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Seismic Performance of High-rise Moment-resisting RC Frame Structures with Vertical Setback

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Abstract

High-rise buildings with vertical setback are widely used in practice. From the field investigation of the past earthquakes, it was found that such kind of vertically irregular high-rise building structures easily suffer severe damage during strong earthquakes. This paper presents an extensive study on the earthquake responses of moment-resisting frame structures (MFS) popularly applied in high-rise buildings with vertical setback. Four groups of MFS are designed, including three groups of structures with vertical setback and one group of structures with the lateral stiffness varying along the building height but without vertical setback. The numerical models of the structures are established, and the time history analysis of the structures under different levels of earthquakes is conducted. The earthquake responses of the structures are compared. The influence of the ratio between the horizontal setback dimension and the previous plan dimension, the eccentricity of setback, and the position where the setback occurs on the seismic performance of structures is studied. The rationality of the provisions for the structures with vertical setback specified in the current design codes is checked by the findings from this study.

Keywords: Vertical setback, High-rise buildings, Moment-resisting frame structure, Seismic performance

1. Introduction

With economic growth and urbanization, the number of high-rise buildings has been keeping increasing. Owing to the wide variety of social requirement for commercial or aesthetic purposes, many high-rise buildings with all kinds of plan or vertical irregularities have been constructed. As one type of vertical irregularities, vertical setback through the abrupt change of horizontal dimensions of plan layout at certain level of the building may cause sudden change in stiffness, strength or mass between adjacent stories. Observed damage after strong earthquakes (Lew et al. 2010; Kim et al. 2009) indicates inferior seismic performance of this type of building structures. Therefore, the reasonable seismic design of high-rise building structures with vertical setback plays an important role in mitigating the earthquake disaster.

The design codes adopt in different countries provide different provisions related with the structures with vertical setback. In current Chinese seismic design code GB 50011 (2010), the vertical setback which causes the total horizontal dimension of the upper floor except the top floor being lower than 75% of that of the adjacent lower floor is defined as one type of lateral stiffness irregularity. In ASCE 7 (2010), the vertical setback which causes 23% reduction of horizontal dimension is defined as the vertical geometric irregularity. In IS 1893-1 (2002), the stepped building form is treated as vertical irregularity when the lateral dimension of the maximum offset at the roof level exceeds 25% of the lateral dimension of the building at the base. In Eurocode 8 (2004), in the case of vertical setback, the requirements on regularity in elevation are specified, considering the factors such as the setback degree, the symmetricity of setback, and the position where the setback occurs. It can be found that certain difference exists in the definition of vertical irregularity caused by setback among these standards. To check the rationality of the definition of this type of irregularity, it is necessary to identify the factors which have influence on the seismic performance of structures with vertical setback and how these factors affect. In this study four groups of high-rise RC moment-resisting frame structures (MFS) which are popularly applied in practice around the world are designed, including three groups of structures with vertical setback and one group of structures with the lateral stiffness varying along the building height but without vertical setback. The earthquake responses of the structures are obtained by time history analysis and compared. The influences of the design parameters on the seismic performance of the structures with vertical setback are investigated.

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2. Structural Design

2.1. Structures of Group A

The RC MFS of Group A with 10 stories and the total height of 36 m are designed according to current Chinese design codes. The thickness of the floor and roof is 100 mm. The structural plan layout of typical floor before setback is shown in Figure 1. The dead load and live load for typical floor are taken as 5 and 2 kN/m^2, respectively. For the roof, the dead load and live load are taken as 6 and 0.5 kN/m^2, respectively. The seismic intensity is 7, the site soil class is IV, the design group is 1, and the

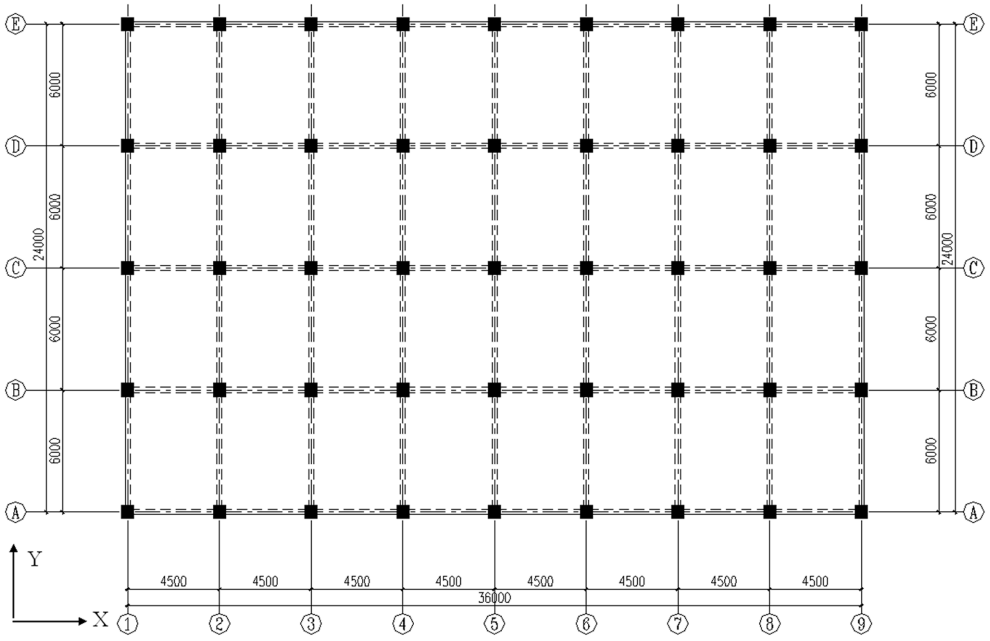
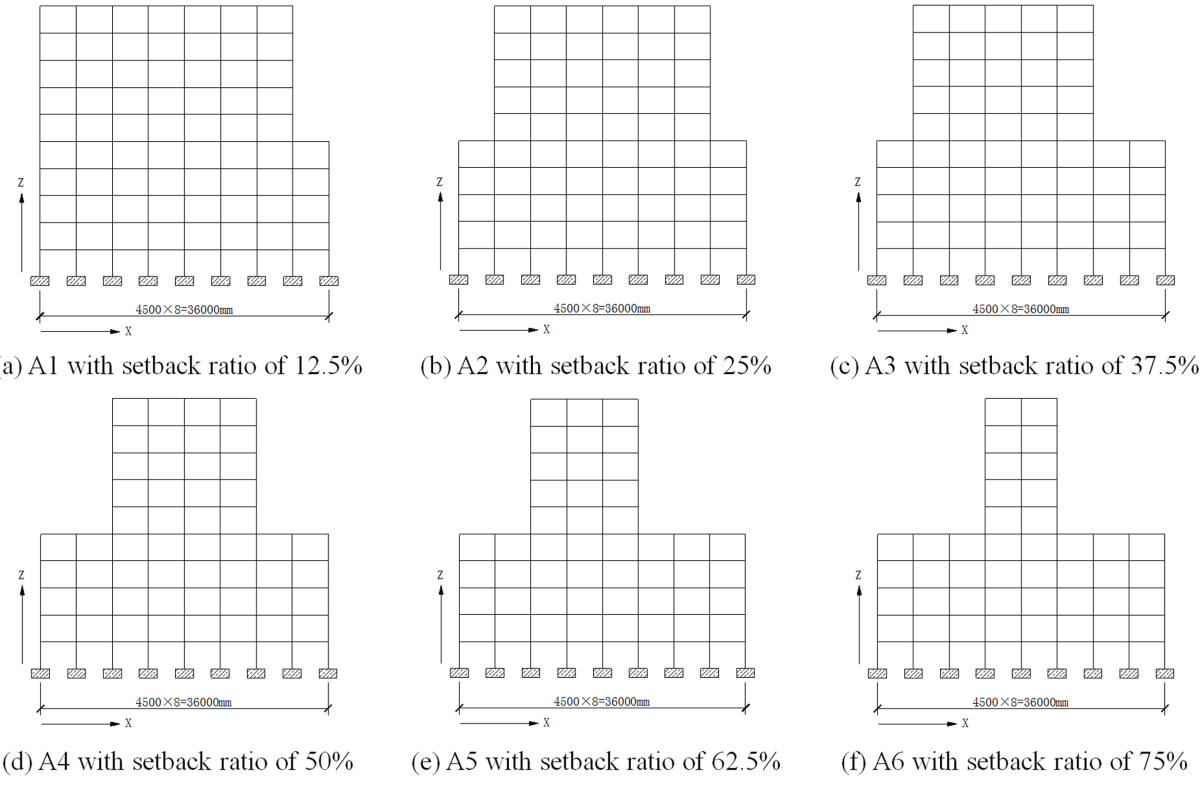


Figure 1. Structural plan layout of typical floor before setback.



(a) A1 with setback ratio of 12.5% (b) A2 with setback ratio of 25% (c) A3 with setback ratio of 37.5%

(d) A4 with setback ratio of 50% (e) A5 with setback ratio of 62.5% (f) A6 with setback ratio of 75%

Figure 2. Elevation view of structures of Group A.

characteristic period of the construction site is 0.9s.

The setback of all structures occurs at the sixth floor in X direction (longitudinal direction). The varied design parameter which is different from each other is the ratio between the horizontal setback dimension and the plan dimension of the adjacent lower floor (called setback ratio in short later). The elevation view in X direction of all structures is shown in Figure 2. The cross-section dimensions of columns below the sixth floor are 600 mm × 650 mm while the dimensions of columns above the sixth floor are 550mm×650mm.

2.2. Structures of Group B

The structures of group B are all geometry regular RC frames without vertical setback. The elevation view in X direction is shown in Figure 3. The structural plan layout is as same as Figure 1. The dimensions of the structural members below the sixth floor are identical to structures of Group A. Above the sixth floor the cross-section dimensions of columns are reduced so that the ratio of lateral stiffness between the sixth story and fifth story as shown in Table 1 is almost the same with structures of Group A. The varied design parameter considered in Group B is the lateral stiffness ratio.

2.3. Structures of Group C

The setback ratio of structures of Group C is 50%. The varied design parameter considered in Group C is the eccentricity of setback. Structure C1 is symmetrical while both Structures C2 and C3 are asymmetric. The elevation view of structures of Group C is presented in Figure 4. The eccentricity, defined as the ratio of the distance between the centroid of the setback plan and that of the previous plan to the total dimension of previous plan, is

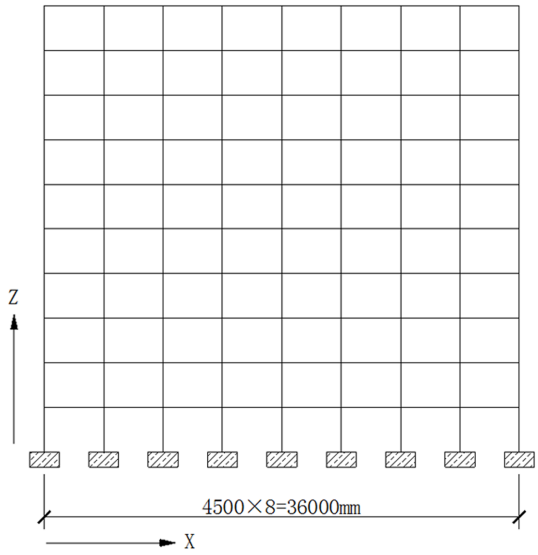
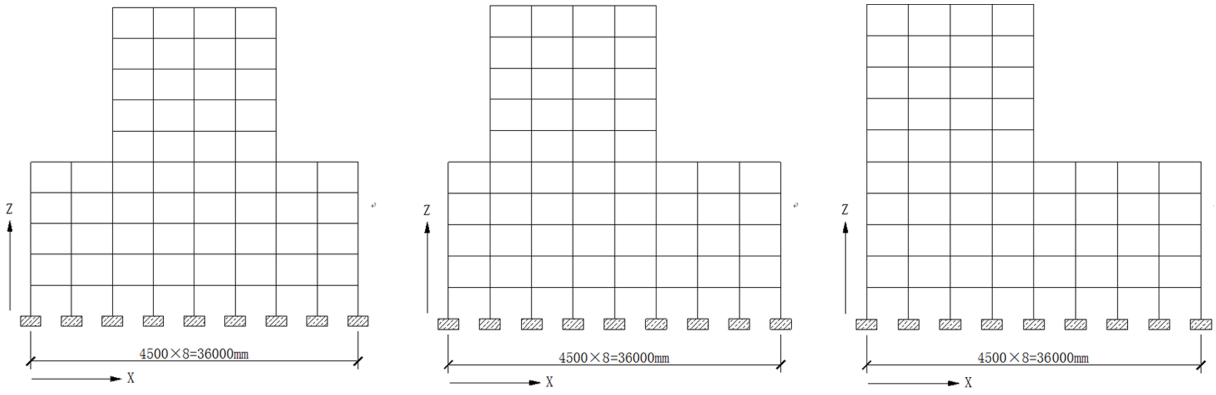


Figure 3. Elevation view of structures of Group B.

Table 1. Comparison of lateral stiffness ratio

Structure number	Lateral stiffness ratio		Structure number	Lateral stiffness ratio	
	X direction	Y direction		X direction	Y direction
A1	0.68	0.81	B1	0.67	0.81
A2	0.60	0.71	B2	0.59	0.71
A3	0.51	0.61	B3	0.51	0.60
A4	0.43	0.51	B4	0.43	0.51
A5	0.34	0.41	B5	0.34	0.41
A6	0.26	0.31	B6	0.26	0.31



(a) C1 with no eccentricity (b) C2 with eccentricity of 12.5% (c) C3 with eccentricity of 25%

Figure 4. Elevation view of Structures of Group C.

0%, 12.5% and 25%, respectively for Structure C1, C2 and C3, respectively.

The structural plan layout below the sixth floor is as same as Figure 1. The dimensions of the structural members below the sixth floor are identical to structures of Group A. Above the sixth floor, the cross-section dimensions of columns are reduced to be 550 mm × 550 mm.

2.4. Structures of Group D

The setback ratio of structures of Group D is 50%. The structural plan layout of the typical floor before setback is shown in Figure 5. The cross-section dimensions of the columns are taken as 700 mm × 700 mm. The varied design parameter considered in Group D is the setback position which is the location where setback occurs. The setback position ratio, defined as the ratio of the height from the bottom to the location where setback occurs to the total height of the structure, is 0.1, 0.2, 0.3, 0.5, 0.7 and 0.9 for Structure D1, D2, D3, D4, D5, D6, respectively. The elevation view of structure of Group D is shown in Figure 6.

3. Numerical Simulation

3.1. Finite Element Model

All structures are designed according to current Chinese design codes. The main indexes of these structures, such as inter-story drift ratio (IDR) and axial compression ratio of columns, meet the code requirements. The numerical models of the structures are constructed with the aid of commercial software Perform-3D (Cui et al., 2017). Beams and columns are simulated by fiber elements. The piecewise linearization model is adopted to simplify the constitutive relationship of concrete, suggested by Chinese design code for concrete structures GB 50010 (2010). The plastic hinges at two ends of the beams and columns are automatically generated by the software, and the

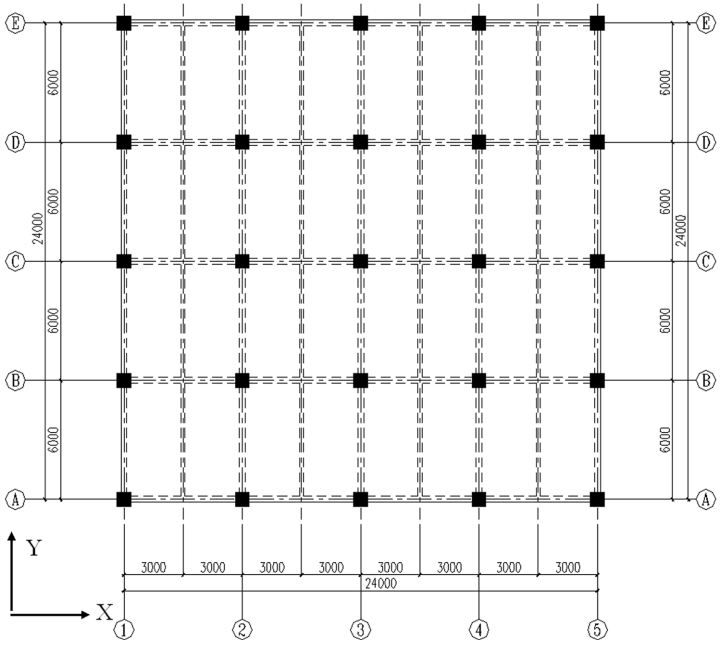


Figure 5. Structure plan layout of typical floor before setback.

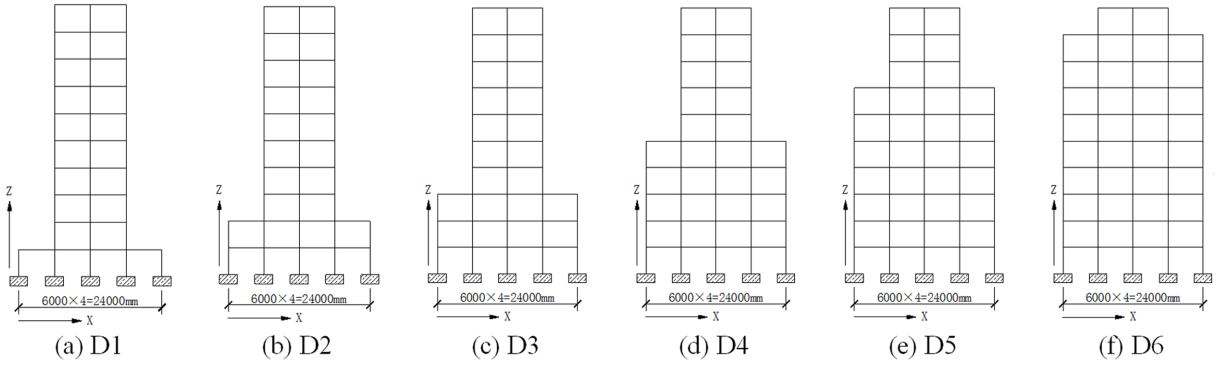


Figure 6. Elevation view of structures of Group D.

Table 2. Fundamental periods of structures

Structure number	Fundamental period (unit: s)			
	Group A	Group B	Group C	Group D
1	1.576	1.620	1.358	1.489
2	1.490	1.621	1.393	1.416
3	1.431	1.624	1.483	1.347
4	1.343	1.629	/	1.265
5	1.264	1.638	/	1.310
6	1.158	1.656	/	1.436

length of the plastic hinge is taken as half of the cross-section height. The elasto-plastic constitutive model is adopted for steel rebars.

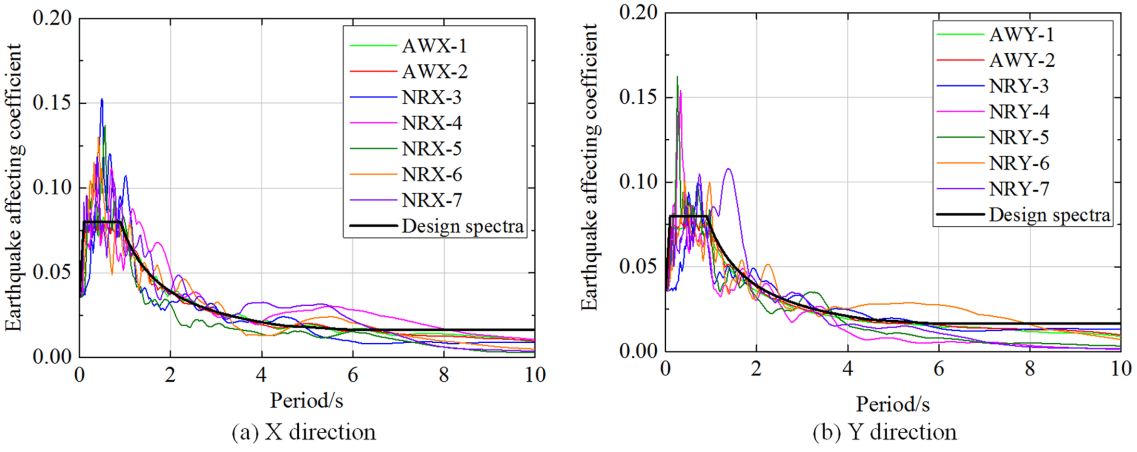
3.2. Dynamic Characteristics

The fundamental periods of all structures are listed in Table 2. It can be found that for structures of Group A, the fundamental period reduces when the setback ratio increases.

Although the lateral stiffness of structures of Group B is almost the same as that of group A, there is some difference of fundamental period between two groups of structures. For structures of Group C, the fundamental period increases with the increases of eccentricity. For structures of Group D, with the increase of setback position ratio the fundamental period decreases at first and then increases.

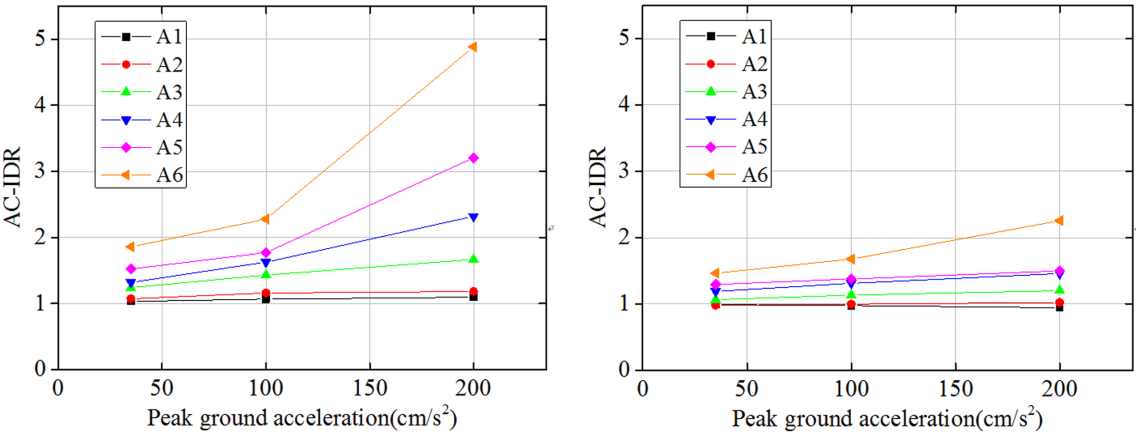
3.3. Input Ground Motions

According to the requirements of Shanghai seismic design code DGJ08-9 (2013), seven sets of seismic waves including five sets of natural ground motions and two sets of artificial motions are selected as input motions. Three levels of earthquakes, i.e. frequent earthquakes, moderate earthquakes, and rare earthquakes, are considered. The peak ground acceleration for three levels of earthquakes is taken as 35 gal, 100 gal, and 200 gal, respectively. Figure 7 shows the comparison of acceleration spectra of each set of ground motions with code design spectrum.



(a) X direction (b) Y direction

Figure 7. Comparison of acceleration spectra of input ground motions with code design spectrum.



(a) X direction (b) Y direction

Figure 8. AC-IDR for structures of Group A.

4. Simulation Results and Discussions

4.1. Inter-story Drift Ratio

4.1.1. GROUP A

The IDR of all structures of group A under the frequent earthquake satisfy the code requirement. Under the rare earthquake, the maximum IDR of A6 in X direction exceeds the code limit of 1/50 required by Chinese seismic design code GB 50011 (2010). The amplification coefficient of inter-story drift ratio (AC-IDR), defined as the ratio of IDR of the upper story with the setback to that of the adjacent lower story, i.e. the ratio of IDR of sixth story to that of the fifth story, is shown in Figure 8. The AC-IDR in X direction with setback is larger than that in Y direction without setback. With the increase of earthquake intensity, the AC-IDR rises, and the detrimental effect of setback on the structure becomes more significant. With the increase of setback ratio, the AC-IDR goes up. For A1 and A2 with the setback ratio not exceeding 25%, the AC-IDR is close to 1.0, which indicates that the detrimental effect of setback is too slight to be negligible.

4.1.2. GROUP B

The IDR of all structures of group B under the frequent earthquake satisfy the code requirement. Under the rare earthquake, the maximum IDR of B6 in X direction exceeds the code limit of 1/50. The AC-IDR is presented in Figure 9. Similarly, the AC-IDR rises with the increase of earthquake intensity. With the increase of earthquake intensity, the nonlinear behavior of the structures becomes more significant, and the detrimental effect of abrupt change of lateral stiffness on the structure becomes more significant. Compared with structures of Group A with similar lateral stiffness ratio, the AC-IDR of structures of Group B is lower. With the decrease of lateral stiffness ratio, the AC-IDR increases. For structures with lateral stiffness ratio lower than 51% (B4, B5, and B6), the AC-IDR increases more significantly with the decrease of lateral stiffness.

4.1.3. GROUP C

Under the frequent earthquake and the rare earthquake, the maximum IDR of all structures of Group C satisfies

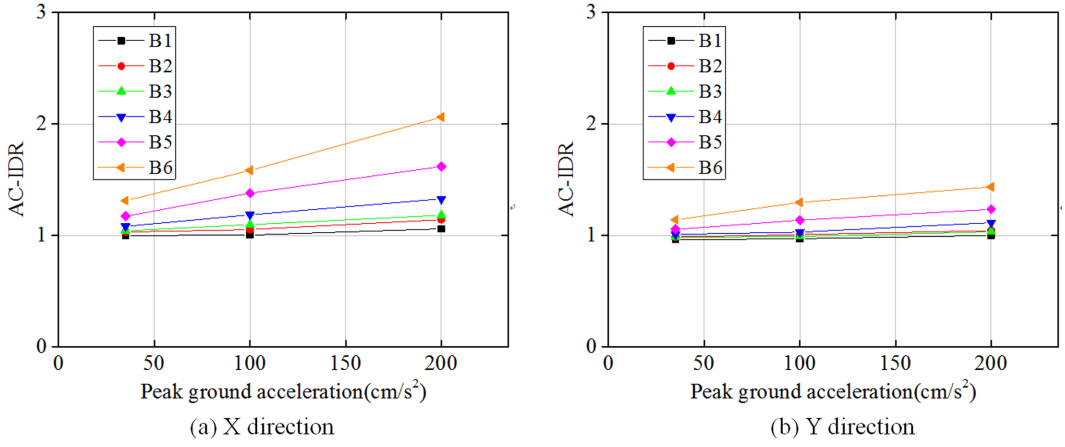


Figure 9. AC-IDR for structures of Group B.

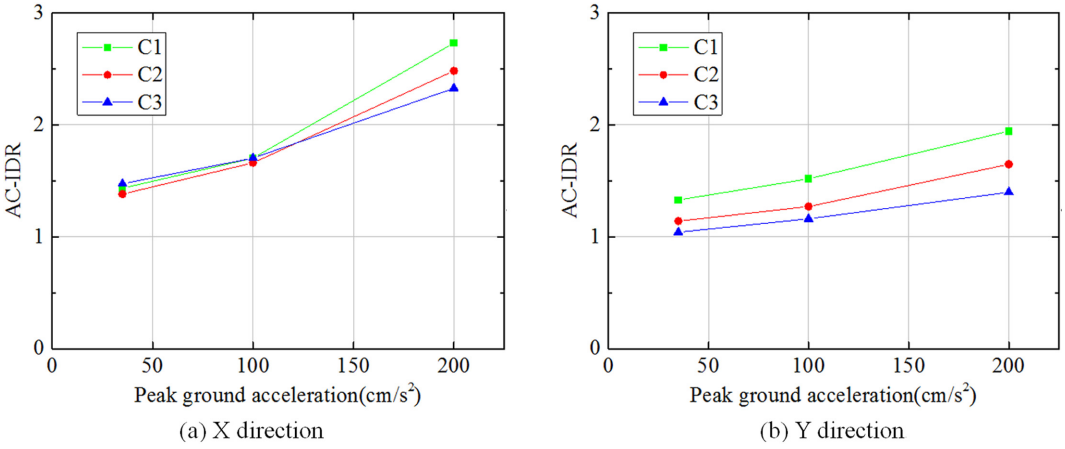


Figure 10. AC-IDR for structures of Group C.

the requirements of the design code. The AC-IDR is shown in Figure 10. Similarly, the AC-IDR rises with the increase of earthquake intensity. The influence of setback eccentricity is not significant. In addition, with the increase of setback eccentricity the AC-IDR in Y direction decreases slightly.

4.1.4. GROUP D

Under the frequent earthquake and rare earthquake, the maximum IDR of all structures satisfies the requirements of the design code. Under the rare earthquake, the AC-IDR between the adjacent two stories is shown in Figure 11. Due to the constrain effect of the fixed end at the base, the AC-IDR between the second story and first story is the largest while the AC-IDR between the top story and the adjacent lower story is the smallest. For other stories, the peak AC-IDR occurs at the story where the setback is located.

4.2. Damage Condition

The criteria specified in FEMA 356 (2000) are adopt to determine the performance level that the structural members stay in. According to the rotation of plastic hinge, the performance level of frame beams and columns can be divided into four levels, i.e. immediate occupancy (IO), life safety (LS), collapse prevention (CP) and not considered (NC). As structures of Group A are concerned, under the frequent earthquake the beams and columns

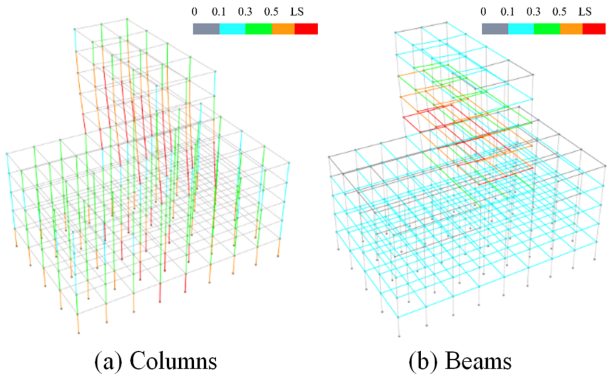


Figure 12. Damage condition of Structure A6 under the rare earthquake.

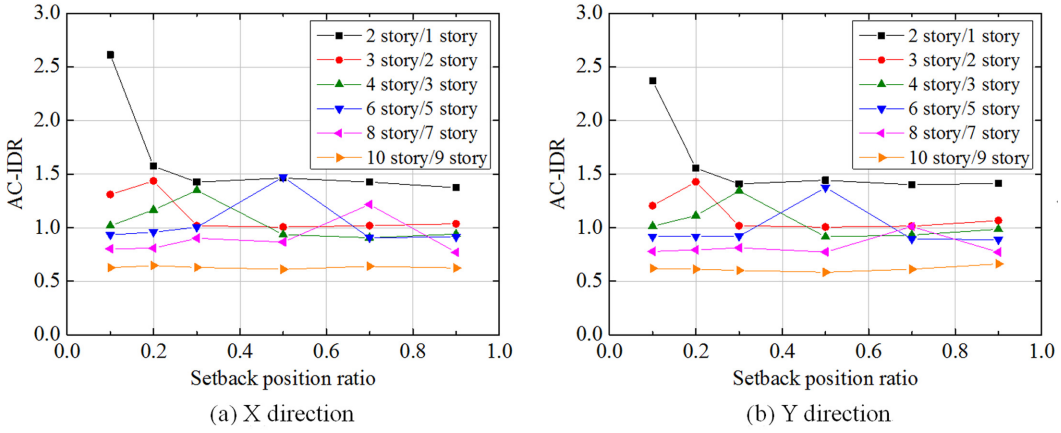


Figure 11. AC-IDR for structures of Group D.

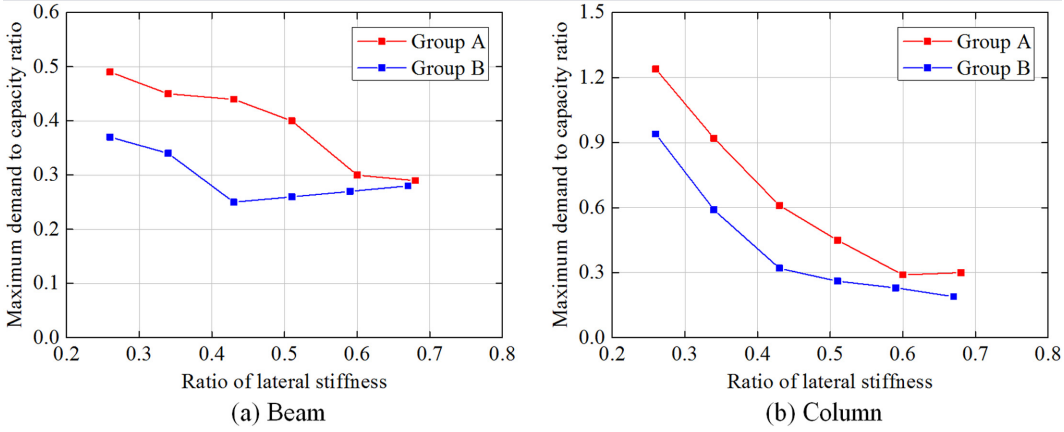


Figure 13. Maximum demand to capacity ratio of members in structures of Groups A and B under the rare earthquake.

stay in the performance level of IO, and under the rare earthquake the damage mainly concentrates on the first story and the story where the setback occurs. Figure 12 shows the damage condition of Structure A6. As structures of Group B are concerned, under the rare earthquake the damage mainly concentrates on the first story.

For structures of Groups A and B under the rare earthquake, the variation of maximum demand to capacity ratio for the beam and column at the outmost of sixth story where the setback occurs in structures of Group A with the ratio of lateral stiffness is shown in Figure 13.

The damage to members in structures of Group A is more serious than that of Group B. In general, with the decrease of lateral stiffness ratio, the damage to members becomes more serious. For structures of Group A, when the setback ratio exceeds 25%, the maximum demand to capacity ratio increases evidently. For structures of Group B, there is no significant damage difference among B1, B2, B3, and B4 while the damage to members in B5 and B6 is much more severe.

Under the rare earthquake, the maximum demand to capacity ratio for the beam and column at the outmost of the story where the setback occurs in structures of Groups C and D is shown in Figure 14. It can be found that the setback eccentricity almost has no influence on the damage to members. With the increase of setback position ratio, at first the maximum demand to capacity ratio of members increases slightly, it reaches the maximum at the mid-height, and then it decreases.

5. Conclusions

In this study, four groups of RC MFS, including three groups of structures with vertical setback and one group of structures with the lateral stiffness varying along the building height but without vertical setback, are designed according to current Chinese design codes. The earthquake responses of the structures are calculated by nonlinear time history analysis and compared. The conclusions are drawn as follows:

1. Despite that the lateral stiffness of structures of Group A is almost same with that of structures of Group B, the AC-IDR and the maximum demand to capacity ratio of members of structures of Group A are larger than that of Group B. The detrimental effect caused by the geometric irregularity is more significant than the irregularity of lateral stiffness.
2. For structures of Group B, with the decrease of lateral stiffness ratio, the AC-IDR and the maximum demand to capacity ratio of members become larger. In current design code, the vertical irregularity of lateral stiffness is defined only for the case that the lateral stiffness of the lower story is smaller than certain percent of that of the adjacent upper story. It is necessary to add another type of vertical irregularity defined for the case that the lateral stiffness of the upper story is smaller than certain percent of that of the adjacent lower story.
3. With the increase of setback ratio, the AC-IDR and the maximum demand to capacity ratio of members become larger. As the index for defining the vertical irregularity caused by setback, the limit around 25% for the setback ratio specified in current design codes is appropriate.
4. The influence of setback eccentricity on the seismic performance of the structure is not significant. With the increase of the vertical level where the setback occurs, at first the seismic performance of the structure becomes slightly worse and then turns better. The most unfavorable position for setback could be around the mid-height.

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