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SEISMIC PERFORMANCE ANALYSIS OF MOUNTAINOUS MASONRY STRUCTURE WITH STILTED RC FRAME AT BOTTOM

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ABSTRACT

Masonry structures, two to four floors, with stilted RC frame structure at bottom, are very common style in villages and towns in mountainous areas. Such structural system is defined as mountainous masonry buildings with stilted RC frame structure at bottom.

The stiffness of the stilted RC frame is much smaller than that of the upper masonry structure, and the plane arrangement of the first floor is irregular, induced by different constraint positions for the RC column. Seismic performances of such structural systems need to be evaluated for guiding seismic strengthen and design in practices.

At the first part, three masonry building models are designed. The upper two layers are masonry structure and the bottom is stilted RC frame structure under fortification intensity of 6, 7 and 8 according to Chinese code for seismic design of buildings. Elasto-plastic time history analyses of the models have been carried out. Seismic performances such as story drift rotation, shear and bending damages of the masonry walls and RC columns are investigated.

Then, two masonry buildings models are designed which have 3, 4 masonry floors respectively at upper part with the bottom floor of stilted RC frame, and both them are under fortification intensity 8. Elasto-plastic time-history analyzing methods are adopted, the results of two models are compared with the model of the upper two masonry floors.

Some design suggestions are put forward based on the analysis results.

Keywords: Mountainous masonry buildings with tilted RC frame structure at bottom; Seismic performance; Stiffness ratio; Time history analysis; Story drift rotation

1. INTRODUCTION

Mountainous areas account for 69% of the whole land area in China, the sites for building are often slopes and terraces. In order to coordinate with the slope fields, the vertical members in the bottom floor always have different length to avoid too much earthwork. Masonry structures, two to four floors generally, with stilted RC frame structure at bottom floor, are very common in villages and towns in mountainous areas. Such structural system is defined as mountainous masonry buildings with stilted RC frame structure at bottom (MMB-SRCF for short).

1.1 Model design

In accordance with Code for Seismic Design of Buildings (GB50011-2010), Code for Structural Design of Masonry Structures (GB50003-2011) and Technical specification for earthquake-resistant of masonry buildings with frame and seismic-wall in the lower stories (JGJ 248-2012) and other related norms, three models with two masonry upper floors and one stilted RC frame at the bottom floor are

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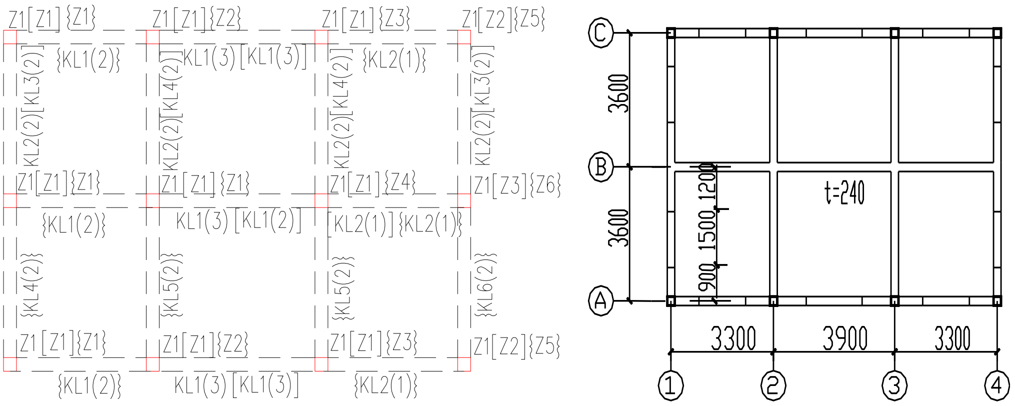
designed.

The fortification intensity was 6(0.05g.), 7(0.10g) and 8(0.20g), respectively. Design earthquake group is the second group, Site-class Ⅱ, Characteristic period T_g is 0.40s. The three models are named as D_f-2-6，D_f-2-7，D_f-2-8. Detailed design information is as presented follows:

(1) Strength of upper masonry brick is MU10, mortar is M10. The thickness of all masonry walls is 240mm. The concrete strength of ring beam and structural column is C20. The cross-section of structural column is 240×240mm, with 4ϕ12 reinforcements; the cross-section of the ring beam are 240×180mm (the third floor) and 240×240mm (the second floor), with 4ϕ12 reinforcements, stirrup spacing at 200mm. The floor thickness is 120mm, the dead load is 2kN/m^2 (except self-weight of the plate), live load is 2kN/m^2; the dead load on the roof is 4kN/m^2 (except self-weight of the roof), live load is 0.5kN/m^2. The height of upper masonry floor is 3m, all windowsills are 900mm and all windows are 1500mm.

(2) The concrete strength of all members in bottom frame floor is C30, the cross section of the beams is 300×500mm, and the columns is 350×350mm. Longitudinal rebar of RC frame are HRB400, structural steel bars and stirrups are HPB300. The layouts of the model are shown in Figure 1, and the elevation of the bottom RC frame layer is depicted in Figure 2. The three models are analyzed and designed in accordance with Code for Seismic Design of Buildings (GB50011-2010).



(a) Layout of the bottom RC frame floor (b) Layout of upper two masonry floors

Figure 1. Layouts of the models (Note: Numbers in [], {} are on behalf of D_f-2-7, D_f-2-8.)

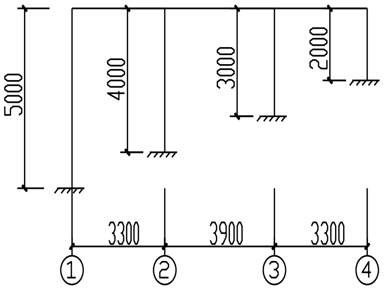


Figure 2. Vertical view of the bottom silted frame floor

1.2 Mechanical parameters used in the analyse

Perform 3D software is adopted in the analysis. Nonlinear fiber cross sections are used to simulate beams and columns, which are divided into concrete fibers and steel fibers. Common wall elements are adopted to simulate masonry walls. Wall section can only adopt fiber model to simulate the performance. Like beams and columns, the fiber section is divided into concrete and steel fibers. The cross section of fiber can be set with linear or non-linear materials. The crush of concrete and yield of the rebar can be considered separately.

The average strength of material is adopted in this test, which is calculated by the standard value, according to the "code for design of concrete structures" and "code for design of masonry structures". The average values of the materials strength are listed in table 1. The compression strength f_m of masonry wall is 4.19 N/mm^2, while the compression strengths of MU10 block and M10 mortar are determined by Shi Chuxian (2003).

Table 1. The average strength of materials in analysis

Strength	**C30**	**HRB400**	**HPB300**	**Masonry wall**
	Compression,f_c	Tension,f_y	Tension,f_y	Compression,f_m
Average strength(N/mm^2)	33.1	463.6	347.7	4.19

(1) Constitutive relation of concrete and steel

The constitutive curve for constrained concrete adopts Scott-Kent-Park model, B.D.Scott et al. (1982). The constitutive curve for normal concrete is applied according to Appendix C of Code for design of concrete structures (GB50010-2010). The constitutive relation of steel is the ideal elasto-plastic relationship provided by Perform-3D.

(2) Compression constitutive relation of masonry wall

The five-fold line model of "YULRX" in Perform-3D is used for compression constitutive curve for masonry material, as shown in Figure 3. "YULRX" is fitting with Yang Weizhong model, Yang Weizhong (2008), which is defined by equation (1).

$$\frac{\sigma}{f_m}=\frac{1.633}{1+0.633(\varepsilon/\varepsilon_0)^{2.580}}\frac{\varepsilon}{\varepsilon_0} \tag{1}$$

Where ε_0 is 0.005, f_m is 4.19MPa.

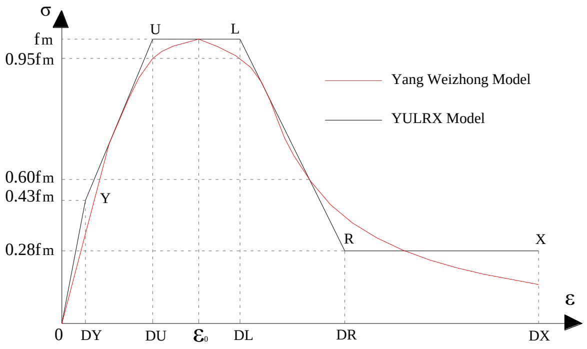


Figure3. Prediction of Compression Stress - Strain Curve of Masonry

X point is the failure point and ε_u is 5 times larger than ε_0.

(3) Shear constitutive relation of masonry wall

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The F-D curve provided by Perform-3D is used as constitutive curve for shear of masonry wall, which is fitted to the area equality principle considering energy loss, as shown in Figure 4.

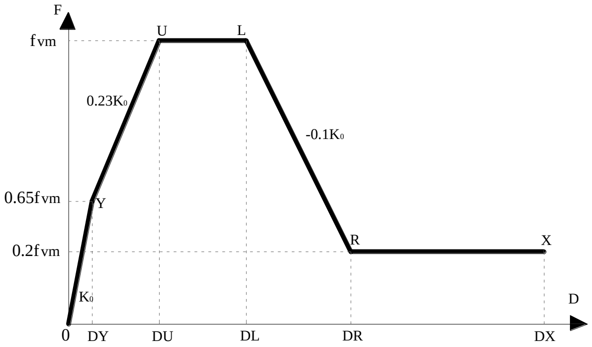


Figure 4. F-D curve for shear of masonry wall

In Figure 4, FU is f_{vm} , which is the smaller value of equation (2) and equation (3). Equation (2) is listed in reference Wang Qinglin (1989), and equation (3) is listed in reference Liu Guangxi and Wang Qinglin (2012).

$$f_{vm} = 0.5f_{v0,m} + 0.7\sigma_y \tag{2}$$

$$f_{vm} = \frac{f_m}{2}\left[(\frac{\sigma_y}{f_m} - m^2 + \sqrt{m^4 - 4m^2\left(\frac{\sigma_y}{f_m} - 1\right)^2} - (\frac{\sigma_y}{f_m})^2\right]^{0.5} \tag{3}$$

Where f_{vm} is the average shear strength of masonry considering compression stress, $f_{v0,m}$ is the average value of pure shear strength when compression stress is zero, $f_{v0,m} = 0.125\sqrt{f_2}, \sigma_y$ is the average compressive stress corresponding to the representative value of gravity load, f_m is the average compressive strength, m is tension and compression strength ratio, $m = f_t/f_m$.
Initial shear stiffness K_0 is calculated by equation (4).

$$K_0 = \frac{\lambda G_w A_z}{\mu H} \tag{4}$$

Where G_w is the shear modulus, H is the height of the masonry wall, μ is the uneven distribution coefficient of shear force, which is 1.2, A_z is the calculating cross-section of the wall, calculated by equation (5), and parameter λ is a coefficient considering shear strain.

$$A_z = A_w(1 + 2\eta\frac{A_c G_c}{A_{wG_w}}) \tag{5}$$

Where A_w is the cross-sectional area of the masonry wall, A_c is the cross-sectional area of structural column, G_c is the shear modulus of concrete, η is equal to 0.26, which is working force coefficient of the masonry wall and structural column.
DU is the corresponding strain of FU, and DL is 1.1 times that of DU, DX is defined as the failure point, generally the value of DX is set to bigger according to the equal area principle to make FR smaller.
(4) Definition of the seismic action
Natural accelerograms Usa04545, Usa00075 are selected for calculation by dual-band wave selection procedures, and ACC1 is the artificial accelerogram referring Code for Seismic Design of Buildings (GB50011-2010). The response spectra of three accelerograms and design response spectrum, which regulated in Code for Seismic Design of Buildings (GB50011-2010) are shown in Figure 5. The information of three accelerograms are showed in Table 2.

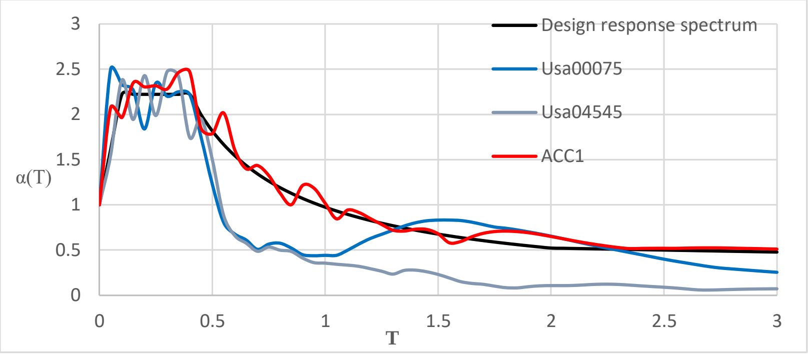


Figure 5. Response spectra of accelerograms and the design response spectrum

Table 2 The information of three accelerograms

Accelerograms	**Earthquake Name**	**Year**	**Station Name**	**Duration**	**Time Step**
Usa04545	NORTHRIDGE	1994	4747 NEW YORK AVE, LA CRESCENTA, CA	40.72	0.02
Usa00075	HELENA MONTANA	1935	HELENA, MONTANA CARROLL COLLEGE	51.06	0.02
ACC1	--	--	--	40	0.02

Plasto-plastic time-history analyzing of three models are carried out under the rare intensity level of 6 , 7 and 8, with two natural accelerograms and one artificial accelerogram. Two-direction seismic inputs are considered, where the maximum acceleration of X-direction to Y-direction is 1:0.85.

2. SEISMIC PERFORMANCE OF MMB-SRCF MODELS IN DIFFERENT SEISMIC INTENSITY

2.1 Dynamic behavior, stiffness ratio and plane regularity

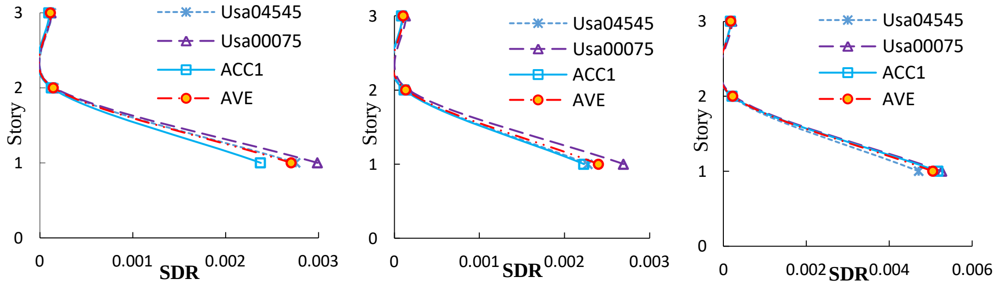
The stiffness ratios of the first masonry story and the s**tilted RC frame** are calculated according to Appendix A of “Technical specification for earthquake-resistant of masonry buildings with frame and seismic-wall in the lower stories (JGJ 248-2012)”. Three models have the same stiffness since they are arranged in the same way. The lateral stiffness K_{eft} of the unequal-height column of the bottom layer is calculated by the method in Wang Liping et al. (2014). The stiffness of the bottom stilted RC frame is relative smaller compared with that of masonry layer, which has a large lateral stiffness; the stiffness ratio in X-direction and Y-direction is as high as 12.4, and 19.88, respectively.
The periods of the three models are listed in Table 3. It can be seen that the first cycles of three models are relatively close, and they are all about 0.32s.
The ratio of the maximum story drift and the average story drift of the bottom floor of D_f-2-6、D_f-2-7 and D_f-2-8, under accelerograms USA01405, are shown in Table 3.
According to provisions 3.4.3 in "Code for seismic design of buildings (GB50011-2011)", the structure is torsionally irregular if the ratio of the maximum story drift to the average story drift is greater than 1.2. It is noticeable from Table 3 that, D_f-2-6, D_f-2-7 and D_f-2-8 are all torsional irregularities.
As the layouts of upper masonry structure are basically symmetrical, the torsional irregularities of the structure are mainly attributed to the different stiffness of the bottom stilted frame column.

Table 3. Dynamic characteristic and plane regularity of three models

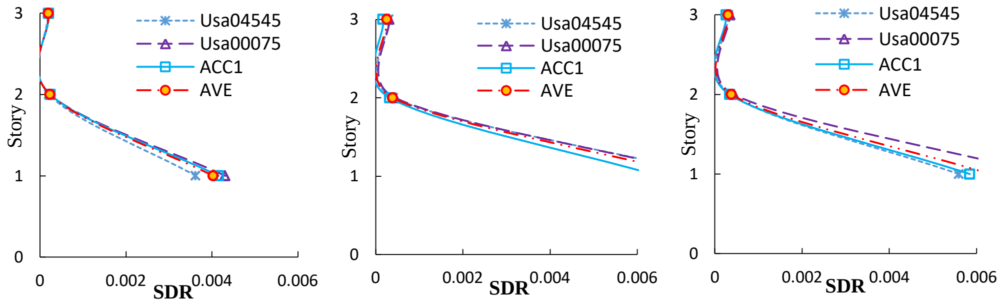
Model	The first period(s)	The second period(s)	The third period (s)	Maximum story drift(MMD) (mm)	Average story drift(ASD)(mm)	MMD / ASD
D_f-2-6	0.33	0.26	0.051	14.66	9.43	1.63
D_f-2-7	0.33	0.25	0.053	24.01	15.19	1.58
D_f-2-8	0.31	0.24	0.052	42.21	25.93	1.63

2.2 Story drift rotation

(1) The story drift rotations (SDR)
The story drift rotation (SDR) represents the ratio of story drift to the story height, The SDR of three models under different earthquake inputs are presented in Figure 6. The comparisons of SDR under different intensities are illustrated in Figure 7.

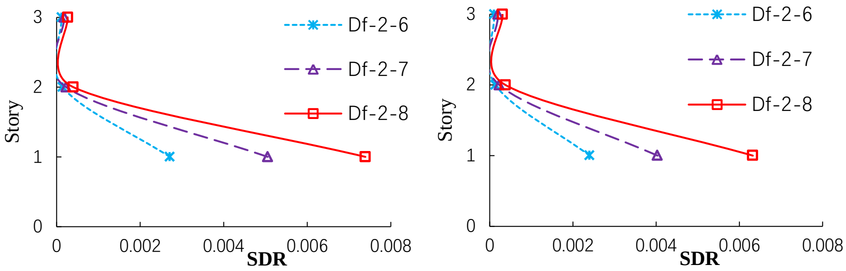


(a) D_f-2-6 X-direction (b) D_f-2-6 Y-direction (c) D_f-2-7 X-direction



(d) D_f-2-7 Y-direction (e) D_f-2-8 X-direction (f) D_f-2-8 Y-direction

Figure 6. Story drift rotations (SDR) of three models



(a) X-direction (b) Y-directions

Figure7. Comparison of average story drift rotations (SDR)

It can be seen from Figure 6 that the calculation results of the elasto-plastic story drift rotation are similar between three waves, and the data deviation is not significant.

It can be noticed from Figure 7 that, the maximum elasto-plastic story drift rotation is in the bottom frame story. With the raise of input intensity, the story drift rotation increase gradually. The story drift rotations of upper masonry floors are very small.

(2)The damage level of the bottom RC frame layer

According to “Code for Seismic Design of Buildings (GB50010-2010)”, the elastic story drift rotation limit of the bottom RC frame story is 1/550, and elasto-plastic story drift rotation limit is 1/50. The overall working state and the overall damage of RC frame structure are specified in Section 3.10.3 of the code, which are graded by story drift rotation limits shown in Table 4.

Table 4. Identification of damage level of the bottom RC frame layer

Damage level	**Basically good**	**Minor damage**	**Moderate damage**	**Serious damage**	**Collapse**
Story drift rotation limits	0.0018	0.0027~0.0036	0.0055~0.0073	<0.018	≥0.02

In this paper, the damage analysis of members is mainly based on the damage judgement of steel members. According to Table 4, the damage state of bottom RC frame structures is evaluated. The results are presented in Table 5.

As shown in Table 5, the bottom story of Df-2-8 is seriously damaged, while the model does not collapse when the story drift rotation is less than 0.02.

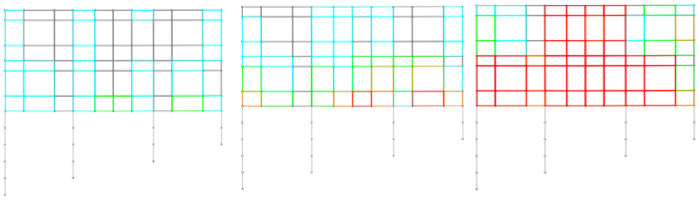
Table 5. Damage level of bottom RC frame

Direction	**D_f-2-6**	**D_f-2-7**	**D_f-2-8**
X	0.0027 Minor damage	0.0051 Slight to moderate damage	0.0074 Serious damage
Y	0.0024 Minor damage	0.0040 Slight to moderate damage	0.0063 Moderate damage

2.3 Shear damage of masonry wall

In the case of damage analysis, the seismic response of the model is the largest when the input is USA04545, thus only the results under USA04545 are listed below. For the upper masonry structure, damage assessment is mainly based on its shear strain. Figure 8 depicts the shear damage of the masonry wall on B-axis, which is the most severely damaged wall.

The greater the utilization, the closer to the shear destruction happening. When the shear strain reaches the cracking strain, the utilization rate is equal to 1, and the masonry cracks. In Perform-3D, different colors represent different strain utilization, sky blue represents 0.5 (the utilization rate reaches 0.5 to 0.7), green represents 0.7 (which utilization rate reaches 0.7 to 0.8), yellow represents 0.8 (which utilization rate reaches 0.8 to 1), red represents 1 (which the utilization rate reaches 1 and above).



(a) D_f-2-6 (b) D_f-2-7 (c) D_f-2-8

Figure 8. Shear strains of wall on B-axis

It can be note from Figure 8 that the masonry walls of D_f-2-6 does not reach the cracking strain. As the level of seismic input increasing, the masonry walls begin cracking and spread from the middle to both sides, the shear strain in the second story is larger than that of the third story.

3. SEISMIC PERFORMANCE OF MMB-SRCF MODELS WITH DIFFERENT STORIES

3.1 Analysis of Basic Dynamic Behavior, Stiffness Ratio and Plane Regularity

In this section, two new models are designed for comparing. Two models both have one story of stilted RC Frame at bottom. Whatmore, one has 3 upper masonry layers (named Df-3) and the other has 4 upper masonry layers (named Df-4). The analysis parameter and condition of model Df-3 and D_f-4 are both the same as that of D_f-2-8. Besides, other respects of Df-3 and D_f-4 also keep the same designs as D_f-2-8, such as the layouts of upper masonry stories, materials, ring beam, structural column material and layout, the bottom beam, column material and beam cross-sectional size, plane load and so on. But the cross-sectional dimensions and reinforcement of the bottom frame columns are different. The column cross sections of D_f-3 and D_f-4 are 400×400mm，450×450mm, respectively. Thus the stiffness ratios of the first masonry story to the bottom RC frame story are different, as listed in table 6. The model layout diagram is already presented in Figure 1.

The periods of the three models and the stiffness ratios of the three models are compared in Table 6. It is can be found from Table 6 that the periods of the first cycle for three models are relatively close, and they are all about 0.31s. The ratio of the maximum story drift and the average story drifts of D_f-2-8, D_f-3 and D_f-4 in the elasto-plastic time-history analysis of USA01405 are also summarized in Table 6, it is obviously that Df-3 and Df-4 are torsion irregularities, too.

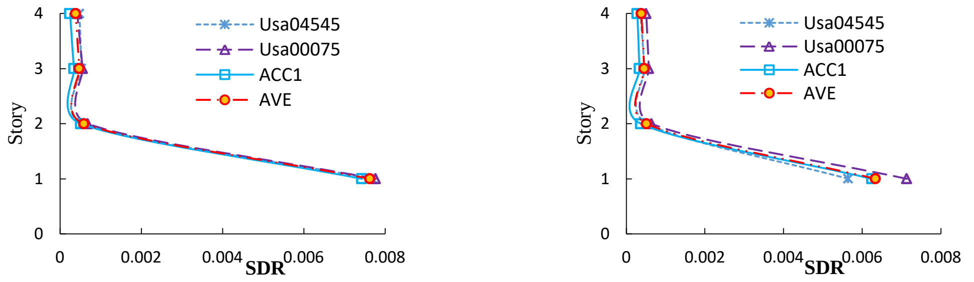
Table 6. Basic information of Df-2-8, Df-3, Df-4

Model	**Stiffness Ratio X-direction**	**Stiffness Ratio Y-direction**	**First cycle(s)**	**Maximum Story drift(MSD/mm)**	**Average Story drift (ASD/mm)**	**MSD / ASD**
D_f-2-8	12.40	19.88	0.307	42.21	25.93	1.63
D_f-3	7.13	15.04	0.307	40.04	24.79	1.62
D_f-4	5.92	12.39	0.309	36.22	22.37	1.62

3.2 Story drift rotation

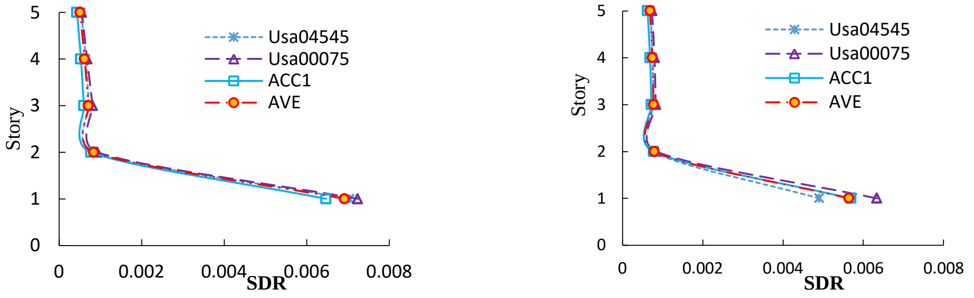
(1) The story drift rotations (SDR)

The SDR of X-direction and Y-direction of each model under different earthquake inputs are demonstrated in Figure 9. The comparative analysis of average SDR for three models are shown in Figure 10.



(a) X-direction of D_f-3

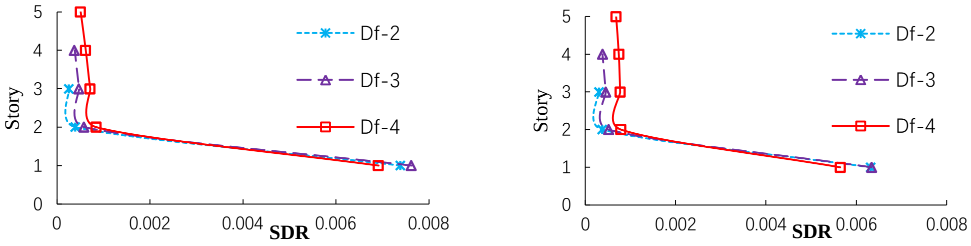
(b) Y-direction of D_f-3



(c) X-direction of D_f-4

(d) Y-direction of D_f-4

Figure 9. The story drift rotations (SDR) of models



(a) SDR in X-direction

(b) SDR in Y-direction

Figure 10. The average story drift rotations (SDR) of models

It can be seen from Figure 9 and Figure 10 that, with the number of upper masonry story increasing, the stiffness ratio of the first masonry layer to the bottom RC frame layer decreases gradually, while the story drift rotations of masonry layers increase gradually, when SDR of the bottom RC frame layer decrease slightly.

(2)The damage level of bottom RC frame layer

According to table 4, the damage state of bottom RC frame layers of three models are evaluated and the results are illustrated in Table 7.

Table 7. Structural damage status of bottom RC frame layer

Direction	**Index**	**D_f-2-8**	**D_f-3**	**D_f-4**
X-direction	**Stiffness Ratio**	12.40	7.13	5.92
	Damage status	0.0074 Serious damage	0.0076 Serious damage	0.0069 Moderate damage
Y-direction	**Stiffness Ratio**	19.88	15.04	12.39
	Damage status	0.0063 Moderate damage	0.0063 Moderate damage	0.0056 Moderate damage

It can be concluded from Table 7 that the deformation of bottom RC frame with different stiffness ratios reaches moderate to severe damage, and no collapse occurs when it is less than 0.02 normative limits. The weak layer of the model is the bottom frame.

3.3 Shear damage of masonry wall

Shearing strain represent the shear damage of the masonry wall, the utilization rate is defined as 1 when the shear strain reaches the cracking strain. Figure 11 presents the shear damage of the masonry wall on B-axis of the three models, which is the most severely damaged wall.

In this contrast, sky blue represents 1(shear utilization rate reaches 1 to 1.5), green represents 1.5(shear utilization rate reaches 1.5 to 2), yellow represents 2(shear utilization rate reaches 2 to 3), red represents 3(shear utilization rate are greater than 3). The greater shear utilization, the closer the wall is to reach shear failure.

It can be seen from Figure 11 that the shear strains of masonry wall increase gradually with the number of upper masonry story increasing, and the shear strain in the first masonry story are greater than that of the second and third masonry story.

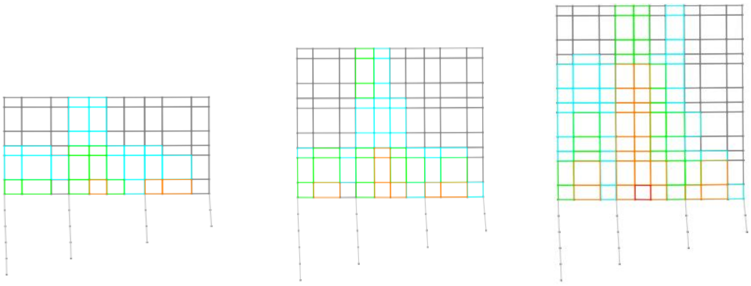

(a) D_f-2-8 (b) D_f-3 (c) D_f-4

Figure 11. Shear strains of wall on B-axis under input of wave USA04545

4. CONCLUSIONS

This paper investigated the seismic performance by time history analysis of two group models for mountainous masonry building with silted RC frame at the bottom. Different seismic intensities and different stories are considered, the following conclusions can be obtained:

(1) MMB-RCF is normally torsionally irregular for the tilted column in the bottom story.

(2) With the seismic intensity increasing, the damage of RC frame at the bottom increases, from minor damage under seismic intensity 6, moderate damage under seismic intensity 7, to serious damage under seismic intensity 8.

（3）With the number of upper masonry story increasing, the damage of RC frame at the bottom increases, too. When the seismic intensity is 8 degree, serious damages occur in the RC frame and the shear failures occur in the masonry walls. The performances cannot meet the requirements of the code overall.

(4) With the increase of the lateral stiffness ratio, the damage of the masonry layer is reducing, the damage of RC frame layer is much severe, and the overall damage degree is serious.

5. ACKNOWLEDGMENTS

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