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SEISMIC FRAGILITY OF TYPICAL STILTED RC FRAME STRUCTURES

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Abstract

Stilted building is a typical residential building style in western mountainous areas of China. It has foundation at different ground levels and columns of varying length to accommodate ground slope, introducing vertical stiffness irregularity at upper base stories. Observations of structural damage from the past earthquakes indicate that the seismic damage of stilted buildings is significantly different from that of buildings on flat ground. In order to investigate the seismic response characteristics of stilted building structures, two reinforced concrete (RC for short) stilted frame structures with different slopes were designed in accordance with Chinese code for seismic design of buildings. 16 strong ground motions were selected and scaled. Damage index corresponding to each damage state are defined by a maximum inter-layer drift value. The incremental dynamic analysis method (IDA) was used to determine the probability of damage states for each stilted reinforced concrete frame structure at different seismic intensity levels. The seismic vulnerability curve of stilted reinforced concrete frame structure was obtained, which can provide scientific reference for evaluating the loss of stilted reinforced concrete frame structures in earthquakes. The results show that earthquake damage of reinforced concrete stilted frame structures mainly concentrate on short columns at ground floor, and reducing the stiffness of short columns can be beneficial to improving the seismic performance of such structures. Compared with ordinary frame structures, the seismic damage of reinforced concrete stilted frame structures is more serious. These conclusions can provide scientific reference for the design of reinforced concrete stilted frame structures.

Keywords: stilted building; RC frame structure; seismic fragility; incremental dynamic analysis

1. Introduction

Many cities in the world are built on sloping terrains. In order to adapt to the sloping terrains, a kind of mountain buildings whose foundation is not at the same elevation was built. Stilted structure is a common structural form among mountain buildings. Columns are arranged with different grounding levels along the slope to form a platform, and then buildings are built on the platform. The stilted structure has uneven vertical stiffness, and the stiffness of the stilted floor is greatly different from that of the upper floor. The length of each column in the stilted layer is different, and this makes columns closed to the upper part of the slope a short column. Under the action of the earthquake, the short columns in stilted layer share more horizontal forces and are more prone to damage. In Wenchuan earthquake, Sikkim earthquake, and Nepal earthquake, the RC stilted frame structure was observed to be more severely damaged than the ordinary RC frame structure [1 ~ 3], and the damage to the short columns of the stilted was particularly serious. In recent years, Chinese scholars have studied the seismic response characteristics of different types of mountain building structures, the applicability of torsional control indicators in mountain building structures, the seismic failure mechanism of step-terrace frame structures. Pseudo-static tests and shaking table tests of step-terrace frame structures were both carried out [4 ~ 7].

Fig. 1 – Seismic damage to stilted structures during the Wenchuan earthquake.

In this paper, two RC stilted plane frame structures with different slopes were designed. The elastoplastic finite element analysis model was established using OPENSEES, and the rationality of the analysis model was verified by the existing pseudo-static test. Based on the static elastoplastic analysis results, the load-deformation curves, failure modes and ductility of two RC stilted frame structures with different slopes was compared and analyzed. Based on the IDA method, through the fragility analysis of the two structures, the fragility curve of the stilted structure was obtained. The probability of different levels of failure of the stilted frame structures under different earthquakes was studied. The seismic safety of the structures was assessed and the seismic losses of the structures were estimated.

2. Model design and analysis model verification

Two RC stilted frame structures with different slopes were designed as shown in Figure 2. The slope of structure DJ-1 is 24 °, and the slope of structure DJ-2 is 19 °. The layout of the two structures is 2×3 spans with a span of 6m, of which there are 2 spans along the slope and 3 spans across. The number of structural layers is 7, the height of the floors above the stilted platform is 3m, and the height of the platform columns is shown in Figure 2. The structural design was carried out according to the requirements of Chinese codes [8 ~ 9]. The site category was Class II, the design earthquake was in Group 1, the seismic fortification intensity was 8 degrees, and the design basic earthquake acceleration was 0.2g. The cross-section dimensions of the columns on the upper floors of the two structures are both 450×450mm and the beam cross-sections are both 150×450mm. The shortest column cross-section size of the structure DJ-1 stilted platform layer is 750×750mm, and the other two column cross-section sizes are 600×600mm. The size of stilted platform columns of structure DJ-2 is 480×480mm. The concrete grades of the two structures are C30, and the grades of the reinforced bars and stirrups are HRB400. The additional dead load on the floors and the roof of structures DJ-1 and DJ-2 is 1.5KN/m^2 and 4.0 KN/m^2 respectively. And the live load of the two structures is 2.0 KN/m^2. All floors are 120 mm thick. YJK structural design software was used for internal force calculation and section reinforcement design of the structures. All of the supports were fixed and the soil-structure interaction was not considered.

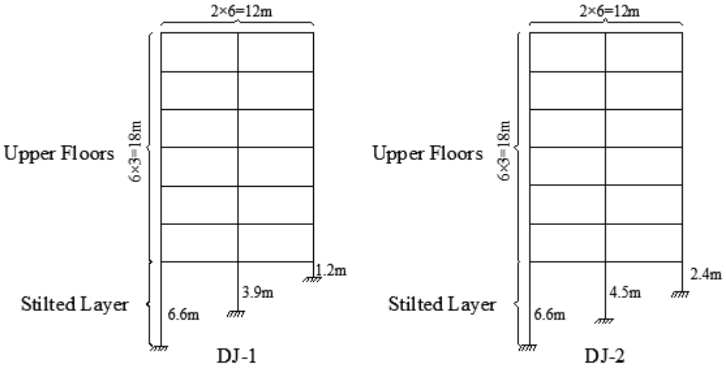
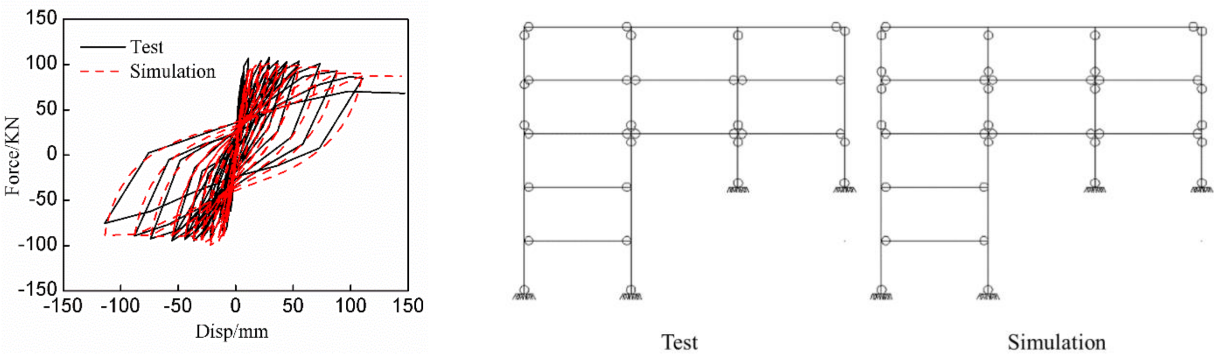


Fig. 2 – Designed stilted RC frames

The along-slope middle frame of the designed structure was selected, and the elastoplastic analysis was performed using OPENSEES. The damping ratio was set to 0.05 in the dynamic elastoplastic analysis. A displacement-based beam-column element based on the finite element stiffness method was used to establish the analysis model. The model considered the restraint effect of stirrups on concrete, and the section was divided into core area and protective layer. The modified Kent-Park model [10] (Concrete 02) was used for the concrete. The ultimate compressive strength of the core concrete was K× f_c', and the ultimate tensile strength was 0.2K× f_c'. K is the strength improvement factor considering the restraint effect of stirrups on concrete. f_c' is the compressive strength of the cylinder of unconstrained concrete. The reinforcing bar used the uniaxial isotropically strengthened Giuffre-Menegotto-Pinto model [11] (Steel 02). The model considers the Bauschinger effect of steel bars and has good consistency with repeated loading tests of steel bars. The model does not take into account the bond-slip effect between steel and concrete. Each beam and column was divided into 4 units, and each unit was provided with 6 integration points.

In order to verify the validity of the elastoplastic analysis model, according to the quasi-static test of the structural frame with different height constraints [12], elastoplastic simulation was conducted. The simulation and test load-displacement curves and failure modes are listed in Figure 3. It can be seen from the figure that the load-displacement curves of the test and simulation are similar, and the structural stiffness and load capacity are close too. The plastic hinge condition of beams and columns of the test is basically consistent with the simulation, so the model can accurately simulate the failure mode of the structure. It shows that the simulation method can accurately simulate the elastoplastic seismic response of RC frame structures with different height constraints.



(a) Load-displacement curve

(b) Failure mode

Fig. 3 – Comparison of simulation and test results of the stilted RC structur

3. Static elastoplastic analysis

Based on the static elastoplastic analysis of the structure, the load-displacement curve, ductility, energy consumption performance and failure mode of the stilted frame structures with different slopes was studied.

Using the inverted triangle horizontal force distribution mode, reciprocating loads was applied to the structures DJ-1 and DJ-2 respectively. The loading process was controlled by the overall structural displacement angle corresponding to the vertex displacement. The initial displacement angle is 1/1000, ensuring that the structure is in an elastic working state at the initial loading section. When the displacement angle is less than 1/25, the plastic deformation of the structure is sufficient, that is, the loading is stopped here. In the figure, the load is the sum of the horizontal forces on each floor of the structure and the deformation is the displacement of the top layer of the structure.

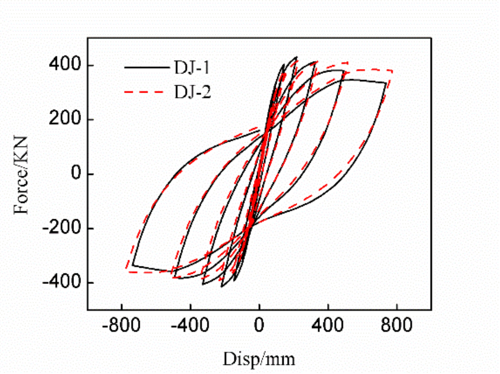
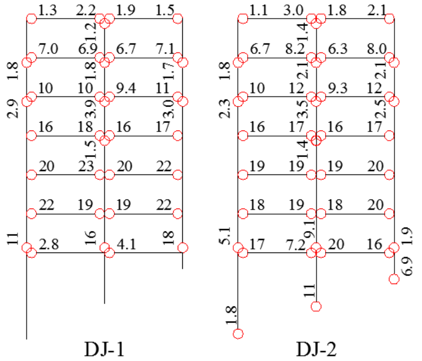


Fig. 4 – Load-deformation curve of the stilted RC frame structures



(Numbers in the figure are the ratio of the maximum strain to the yield strain of the longitudinal bars)

Fig. 5 – Plastic hinge distribution of the structures in static elastoplastic analysis

It can be seen from Figure 4 that there is no significant difference in the maximum load of the stilted frame structures with different slopes, indicating that the horizontal peak load capacity of the two structures is not significantly different. With the increase of the displacement of the top floor, the peak load capacity of the stilted frame structure DJ-1 with a larger slope decreases faster than that of DJ-2. It shows that the ductility of the structure DJ-1 is slightly worse than that of DJ-2, that is, the lower the slope of the stilted frame structure, the better the ductility.

Figure 5 is the distribution diagram of plastic hinges at ends of beams and columns in the structures DJ-1 and DJ-2 obtained through static elastoplastic analysis. In the figure, the hinges at the ends of the beams are more than the ends of the columns, which meets the seismic design principles of strong columns and weak beams. In both structures, hinges only appear at the lower end of the columns of the stilted platform and the first upper floor, and the upper end of the columns of the upper floors. No layer displacement mechanism is formed, which validates the seismic performance of the stilted frame structure.

There is no significant difference in the number and the degree of hinges in the two structures above the second floor. However, at the stilted platform, the hinges at beam ends and column ends of the structures DJ-1 and DJ-2 are significantly different from each other. The beam of structure DJ-1 has hinges only at the left end, while the beam of structure DJ-2 has hinges at the left and right ends. In addition, the column ends of DJ-1 are not hinged on the platform layer, while the shortest columns of DJ-2 are hinged at the lower end. This shows that under the action of earthquakes, compared with the structure with a lower slope, the structure with a larger slope suffers less bending damaged at the stilted platform. On the first floor above the stilted platform, the plastic hinge at the column end of the DJ-1 is more developed than the DJ-2. The plastic hinge at the lower end of the DJ-1 structure is more developed and higher ductility is required there. In the design, attention should be paid to the columns on the first floor above the stilted platform to prevent the occurrence of weak layers.

4. Fragility analysis based on the IDA method

4.1 Fragility analysis method

The seismic fragility of structures refers to the probability of occurring various failure or reaching a certain limit state of structures under the action of ground motions with different intensity. The expression of this probability is as follows:

$$F_R=P[D\geq LS \mid IM=x] \tag{1}$$

Where：FR is the seismic fragility; P is the failure probability; D is the damage of structures; LS is the failure state or some limit state of structures; IM is the seismic intensity parameter.

Incremental dynamic analysis (IDA) is to carry out a series of monotonic amplitude modulation on the intensity index of a specific ground motion, and take each seismic wave after amplitude modulation as the input ground motion for time history analysis, and then get the corresponding structural seismic response of each seismic motion after amplitude modulation. The seismic response data of each seismic motion are analyzed statistically, and the fragility curve corresponding to a certain limit state is obtained. By analyzing the fragility curve of the structure, the structural safety and seismic loss are evaluated.

4.2 Selection of ground motion and intensity measure

Uncertainty of ground motion is one of the important factors that affect the rationality of fragility analysis. In this paper, according to the site classification of the structure, 16 ground motions satisfying the requirements of epicenter distance and duration were selected from PEER Strong Motion Database for analyzing the fragility of the structures. See Figure 6 for response spectrums of selected ground motions. The black line is the design response spectrum, and the rest are the selected ground motion response spectrums.

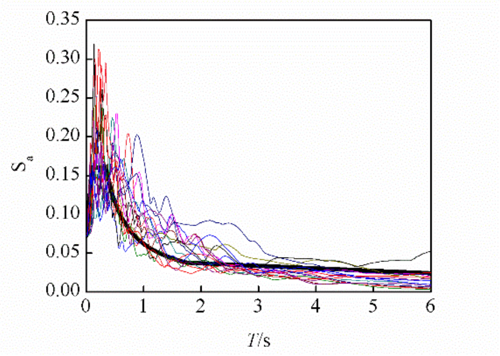


Fig. 6 – Response spectrums of selected ground motions

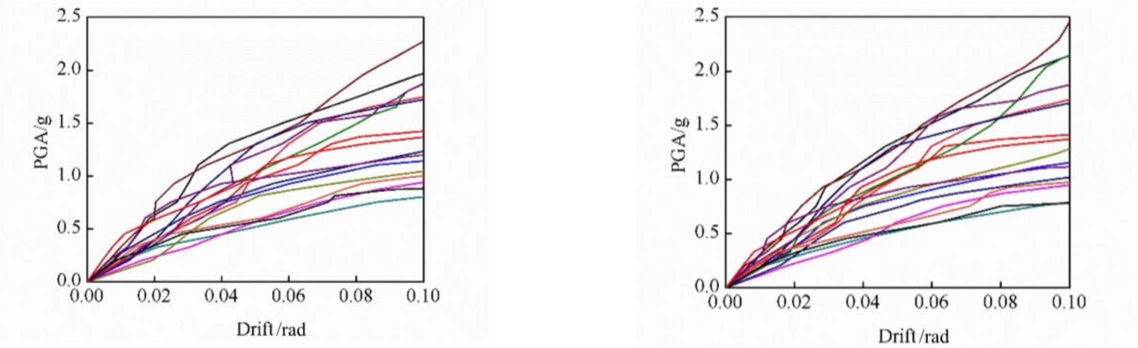
Choosing reasonable parameters to reflect and quantify the intensity of ground motion is the key step of the IDA analysis. PGA is one of the most intuitive parameters to describe the intensity of ground motion when an earthquake occurs, which has been widely recognized and used in practical engineering. Therefore, PGA was selected as the seismic intensity measure IM in this paper.

4.3 Structural damage measure DM

Luco N [14] etc. pointed out that the maximum inter story drift can reflect the comprehensive results of the elastic-plastic deformation of the beams, columns and joints, and the relative strength relationship of the beams and columns. Moreover, it can comprehensively reflect the performance of the whole structure. For the frame structures, the maximum inter story drift is usually selected as the damage measure index. In addition, in the code for seismic design of high-rise buildings based on performance [15], the maximum inter story drift is taken as the index for evaluating each performance level. In Chinese code for seismic design of building, the maximum inter story drift is also the basis for evaluating the structure to achieve the seismic fortification goal (no damage under small earthquake, can be repaired under medium earthquake, not collapse under large earthquake). Therefore, the maximum inter story drift was selected as the index of seismic damage measure. The ratio of the horizontal displacement of the upper and lower ends of the shortest column was defined as the inter story drift of the stilted platform layer.

5. Fragility analysis results

The hunt&fill algorithm [16] was used to adjust amplitude of the intensity of selected strong ground motions one by one. The amplitude modulation step is 0.2g, the step increment is 0.05g, PGA = 0.005g in the first analysis. After getting the maximum inter story drift corresponding to each level of ground motion, the IDA curve of each ground motion was obtained by interpolation method, as shown in Figure 7. According to the performance-based high-rise building structural design code of the United States, the maximum inter story drift corresponding to IO, LS and CP performance levels are 1%, 2% and 4%, respectively.

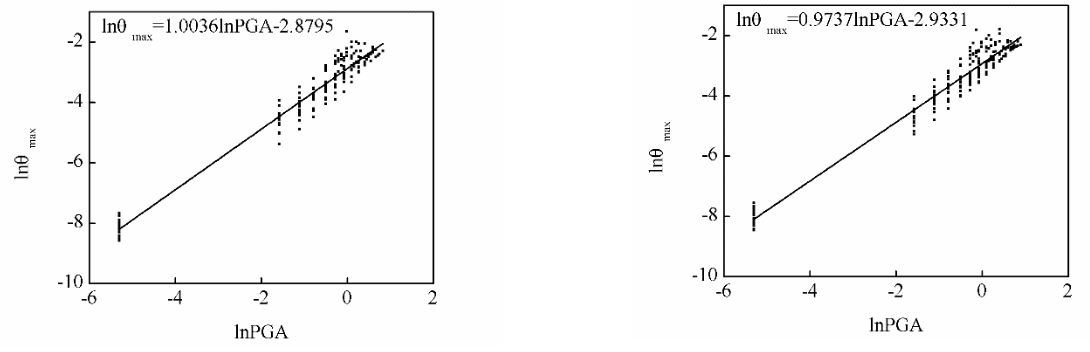


(a) DJ-1 (b) DJ-2

Fig. 7 – IDA curves of stilted RC frames

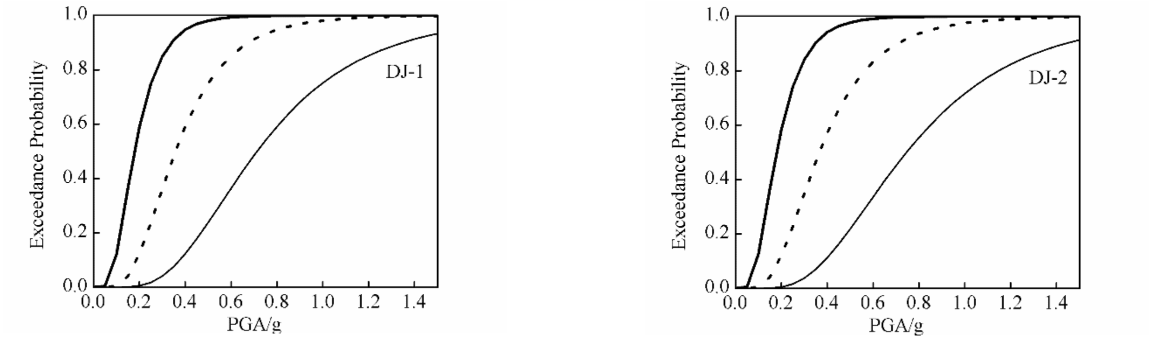
It can be seen from Fig. 7 that when the PGA is low the IDA curves increases approximately linearly in the initial stage, the structure is in the elastic state. With the increase of the PGA, the overall slope of IDA curves decreases, which indicates that the structure is in the elastic-plastic state. The PGA value of each ground motion corresponding to DJ-1 and DJ-2 is between 0.4g and 1.3g at the maximum inter story drift 4% that corresponds to the collapse state.

The natural logarithm of the independent variable (PGA) and the natural logarithm of the dependent variable (inter story drift) were obtained by analyzing and calculating the data form IDA curves of DJ-1 and DJ-2, and the corresponding scatter diagram was drawn. By statistical analysis of the data in the scatter diagram, the regression linear equations of independent variables and dependent variables were obtained (Figure 8). According to the obtained linear regression equation and the defined limit state of the structure, the fragility curve corresponding to each limit state was obtained, as shown in Figure 9.



(a) DJ-1 (b) DJ-2

Fig 8 – Linear regression analysis



(a) DJ-1 (b) DJ-2

Fig. 9 – Fragility curves of stilted RC frames

It can be seen from Figure 9 that the exceedance probability curve corresponding to IO, LS and CP states of the structure DJ-2 with a lower slope is smoother compared with that of the structure DJ-1 with a larger slope, proving that the exceedance probability of DJ-2 is lower than that of DJ-1. When PGA = 0.5g, the exceedance probability of DJ-1 and DJ-2 corresponding to CP state is 0.24 and 0.22 respectively. When PGA = 1.0g, the exceedance probability of DJ-1 and DJ-2 corresponding to CP state is 0.75 and 0.71 respectively. It shows that the collapse resistance of the structure with a lower slope is slightly stronger than that of the structure with a larger slope.

According to Chinese code for seismic design of building, the peak ground acceleration for time history analysis of rare earthquake with the seismic fortification seldom intensity 8 is 400cm / s2, i.e. PGA ≈ 0.4g. In Figure 9, when PGA = 0.4g, the exceedance probability of DJ-1 corresponding to CP state is 0.12, and that of DJ-2 is 0.11. It shows that the collapse probability of the two stilted RC frames is low under rare earthquake, so the stilted structures can achieve the design goal that structure not collapse.

6. Conclusions

In this paper, two RC stilted frame structures with different slopes were designed. Through the static elastoplastic analysis and the incremental dynamic analysis, the load-deformation curves and the plastic hinge distribution characteristics of the stilted structures was obtained, the IDA curves and corresponding statistical curves were obtained, and then the fragility of the structures was analyzed. The main conclusions are as follows:

(1) The horizontal peak load capacity of the stilted structures with different slopes is not significantly different. And the ductility of the structure with a lower slope is better than that of the structure with a larger slope.

(2) In both structures, column hinges only appear at the lower end of the columns of the stilted platform and the first upper floor, and the upper end of the columns of the upper floors. No layer displacement mechanism is formed, which validates the seismic performance of the stilted frame structures. At the stilted platform, the damage state at beam ends and column ends of the structures with different slopes are significantly different from each other. The structure with a larger slope suffers less bending damage at the stilted platform, but the columns on the first floor above the stilted platform suffer more serious damage. In the design, seismic capacity of the columns on the first floor should be improved for the stilted structures with a large slope.

(3) The collapse probability of the stilted structures designed in accordance with seismic design code is low under the action of rare earthquake, which can achieve the design goal of earthquake resistance. And the collapse resistance of the structure with a lower slope is slightly stronger than that of the structure with a larger slope.

7. Acknowledgements

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