



SEISMIC FAILURE MODES IDENTIFICATION OF SPLIT-FOUNDATION RC FRAME STRUCTURES

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Abstract

Buildings on steep slopes, with vertical discontinuities both in stiffness and mass between adjoining stories, are strongly irregular in elevation. Such a structural configuration causes non-uniform lateral stiffness distribution among columns in the first upper ground floor. According to capacity design principles, this lateral stiffness uneven is undesirable as it may lead to unexpected failure modes, such as shear failure of the upper base columns or tensile failure of the earthing beams. In this study, the shear and axial failures of the split-foundation RC frames (SFRCF) are simulated in OpenSees by adding zero-length Limit State springs at the end of the upper base columns. The “MinMax” material in OpenSees, is used in conjunction with the Steel02 material model to specify an upper bound of rebar strains, it detects the axial tensile failure of the earthing beams. The reliability of the proposed simulation approach is validated by comparing the seismic failure modes of the SFRCF with different structural configurations. The results indicate that the maximum roof drift ratio at the failure points of the SFRCF is reduced by increasing the upper base bays. Meanwhile, the local damage level of the upper base columns and earthing beams are also increased largely. The upper base columns should be strengthened or based isolated depend on the structural irregularity levels. And the earthing beams are severely damaged under rare earthquakes, although there is no completely axial failure detected in them, they still need to be designed as a tension-bending member with higher seismic measure grade.

Keywords: split-foundation RC frames; seismic failure mode; limit state material; vertical irregularity



1. Introduction

In traditional RC frame structures, flexural failure is the desirable failure mode, which agrees with the requirement of performance-based seismic design principles. For split-foundation RC frames (SFRCF), its foundations can only be located at different ground levels [1], which causes a sudden change of structural stiffness and mass in the upper ground story [2, 3]. Thus, the upper base columns sustain much larger bending moments and shear forces than the remain columns in the upper ground story, which may cause unexpected seismic failure modes [4].

The local failure mode of SFRCF has occurred in several destructive earthquakes (e.g., 2008 Wenchuan [5], 2011 Sikkim [6], and 2015 Nepal [7] earthquake), which induces local collapse of the whole building structures. In such cases, nonuniform seismic failure of the lateral resistance members in the upper ground story occurs, and the seismic capacity of these structures are not fully developed.

Therefore, it is very important to further improve the seismic performance of the SFRCF by analyzing their seismic failure mechanisms, accurately identifying the possible seismic failure paths, and finding out the key factors that affect the seismic failure modes. In this study, we introduced the zero-length elements for the upper base columns include shear and axial springs whose behavior is defined by Limit State material models for shear and axial failure [8, 9]. The “MinMax” material is used in conjunction with the steel material model to detect the axial tensile failure of the earthing beams. Then, the failure of these elements in SFRCF can be identified when their deformation beyond the predefined limit values.

2. Seismic failure mechanism of SFRCF

2.1 RC frames on flat ground

For RC frame structures on flat ground, there are three typical seismic failure mechanisms: beam mechanism, story mechanism, and intermediate mechanism [10] (Fig. 1). However, the desirable seismic failure mode can only be achieved in structures with global failure mechanisms, including intermediate mechanism and beam mechanism [11]. The story mechanism will not induce the total collapse of the whole structural system, it should be avoided during the design process.

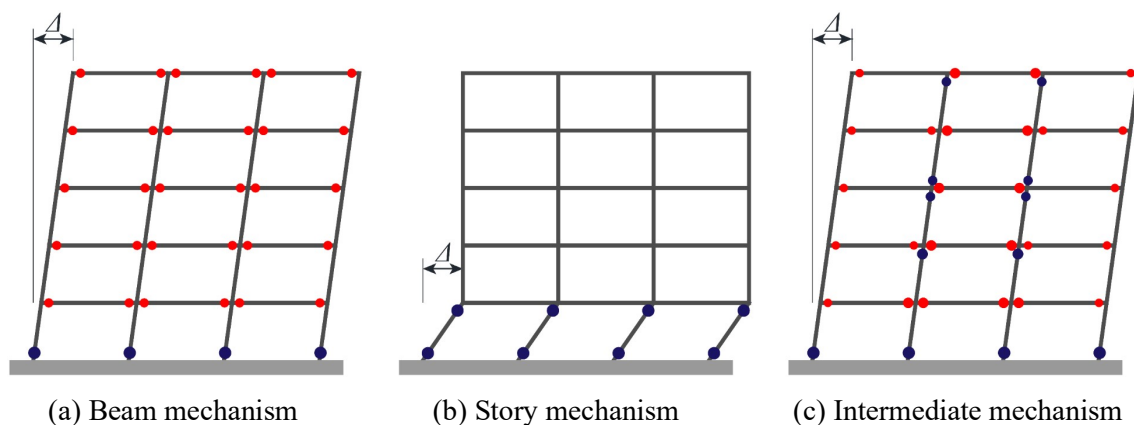


Fig. 1 Main seismic failure mechanisms of RC frame structures on flat ground

Generally, it's difficult to achieve the beam mechanism in actual engineering design. The method of using seismic measures can significantly improve the seismic performance of RC frames structures by reducing axial force ratio, increasing cross-section size or increasing the reinforcement ratio of the columns, which often result in developing an intermediate mechanism.



2.2 SFRCF

Unlike the seismic failure mechanism of RC frames on flat ground, the upper base columns will yield first due to their larger lateral stiffness than the remain columns in the upper ground story that result in more bending moments and shear forces in them. When the collapse of one of the upper base edge column or all the upper base interior columns occurs, the “half-story mechanism” happens (fig. 2).

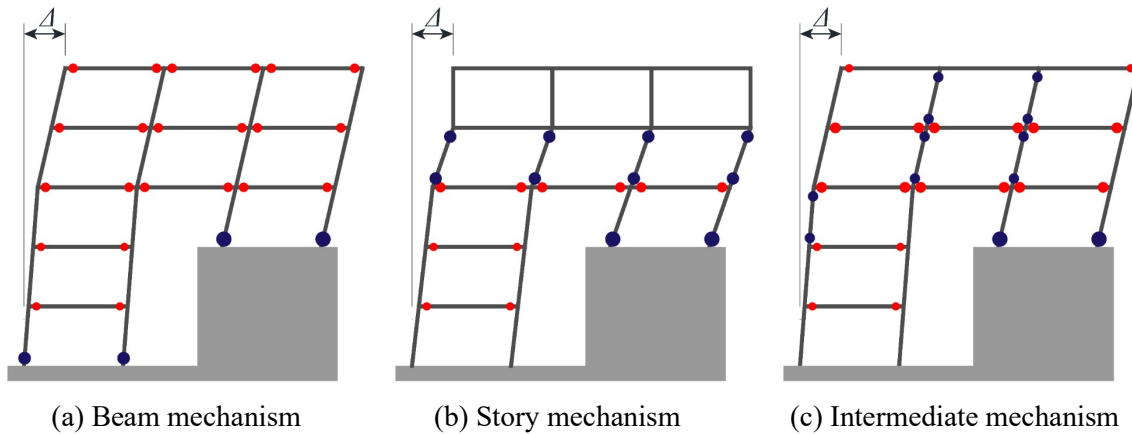


Fig. 2 Main seismic failure mechanisms of SFRCF

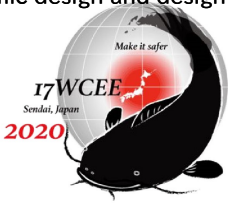
The extent of the "half-story mechanism" of SFRCF under strong ground motions mainly depends on the structural configuration of the lower stories. When the number of lower stories and lower bays are small compared to the total number of stories and bays, the extent of "half-story mechanism" is not significant, the maximum damage level of the structural components in the weak story is also very low. However, when increasing the number of the lower stories or lower bays, the lateral stiffness distribution of the columns will be pushed into a more uneven distribution, which will result in severe damage in the upper base columns. The "half-story mechanism" is not conducive to the development of the global deformation and energy dissipation of the structural system, it is a special seismic failure mechanism mainly based on local damage. In the structural design, the damage level of the structural components in SFRCF should be controlled to achieve a more reasonable seismic failure mode of the whole structural system.

2.3 Seismic damage levels

The evaluation criteria for seismic damage level of RC structural components are in accordance with the recommended values in the Chinese structural collapse resistance design code [12], as shown in Table 1.

Table 1 Strain-based seismic damage levels for RC components under flexural failure

Damage level	Damage description	Criteria	
		Concrete	Rebar
1	No damage	$ \varepsilon_3 \leq \varepsilon_p $	and $\varepsilon_1 < \varepsilon_y$
2	Slight damage	$ \varepsilon_3 \leq \varepsilon_p $	and $\varepsilon_y < \varepsilon_1 \leq 2\varepsilon_y$
3	Minor damage	$ \varepsilon_p < \varepsilon_3 \leq 1.5 \varepsilon_p $	or $2\varepsilon_y < \varepsilon_1 \leq 3.5\varepsilon_y$
4	Moderate damage	$1.5 \varepsilon_p < \varepsilon_3 \leq 2.0 \varepsilon_p $	or $3.5\varepsilon_y < \varepsilon_1 \leq 8\varepsilon_y$
5	Major damage	$2.0 \varepsilon_p < \varepsilon_3 \leq \varepsilon_{cu} $	or $8\varepsilon_y < \varepsilon_1 \leq 12\varepsilon_y$
6	Collapse	$ \varepsilon_3 > \varepsilon_{cu} $	or $\varepsilon_1 > 12\varepsilon_y$



Where, ε_1 and ε_3 are the principal tensile and compressive strain values, respectively; ε_p and ε_{cu} are the peak and ultimate compressive strain of the concrete under uniaxial compression, respectively; ε_y is the yielding strain of rebar.

3. Case study

3.1 Description of selected structures

In order to investigate the influence of lower bays on the seismic failure mechanism of SFRCF, four 6-story SFRCF with different number of lower bays in the regions of SFI 8 (SFI: seismic fortification intensity, PGA=0.2 g), Site Class II, Seismic Design Group I were designed as per Chinese seismic design code GB 50011-2010 [13]. The structural elevation is shown in Fig. 3. These buildings have a story height of 4.2 m at the lower ground floor, and 3.6 m for all other floors. The dead load (including the weight of the slab) and the live load applied on the slab were 5.0 kN /m² and 2.0 kN /m², respectively. The steel rebars had a standard yielding strength of 400 MPa, whereas the standard cube compression strength of the concrete was 30 MPa. The columns have a cross-section of 0.60 m and 0.55 m, respectively, and all the beam cross-section is 0.3 m × 0.55 m. Further details on the reinforcement can be found in [14].

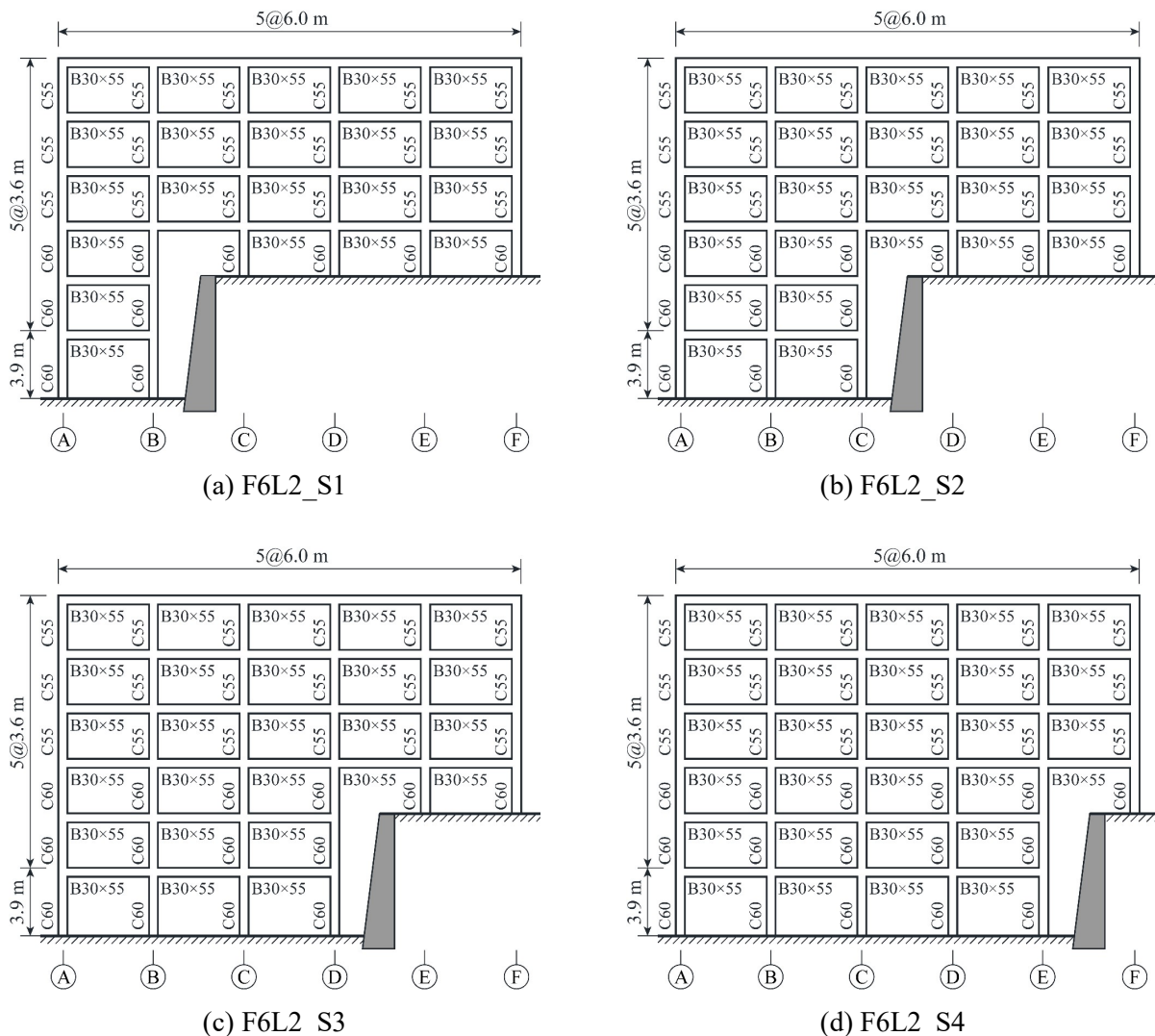
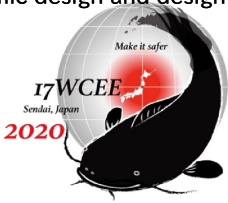


Fig. 3 Elevation of the considered 6-story SFRCF with different lower bays (unit: cm)



3.2 Description of the analytical model

The finite element model was developed via OpenSees software. The Displacement-based beam-column element was used for beam and columns with five integration points at each element. Concrete02 with modified Kent-Park [15] constitutive model was applied for the confined concrete, and Steel02 was used to construct a uniaxial Menegotto-Pinto [16] steel material model for rebars. To simulate the coupling effect with flexure and shear mechanism of the columns, the shear spring was attached to the upper base columns by using shear limit curve and limit state material, and the axial spring was also attached to the columns by using axial limit curve and limit state material. The “MinMax” material in OpenSees was used in conjunction with the Steel02 material model to specify an upper bound of rebar strains, it can detect the axial tensile failure of the earthing beams. The layout of nodes and elements for the analytical model is shown in Fig. 4.

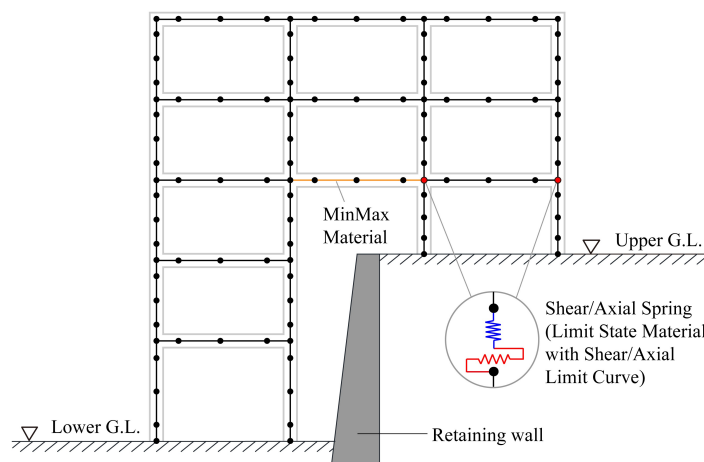


Fig. 4 Model of SFRCF

3.3 Overall failure mechanism

To investigate the seismic failure mechanism of the SFRCF with different structural configurations, a modified piecewise lateral load procedure (APA + Uniform) [14] which can reflect the difference of seismic inputs between the lower and upper ground levels was performed. All the SFRCF were pushed from left to right (LR) and right to left (RL), respectively. The results are expressed as base shear-roof drift curves presented in Fig. 5.

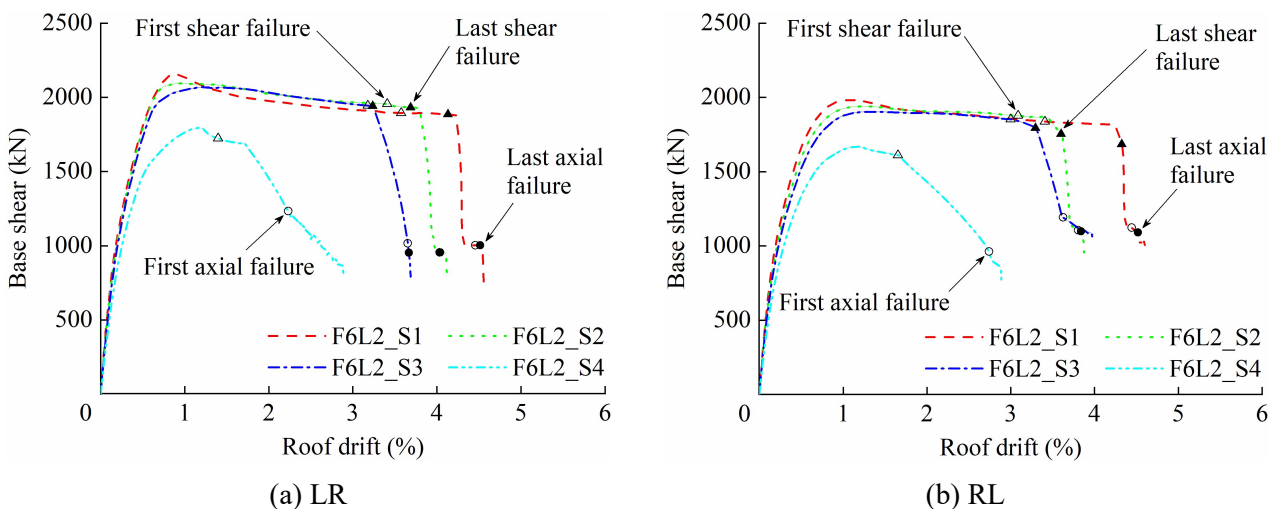
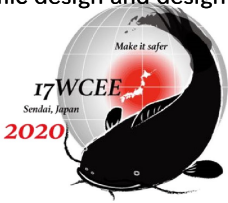


Fig. 5 Pushover curves of the considered 6-story SFRCFs with different lower bays

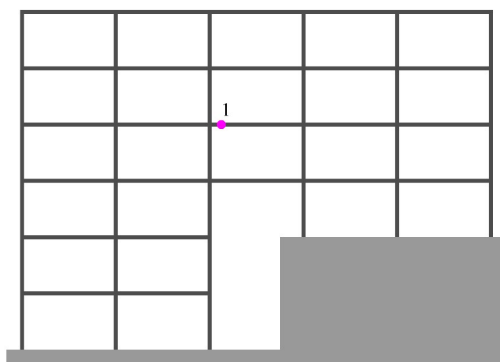


Above figures show that the roof drift capacity for SFRCF at the failure points is reducing with increasing the lower story bays. When the first shear failure was detected in the upper base columns, the SFRCF experience strength degradation, and consequently the lateral force which should be carried by the collapsed column transferred to the remaining upper columns. A sudden shear capacity degradation would happen after the last shear failure was detected. So, the upper base columns are the weakest structural components of the whole structural system. The primary reason is the uneven distribution of lateral stiffness between the upper base columns and the columns at the lower story side. The more the lower story bays, the larger the average lateral stiffness of the upper base columns, the lower bearing capacity of the whole structural system.

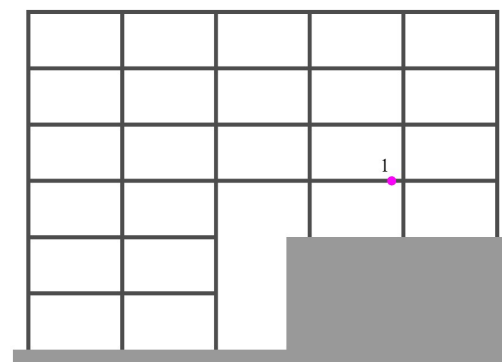
However, all the shear failures of SFRCF were detected after the base shear peak point, which met the requirements of “strong shear-weak bending” in the codes.

3.4 Failure path

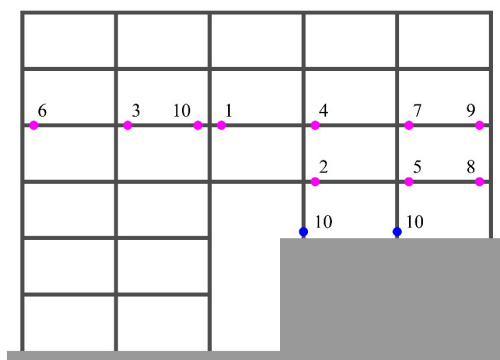
Using the fiber strains of rebar and core concrete to detect the sequences and damage levels of the plastic hinges in beams and columns, which reflect the failure path of the structure. The failure path can include: flexural yielding at the beam ends in the upper ground story → flexural yielding at the upper base column base → flexural yielding at the beam ends in other upper stories → shear failure at the upper base column → axial failure at the upper base column → collapse. Generally, it is an intermediate mechanism. Limit to the space, only the results of frame F6L2_S2 are presented here (Fig. 6).



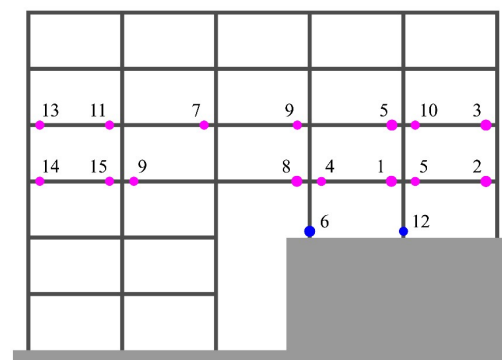
(a) LR beam hinge ($\bar{\theta}=0.46\%$)



(b) RL beam hinge ($\bar{\theta}=0.42\%$)



(c) LR column hinge ($\bar{\theta}=0.57\%$)



(d) RL column hinge ($\bar{\theta}=0.71\%$)

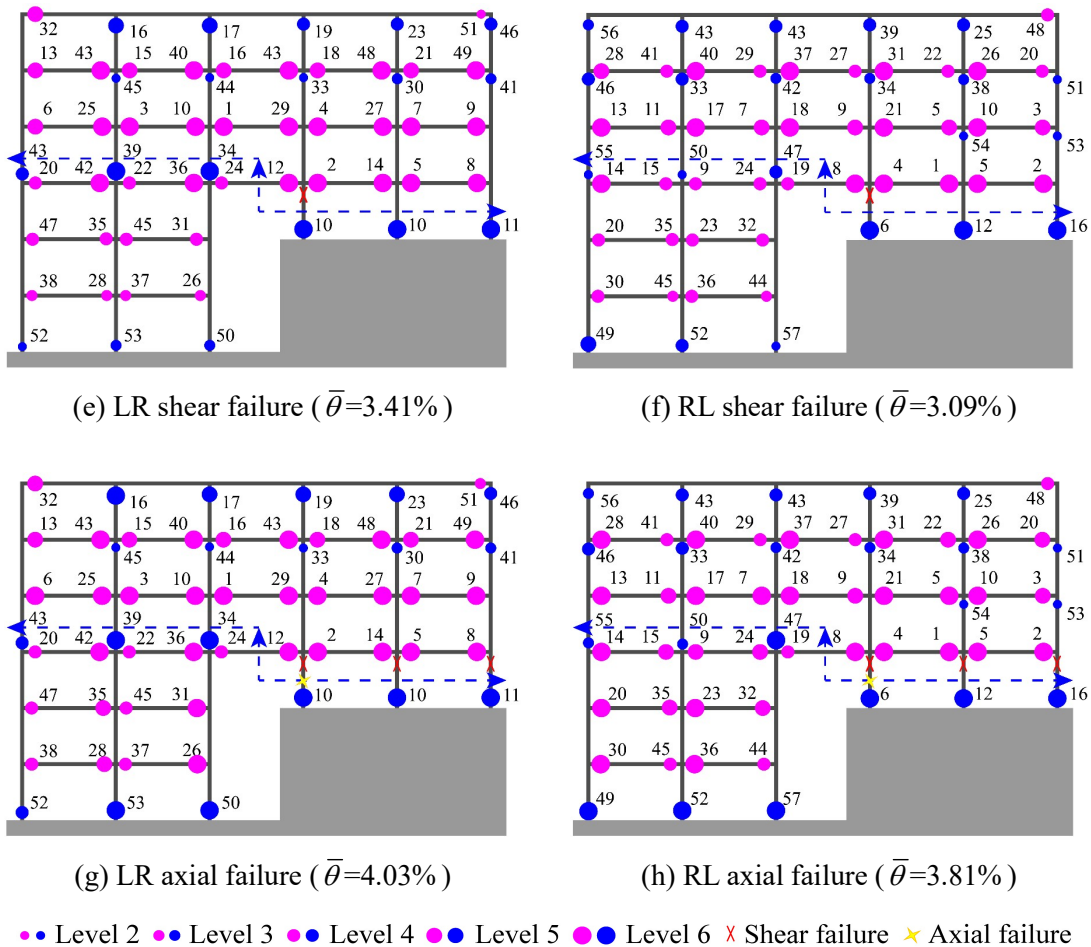


Fig. 6 Seismic failure path of F6L2_S2

For F6L2_S2, with push loads, the roof drift was reached at 0.46 %, at which the upper ground beam began to yield, and the structure was still maintained in elastic state, with no obvious deformation and failure phenomenon were observed (Fig. 6(a)). At a roof drift of 0.57%, the upper base interior column began to yield. Meanwhile, several beam hinges were formed in the upper ground and the second stories with minor damage level (Fig. 6(c)). With the increasing of lateral loads, more plastic hinge formed at beam and column ends, and their damage levels were increasing. The first shear failure occurred at the upper base column base after a roof drift of 3.41%, then the shear bearing capacity of this column declined rapidly, its original shear was borne by the remaining upper base columns. Plastic hinges formed in about 80% of the upper stories, and more than half of them were in major damage levels (Fig. 6(e)). As the lateral loads continued to increase, shear failure also occurred in other upper base columns, and the shear strength of the structure degraded suddenly (Fig. 5). When roof drift reached 4.03%, the axial failure of the upper base column happened, then the structural system collapsed (Fig. 6(g)). In addition, no tensile failure was detected in the earthing beam under rare earthquakes, but it was severely damaged. So, it suggested being designed as a tension-bending member with higher seismic measure grade.

4. Conclusions

In this study, a seismic failure mode identification method for SFRCF is proposed, and its effectiveness and rationality are preliminarily verified. The salient conclusions are as follows:



The pushover analyses show that a "half-story mechanism" is likely to occur causing significant deformation concentration in the upper base story of SFRCF. Once the shear failure has occurred in all the upper base columns, the whole structure collapses immediately.

Structural configuration of the lower stories has a significant impact on the seismic failure mode of the SFRCF and the maximum seismic damage level of the structural components. The more the number of lower story bays, the more damage is concentrated on the upper base columns and beams. The upper base columns should be strengthened or based isolated depend on the structural irregularity levels. And the earthing beams still need to be designed as a tension-bending member with higher seismic measure grade.

Although the SFRCF designed according to the current Chinese code meet the principle of "strong shear-weak bending", but most of the plastic hinges with high damage level are concentrated on the upper ground story, that limits the overall energy dissipation ability of the structural system to achieve the desirable performance. Hence, some anti-seismic measures should be considered to improve the seismic failure mode of SFRCF.

5. Acknowledgements

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