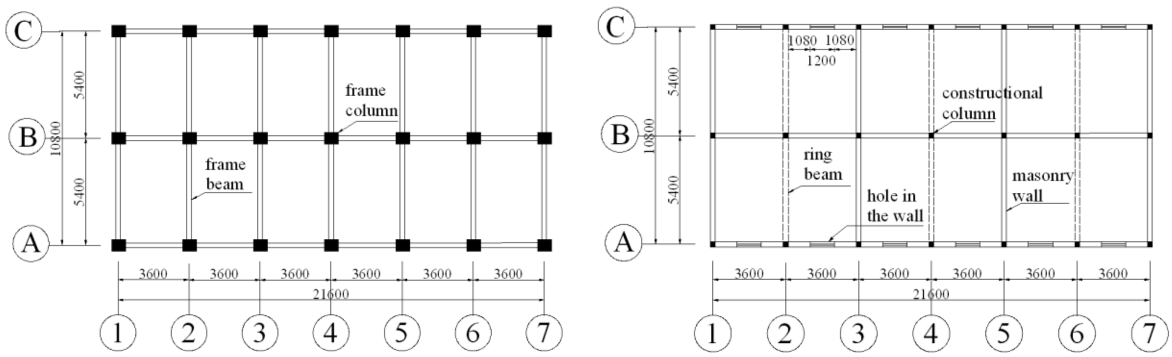
Masonry structures with framework at the bottom have both reinforced concrete structure and masonry structure, which need to be simulated by different element models and material models. In this paper, fibre model is used to simulate the reinforced concrete structure, which can consider the coupling effect of axial force and bending moment during the loading process. Shell model is used to simulate the masonry wall, which can reflect the cracking and force deformation characteristics of the wall.

Tsinghua University developed THUFIBER (Lu et al. 2009), reinforced concrete fiber model program, based on the finite element analysis software program MSC.MARC. This paper uses this program to analysis models. Uniaxial stress-strain curve of concrete used in the program is divided into two parts. Ascending part of curve is parabola and descending part of curve is straight line, without considering the concrete tensile strength. Reinforced model is ideal elastic-plastic model. Reinforced quit working when the tensile strain of reinforced reaches fracture strain. Liu (2005) summarizes the uniaxial compression stress-strain curves of masonry proposed by some scholars and makes certain improvement. Similar to concrete, it is also divided into two parts. Ascending part of curve is parabola and descending part of curve is straight line, without considering the masonry tensile strength. Masonry can crack when tensile strength is achieved. The material models mentioned above are used in the model analysis.

3. STRUCTURE MODEL AND ANALYSIS METHOD

To satisfy the objective of this study, a small but representative model of masonry building with framework at the bottom, named Standard Model, is established by the structural design software PKPM, which is developed by China Academy of Building Research.

The plane of the model is shown as Fig. 3.1. The ground floor is 3.6m high, and other three floors are 3.0m high. Roof and floor panels are 100 mm-thick slab. The size of section of frame columns and frame beams are 700mm×600mm and 240mm×600mm, the size of section of ring beams and constructional columns are both 240mm×240mm, and the masonry wall is 240mm thick. The concrete is C30, the masonry is Mu10 and the mortar is M10. Floor dead load and roof dead load are 6.0 kN/m^2, while live load is 2.0 kN/m^2. The seismic fortification intensity is 7 degree, the type of the site soil is Ⅱ, and the design seismic group is the first.



(a) Frame layer (b) Masonry layer

Figure 3.1. Plane of the structure

In standard model established above, the storey rigidity ratio of adjacent masonry storey and framework storey is 1.8 provided by PKPM, or could be get by the calculation of the storey shear force divided by storey displacement. By adjusting the height of columns of framework storey, the storey rigidity ratio can be changed, as shown in table 3.1.

Table 3.1. Models of different storey rigidity ratio

Number of model	1	2	3 (Standard Model)	4	6
Height of columns of framework storey (m)	2.4	3.0	3.6	4.2	4.8
Storey rigidity ratio	0.7	1.2	1.8	2.4	3.3

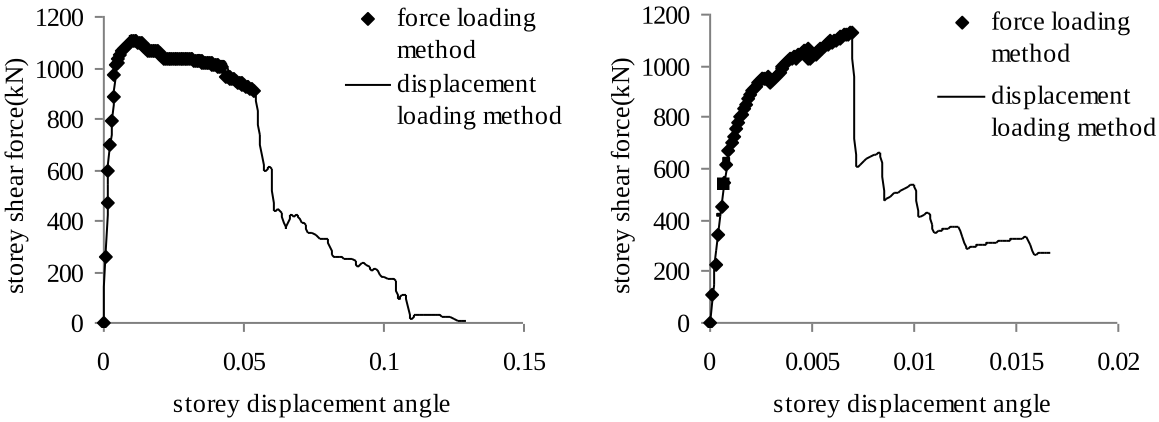
This paper uses pushover analysis method to study seismic performance of the structure. This method has been included in seismic codes in some countries, such as ATC-40, FEMA-273, Japan and other country norms. It is gradually used in many structural problems (Faella, 1996) (Requena, 2000). Pushover is one efficient method to study the whole process of the seismic behaviour of the structure and can get the failure mode at final. It is benefit to find the weak parts of the structure and optimize the design. Plane structure at axis 4 in the model is taken out for next pushover analysis.

4. ANALYSIS RESULTS

4.1. Force and Deformation Characteristics of Storeys

As one type of mixed structure, the seismic performance of masonry structure with framework at the bottom depends on the characteristics of different structure layers. Masonry storey and framework storey have different force characteristics and deformation capacity due to different material properties of masonry and reinforce concrete. In order to better study the seismic behaviour of the overall structure, masonry storey and framework storey of Standard Model are separated to be considered and the mechanical characteristics of the local structures are analysed. For framework storey, add horizontal load at the top of the framework and take into account the effect of gravity load of framework storey and the upper three masonry storeys. For adjacent masonry storey, constrain the horizontal displacement of the underlying framework storey, add horizontal load at the top of the adjacent masonry story, and take into account the effect of gravity load of the upper three masonry storeys. Concentrated force loading method and displacement loading method are used to pushover analysis and be contrasted.

As shown in Fig. 4.1.(a), the framework storey has much better characteristic of ductility after the storey shear force reaches ultimate bearing capacity. When the storey displacement angle increases to about 1/20, the lateral displacement of the structure is too large due to plastic development of column endpoint of the framework, and the lateral force resisting capacity of the framework storey is significantly degraded, which leads to the entire structure falling at final. However, the adjacent masonry storey shows obvious brittleness in the horizontal lateral force in Fig. 4.1.(b). With the increase of lateral load, masonry storey gradually cracks because of the low strength of the masonry itself. The development of cracking continuously reduces the lateral stiffness of the structure. When the masonry storey shear force reaches ultimate bearing capacity, it shows severe brittle failure and the load capacity of the storey is rapidly reduced by about 50%. The adjacent masonry storey is destructed with the lateral stiffness apparently weakened and the lateral displacement significantly increasing. In addition, due to local brittle destruction of the masonry leading to not convergence of numerical calculation, concentrated force loading method can not reflect the force and deformation of the structure coming into damaging state, compared to displacement loading method, which shows more advantage.



(a) Framework storey (b) Masonry storey

Figure 4.1. Shear force-storey displacement angle curves of different storeys of the standard model

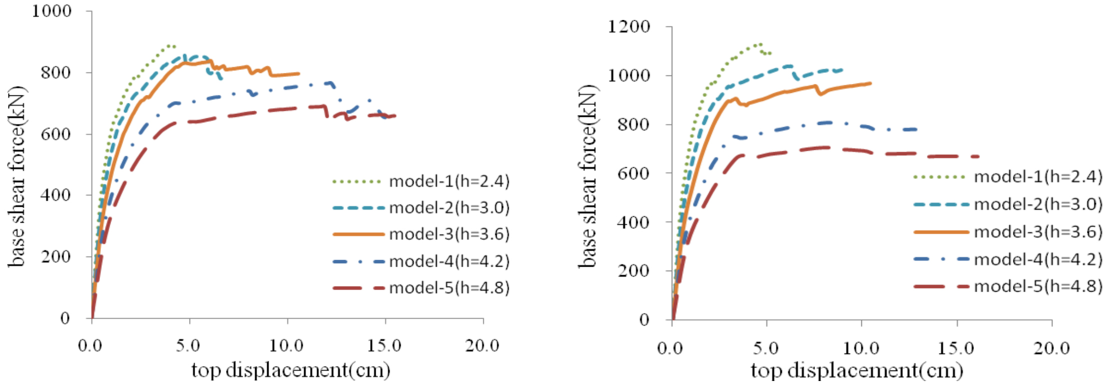
Further comparison can be seen from Table 4.1. The maximum load capacity of framework storey and adjacent masonry storey are close. But they have significantly different seismic performance. Masonry storey is easy to cracking, and thus the structure is earlier into the yield state. The framework storey has a relatively small lateral stiffness but a better deformation capacity, while the masonry storey has a relatively large lateral stiffness but a poor deformation capacity. For example, when the storey displacement angle reaches 0.007, the masonry storey comes into destruction state, but the framework storey still has a better ductility with maximum storey displacement angle of 0.054.

Table 4.1. Force and deformation characteristics of storeys

Structural state	Underlying framework storey		Adjacent masonry storey	
	Storey shear force (kN)	Storey displacement angle	Stoey shear force (kN)	Storey displacement angle
Yield state	1011.4	0.004	666.3	0.001
Ultimate state	1106.2	0.011	1130.8	0.007
Destruction state	908.0	0.054	—	—

4.2. Effects of Storey Rigid Ratio

Then the effects of changing storey rigid ratio are mainly studied. In addition, different loading methods need to be considered in the pushover analysis. For masonry structure with framework at the bottom, both inverted triangle loading method and uniform loading method are used to compare.



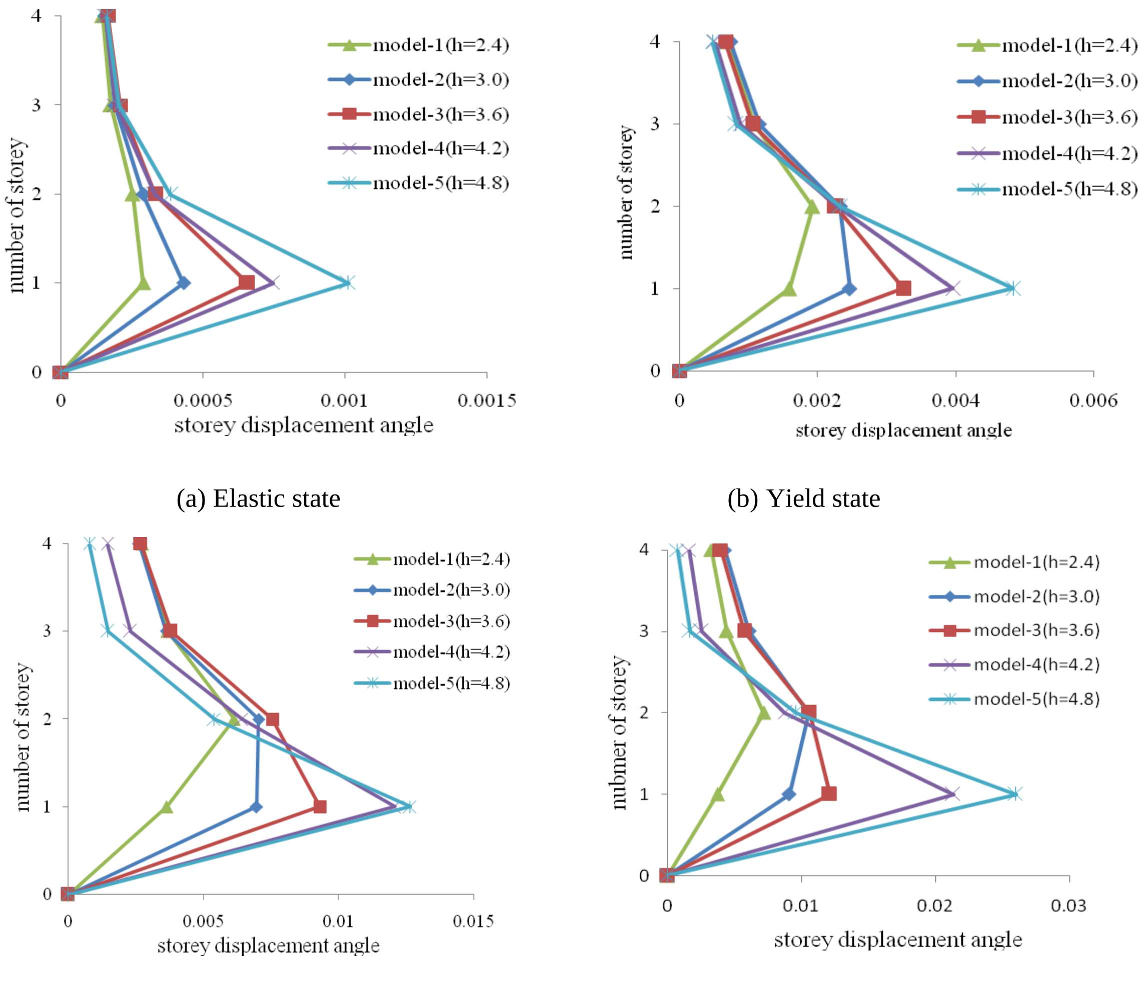
(a) Inverted triangle load (b) Uniform load

Figure 4.2. Base shear fore-top displacement curves of the models under different loading method

Fig. 4.2. shows base shear force-top displacement curves of the structural models. With the increase of storey rigidity ratio of adjacent masonry storey and framework storey, the underlying framework changes from rigidity to flexible. When the stiffness of the bottom framework layer is too large, the structure has a large lateral force bearing capacity, but a poor ductility. The performance of masonry storey is the key to the seismic behaviour of the entire structure. At this time, the curve is similar to the shape of storey shear force-displacement curve of masonry storey. When the stiffness of the bottom framework layer is too small, the structure has a small lateral force bearing capacity and a large lateral displacement. The performance of framework storey is the key to the seismic behaviour of the entire structure. At this time, the curve is similar to the shape of storey shear force-displacement curve of framework storey. For the models having moderate storey rigidity ratio, structures have a high lateral load bearing capacity and maintain a certain degree of ductility, which show a relatively good seismic effects. Considering different loading methods, the results show that the structures have lower lateral load bearing capacity under the load of inverted triangle.

Fig 4.3. shows number of storeys-storey displacement angle curves of the structural models in different stages under uniform load, for example. When the stiffness of the bottom framework layer is too large, the masonry storey force is concentrated and brittle failure is early to occur. The storey displacement angle of adjacent masonry storey is greater than that of framework storey. The ductility of framework dose not play a good role under the earthquake. Thus the design of framework is relatively conservative and a kind of waste. When the stiffness of the bottom framework layer is too smaller, the storey displacement angle of adjacent masonry storey is smaller than that of framework storey. Upper masonry storeys keep in good working condition, while the lateral displacement of framework storey is so large under lower earthquake which may cause the structure to collapse. This is not benefit to realize the seismic design principles of ensuring buildings not falling under earthquake.

Therefore, under uniform load, when the storey rigidity ratio of adjacent masonry storey and framework storey is controlled in the range of 1.2~2.4, the lateral load bearing capacity of masonry storey and the ductility of framework storey can be fully utilized. The entire structures show great seismic performance. For the models established above, inverted triangle loading method can get the same range of storey rigidity ratio.



(a) Elastic state (b) Yield state

(c) Ultimate state (d) Destruction state

Figure 4.3. Storey displacement angle of the models in different states under uniform load

5. CONCLUSIONS

Pushover analysis method is one more convenient access to get the elastic-plastic behaviour of masonry structure with framework at the bottom under horizontal seismic input. Finite element models of structure are established, and the difference of storey displacement and storey shear force between masonry storey and framework storey is studied. Masonry storey shows brittle characteristic, while framework storey shows apparent ductile characteristic. The failure modes of analysis models with different storey rigidity ratio are compared and the effects of two loading methods, including the inverted triangle loading method and the uniform loading method, are considered. The result shows that when the storey rigidity of structures is controlled in the reasonable range, the whole structures have better ability to withstand lateral force and remain integrity. With the increase of horizontal seismic action, both framework storey and adjacent masonry storey show a certain degree of damage before the framework has large lateral displacement and adjacent masonry storey failed due to compression.

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REFERENCES

Zheng Shansuo, Zhang Xinghu, Shen Chaoyang. (1998). Shaking table experiment of masonry building model with frame structure at first storey. *Journal of Xi'an University of Architecture & Technology* **30:3**, 280-283.

Zheng Shansuo, Wang Jianping. (1999). An analysis on the anti-seismic behavior of masonry building with frame structure at first storey. *Journal of Xi'an University of Architecture & Technology* **31:3**, 304-306.

Code for seismic design of buildings (GB50011-2010).(2010). China Architecture & Building Press.

Jia Qiang, Sun Jianping. (2008). Reports on the damages of bottom reinforced concrete frame structrues in great Wenchuan Earthquake. *Journal of Shangdong Jianzhu University* **23:6**, 560-564.

Lu Xinzheng, Ye Lieping, Miao Zhiwei. (2009). Elasto-plastic analysis of buildings against earthquake. China Architecture & Building Press.

Liu Guiqiu. (2005). The research on the basic mechanical behavior of masonry structure. College of Civil Engineering, Hunan University, China.

Federal Emergency Management Agency. (1998). Guidelines and Commentary for the Seismic Rehabilitation of Buildings. FEMA274: 24-28.

Faella Giuseppe. (1996). Evaluation of the structures seismic response by means of nonlinear static pushover analysis. *11th World Conference on Earthquake Engineering*: 47-60.

Requena Misael. (2000). Evaluation of a simplified method for the determination of the nonlinear seismic response of RC Frames. *12th World Conference on Earthquake Engineering*: 1325-1333.