SEISMIC PERFORMANCE OF SET- BACK AND STEP-BACK RC FRAME STRUCTURES

L. P. Liu(1), Y. R. Yin(2), Y. J. Yu(3), J. Xu(4), J. Han(5), P. Yang(6), Y. F. Dong (7) , R. F. Li(8)

(1) *Professor, School of Civil Engineering, Chongqing University, liuliping@cqu.edu.cn*
(2) *Graduate student, School of Civil Engineering, Chongqing University, 1294275220@qq.com*
(3) *Graduate student, School of Civil Engineering, Chongqing University, 20145142@cqu.edu.cn*
(4) *PhD candidate, School of Civil Engineering, Chongqing University, junxusc@gmail.com*
(5) *Assoc. Professor, School of Civil Engineering, Chongqing University, hanjun009@126.com*
(6) *Professor, School of Civil Engineering, Chongqing University, yangpu@cqu.edu.cn*
(7) *Assoc. Professor, School of Civil Engineering, Chongqing University, dongyinfeng@cqu.edu.cn*
(8) *Graduate student, School of Civil Engineering, Chongqing University, 201716021060@cqu.edu.cn*

Abstract

Stilted structures are a common building type in sloping structures. In order to adapt to the terrain change of the sloping field, sometimes the upper part of the structure also retreats to form a stilted-set back structure. The stilted-set back structure has both grounding ends with unequal heights and the step-up superstructure. Therefore this kind of structure is obviously vertically irregular. In order to study the seismic performance of the stilted-set back structure, three types of stilted-set back RC structure were designed and the corresponding elastoplastic finite element analysis models were established. The dynamic time history analysis method is used to compare and analyze the influence of the number of set-back storeys on horizontal displacement, the seismic shear force, the failure location, and the damage degree of the structures. The seismic response characteristics and failure mode of stilted-set back RC frame structures are proposed. The study shows that the number of set-back storeys has a little effect on the seismic performance of the structure. A small number of set-back storeys can improve the seismic performance of the structure, while too many set-back storeys will increase damage under the earthquake and damage location will go upward. Plastic hinges will appear at the beam ends at the joints between the upper and lower set-back storeys. Strengthening storeys adjacent to the set-back storey will help to reduce the damage. This result can provide as reference for the seismic design of stilted-set back RC structures.

Keywords: *stilted- set back structures*; *RC frame; seismic response; slope terrain*

1. Introduction

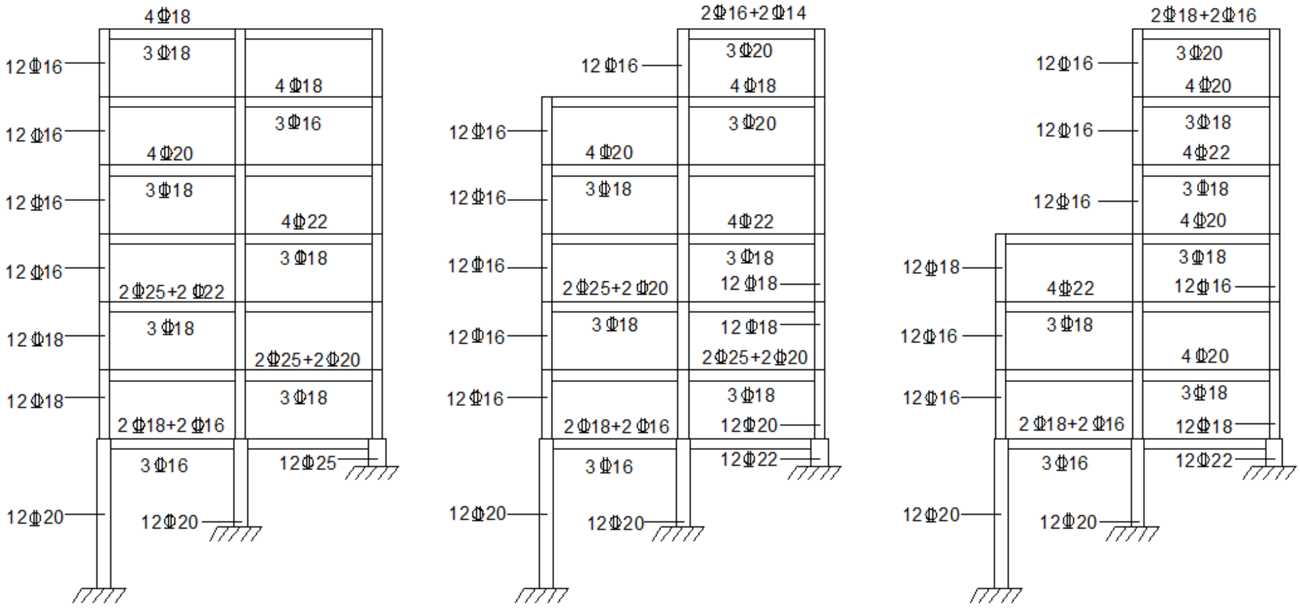
There are a lot of slopes in mountainous and hilly areas. If the method of flattening is adopted, not only the engineering cost is high, but also a series of new problems such as the environment, geological disasters, and transportation may be caused after the excavation. Therefore, for the hilly terrain, buildings built against mountains such as stilted and step-terrace structures are mostly used. The slope buildings make full use of the mountain terrain and keep the original ecology of the mountain area, which has good applicability in the mountain towns.

Researchers around the world have carried out in-depth studies on the stilted structure and step-terrace structures. Han Jun et al. [1] studied the influence of ground support type on the seismic performance of step-terrace frame structures, and found that when the bottom ends of the upper ground columns are fixed, the weak storeys are the upper 1st and 2nd storey; when the bottom of the upper ground columns are hinged, the lateral deformation of the upper grounding storey is larger, and the damage position goes upper; when the bottom of the upper grounding column adopts an isolation bearing or a sliding bearing, the weak storey is located at the step-terrace part. Xu Gang et al. [2] carried out elastoplastic analysis and vulnerability analysis of the step-terrace frame structure, and found that the collapse resistance of the step-terrace frame structure is weaker than that of ordinary frame structures. The ductility requirement of the upper ground floor columns is larger, and the damage occurs there first under the earthquake. The addition of tension beams in the upper ground floor has a certain effect on the failure mode of the step-terrace frame structure, but it cannot improve the structure's collapse resistance. Xu Jun et al. [3] used numerical simulation methods to study the seismic performance of a step-terrace frame structure with a connecting beam on the upper ground floor, and found that the tension beam significantly improved the seismic bearing capacity of the dropped frame and improved its failure mode, so that the seismic performance of the structure above the step-terrace part is equivalent to that of the ordinary frame, and the step-terrace part is just slightly damaged. S.J. Welsh-Huggins et al. [4 ~ 5] used fragility analysis method to study the seismic performance of reinforced concrete stilted structures in Indian mountain area, and found that it has a certain seismic capacity. Sometimes in order to coordinate with the sloping field, the upper part of the stilted structure is setbacked to form a set-back and step-back structure. Tamboli N. et al [6].used the response spectrum method to analyze the seismic performance of four RC stilted structures and set-back and step-back structures with different grounding constraints and number of floors. At present, the research on the set-back and step-back structure mainly focuses on the analysis of the elastic seismic performance of the structure, and pays little attention to the elastoplastic seismic performance of the structure under large earthquakes.

In this paper, the set-back and step-back RC frame structure is taken as the research object, and three different methods of setback are designed. The elastoplastic finite element analysis model is established using OPENSEES, and the dynamic time history analysis method is used to study the seismic performance of the set-back and step-back RC frame structure.

2. Analysis model and verification

In this paper, three Set-back and step-back RC frame structures are designed, including a non- setback stilted frame model (denoted as M1), a top-storey-setback stilted frame model (denoted as M2), and a top-three-storey-setback stilted frame model (denoted as M3). The seismic fortification is 8 degree (0.2g), the seismic design is grouped into the first group, and the site category is type II. The downslope direction of the structure is two-span, the transverse slope direction is 4-span, and the length of each span is 6m. The total number of storeys of the structure is 7. The maximum column height of the bottom layer is 6.6m, the center column is 3.9m, and the shortest column is 1.2m, and the height of the other storeys is 3m. The additional dead load of the structure floor is 1.5 KN/m^2, and the live load is 2 KN/m^2. The section size of the shortest column at the bottom of the structure is 750 mm×750 mm, and 600 mm×600 mm for other columns. The section size of the columns in other storeys is 450 mm×450 mm, and the section size of beams is 300 mm×450 mm. The concrete strength grade of the structure is C30, and the reinforcement strength grade is HRB400. According to the requirements of Chinese codes [7] [8], the internal force analysis, load combination, and cross-section reinforcement calculation of the structure are performed by PKPM. For all three structures, the middle frame is taken as the analysis object. The elevation and reinforcement diagrams are shown in Figure 1, labeled with M1, M2, and M3, respectively.



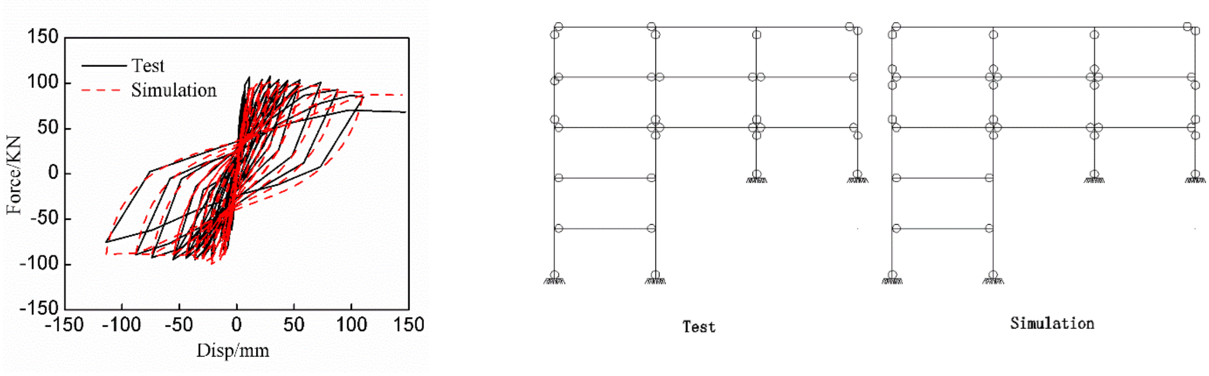
(a) M1 (b) M2 (c) M3

Fig. 1 – Set-back and step-back RC structure models

Note: When the reinforcement information is not marked on the same floor column, the reinforcement is the same as the left column; the beam reinforcement on the same floor is the same; the beam and column stirrups are Φ8 @ 100/200.

The downslope middle frame of the designed structure was selected, and the dynamic elastoplastic analysis was performed using OPENSEES. The damping ratio was set to 0.05. A displacement-based beam-column element based on the finite element stiffness method was used to establish the analysis model. The model considers the restraint effect of stirrups on concrete, and the section is divided into core area and protective layer. The modified Kent-Park model[9] (Concrete 02) is used for the concrete. The ultimate compressive strength of the core concrete is $K \times f_c'$, and the ultimate tensile strength is $0.2K \times f_c'$. 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 uses the uniaxial isotropically strengthened Giuffre-Menegotto-Pinto model[10] (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 is divided into 4 units, and each unit is provided with 6 integration points.

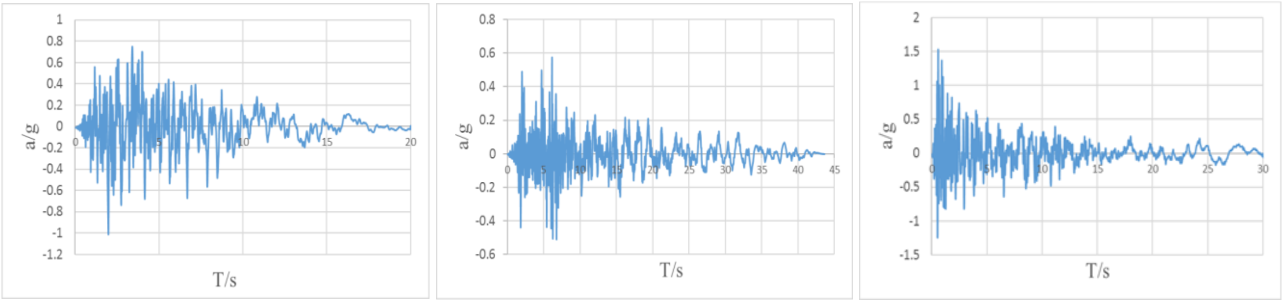
In order to verify the validity of the elastoplastic analysis model, according to the quasi-static test of the structural frame with different height constraints, elastoplastic simulation was conducted. The simulation and test hysteresis curves and failure modes are listed in Figure 3. It can be seen from the figure that the hysteresis 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. 2 – Comparison of simulation and test results

According to the Chinese seismic design code [8], two actual ground motion records were selected, and one artificial wave was fitted according to the demand spectrum, and all were input to the analysis model for elastoplastic time history analysis of the structure. The three selected ground motion waves are shown in Figure 3.



(a) artificial wave (b) Parkfield wave (c) San Fernnando wave

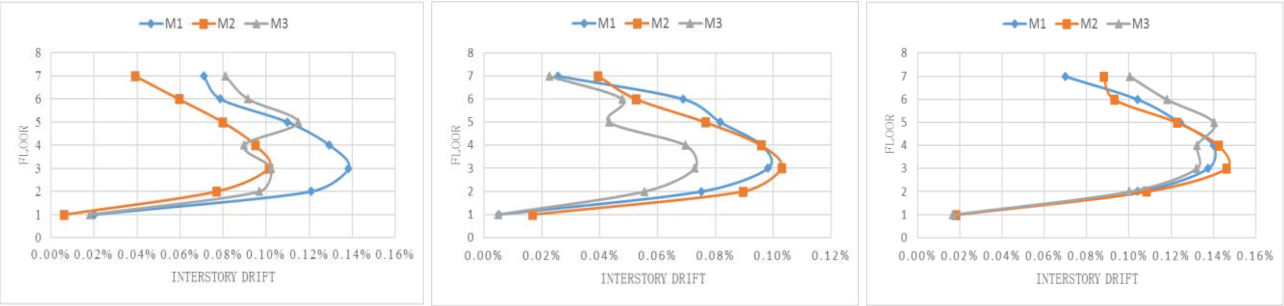
Fig. 3 – Three ground motion waves

3. Response of structures under frequent earthquake

The seismic performance of three set-back and step-back RC structures under frequent earthquakes is analyzed in this section. After adjusting the 3 seismic waves selected in Figure 3 to a PGA of 0.16g corresponding to 8 degree (0.2g) frequent earthquake, the elastic time history seismic responses of the three models are calculated. The seismic response characteristics are analyzed from the interstory drift and interstory shear forces.

3.1 Interstory drift

The interstory drift of the three set-back and step-back RC structures under frequent earthquakes are shown in Figure 4. It can be seen from the figure that the changes of the interstory drift of the three structures are similar, starting from the top layer, gradually increasing downward, and then gradually decreasing after reaching the maximum value in the middle storey. The interstory drifts of the three structures are all smaller than the limit value of 1/550 specified in the Chinese code [8], which meets the seismic requirements of the structure under frequent earthquakes. The interstory drift of the M2 is similar to that of the M1, but it increases at the top setback part in M2. The interstory drift of the M3 at the 4th floor and below is smaller than the M1 model, but it is larger than that of the M1 model above 4th floor. Therefore, compared with the non- setback stilted RC structure (M1), the interstory drifts above the setback storey in set-back and step-back RC structures (M2, M3) is significantly increased, which is mainly because the interstory stiffness of the setback part is significantly reduced, but the seismic shear force undertaken does not decrease simultaneously. In the design of the set-back and step-back RC structures, attention should be paid to the sudden change in the stiffness of the setback part.

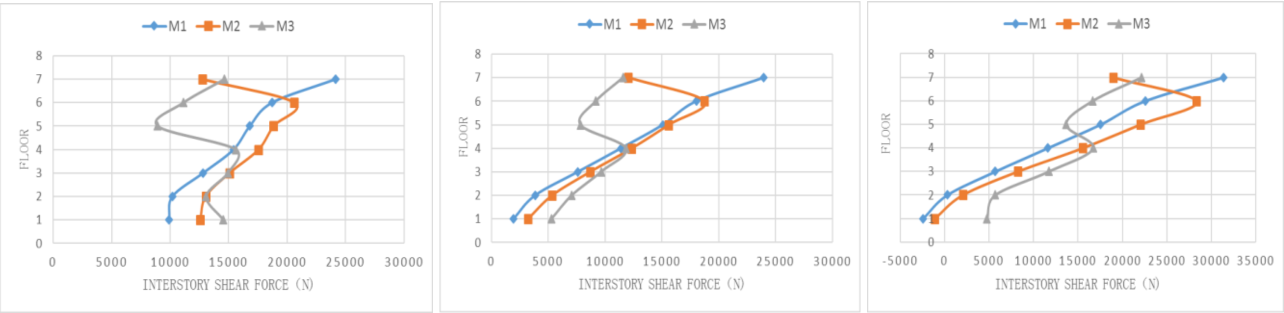


(a) artificial wave (b) Parkfield wave (c) San Fernnando wave

Fig. 4 – Interstory drifts of set-back and step-back RC structures under frequent earthquakes

3.2 Interstory seismic shear force

Figure 5 shows the interstory seismic shear forces of M1, M2, and M3 under frequent earthquakes. The interstory shear forces of M1 show an inverted triangle distribution. Compared with the interstory shear forces of M1, interstory shear forces of M2 decreased significantly at top setback part and increased below the setback part. This shows that the seismic shear force of the set-back and step-back RC structures (M2, M3) at the setback level and above will have a significant change. In combination with the distribution mode of interstory drift, these show that attention should be paid to the seismic performance of the setback part for set-back and step-back RC structures.



(a) artificial wave (b) Parkfield wave (c) San Fernnando wave

Fig. 5 – Interstory shear forces of set-back and step-back RC structures under frequent earthquakes

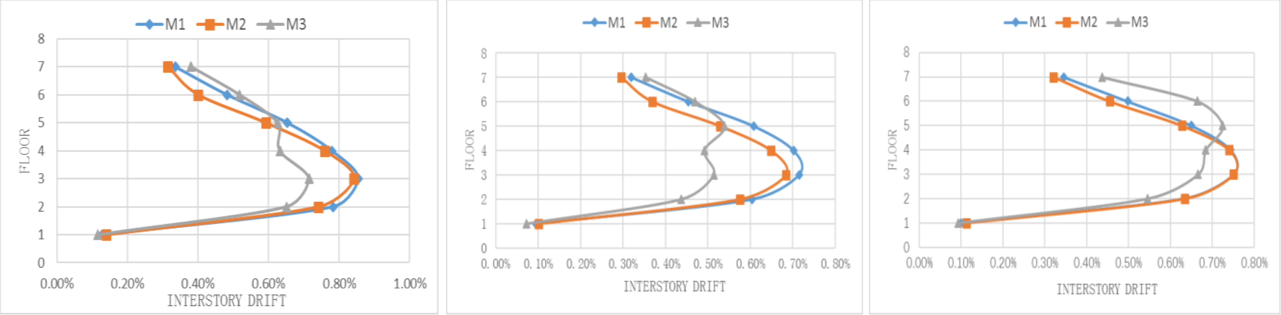
4. Response of structures under rare earthquakes

In order to further study the influence of the number of set-back storeys on frame structures, M1, M2, and M3 models were used to perform elastoplastic time history analysis under rare earthquakes. After adjusting the 3 seismic waves selected in Figure 3 to a PGA of 0.4g corresponding to 8 degree (0.2g) rare earthquake, the elastoplastic time history seismic responses of the three models are calculated. By analyzing the results of the distribution angles of interstory drift, interstory shear force, and the distribution of plastic hinges, the seismic performance of the structure is studied.

4.1 Interstory drift

Figure 6 shows the distribution of the maximum interstory drift of 3 models under the action of the artificial wave and two natural waves, respectively. It can be seen from the figure that the elastoplastic interstory drift of each structure meets the code limit. The interstory drift gradually increases from the top floor to third floor, and then decreases. The interstory drift of M1 and M2 are basically the same, while that of M3 below the set-back storey is much smaller than the other two structures. However, the abrupt change occurred above the set-back storey, and the interstory drift become larger than the other two structures, but it also meets the requirements under rare earthquakes. Therefore all three structures meet the requirements for interstory drift.

However, the interstory drift between each floor of M2 is smaller than that of M1, and the interstory drift of the top storey of M3 is larger than the other two structures after abrupt changes. So the M2 model has a relatively good performance.

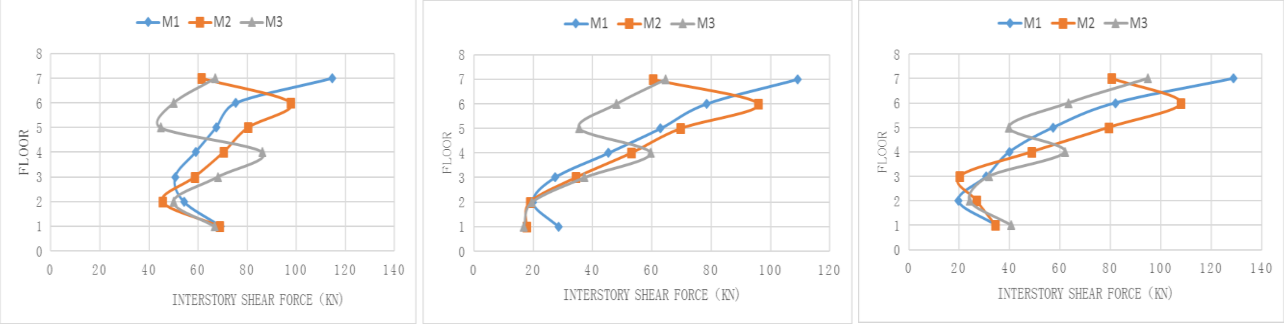


(a) artificial wave (b) Parkfield wave (c) San Fernnando wave

Fig. 6 – Interstory drifts of set-back and step-back RC structures under rare earthquakes

4.2 Interstory shear force

Figure 7 shows the distribution of inter-story shear forces along the floors in the three models. Shear forces of M1 gradually decreases from the top to the lower layers, and suddenly increases at the stilted storey, and the overall shear force distribution is inverted triangle. For the two set-back structures, a more than 20% reduction in the shear force occurs between the upper and lower set-back storeys. The M2 model's inter-story shear forces are slightly greater than the M1 model. After the inter-story shear force of M3 decreases at set-back storey, it will continue to increase again with the increase of storeys. The inter-story shear force of the top storey is basically the same as that of the M2 model, and is much smaller than that of the M1 model. The set-back structures have uniform inter-story shear force distribution, and the shear force on the top storey is relatively small. Overall, the M2 model is better than the other two structures.

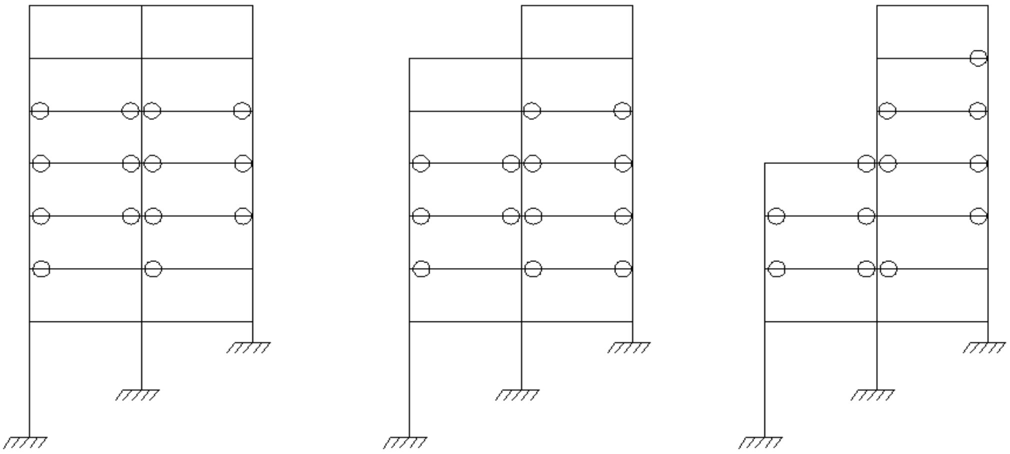


(a) artificial wave (b) Parkfield wave (c) San Fernnando wave

Fig. 7 – Interstory shear forces of set-back and step-back RC structures under rare earthquakes

4.3 Distribution of plastic hinges

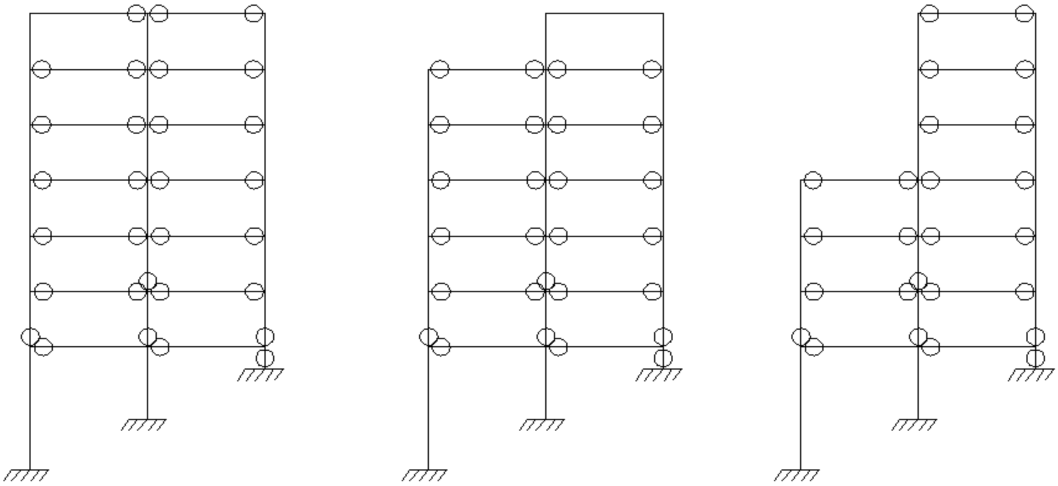
In order to study the seismic performance of setback structures under rare earthquakes, the development of plastic hinges at the beam-column ends of three structures was compared and analyzed. By observing the damage position and comparing the damage degree of the structures, the characteristics of seismic response and failure mode of set-back and step-back RC frame structures are proposed. Under the rare earthquake level of 8 degree (0.2g), the elastoplastic time-history analysis with San Fernnando wave was performed, and the position of plastic hinges is shown in Figure 8. Under the rare earthquake level of 8 degree (0.2g), only the beam end failure occurred in all three structures, meeting the requirements of "strong column and weak beam". The beam-end failures of the M1 and M2 models are concentrated in the second to fifth storeys, and the structural form of the M2 model will reduce the damage of beams in the fifth storey. In comparison, the M2 model is better than the M1 model structure. For M3, beam damage occured at the upper and lower storeys of the setback, and the damage of the beam will expand to the upper, and the beam ends at the sixth storey will also be damaged in varying degrees. In summary, from the perspective of the development of plastic hinges, the M2 model structure is better than the other two structures.



(a) M1 (b) M2 (c) M3

Fig. 8 – Plastic hinges of stilted-setback RC structure under San Fernnando wave, PGA = 0.40g

In order to further study the development of plastic hinges at column ends, the elastoplastic time history analysis of three structures under San Fernnando wave is performed at the rare earthquake level of 8 degree (0.3g). The development of structural plastic hinges is shown in Figure 9. In all three structures, plastic hinges appear at the bottom of the 2nd-storey columns and the bottom of the 3rd-storey middle columns, and the damage degree is basically the same. The beam ends are generally damaged, but no plastic hinge appears on the top beam of the M2 model. Therefore, all three types of structures meet the requirement of "strong columns and weak beams" when the ground motion become stronger, and the M2 model structure is better than the other two structures in seismic performance.



(a) M1 (b) M2 (c) M3

Fig. 9 – Plastic hinges of stilted-setback RC structure under San Fernnando wave, PGA = 0.51g

5. Conclusions

Based on the analysis of the elastic and elastoplastic time history of three set-back and step-back RC frame structures, the following conclusions are obtained:

(1) Under the action of frequent earthquakes, the elastic inter-storey displacement angle of the three structures meets the limit requirements of Chinese specification. However, the elastic inter-storey displacement angle of Model M2 and M3 will increase significantly at the set-back position, and the seismic shear force at the set-back position will change greatly. This is mainly because the lateral stiffness at the set-back position decreases but the seismic shear force at the set-back position does not decrease synchronously.Therefore, it is necessary to pay attention to the change of the lateral stiffness at the set-back position and improve the seismic performance at the set-back position.

(2) Under the action of rare earthquakes, the elastoplastic inter-storey displacement angles above the set-back position of Model M3 (3-layers set-back) is greater than that of Model M1 (no layer set-back), and the hinge range and hinge degree of Model M3 are greater than that of Model M1; the elastoplastic inter-storey displacement angle of Model M2 (1-layer set-back) is slightly smaller than that of Model M1 (no layer set-back), and the hinge range and hinge degree of model M2 are smaller than that of model M1. This indicates that the seismic performance of structures with more set-back layers is worse than those with set-back layers.

(3) It should be noted that the examples in this paper are only planar frame structures, and the applicability of the conclusions to spatial structures should be further studied.

6. Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC) (No. 51878101).

7. References

[1] J. Han, Y. M. Li, G. L. Tang,et al(2014): Influence of ground support types on the seismic performance of structures supported by foundations at different ground levels [J]. *China Civil Engineering Journal*, 47(2) :94-100.

[2] G. Xu, A. Q. Li, S. F. Chen(2017): Seismic Vulnerability Analysis of Moment Frames Supported by Stepped Foundation [J]. *Journal of Disaster Prevention and Mitigation Engineering*, 37(3) :341-347.

[3] J. Xu, Y. M. Li, Y. Y. Lai, B. L. Jiang, J. Han, L. P. Liu(2019): Experiment and finite element analysis of seismic behavior of split-foundation RC frame with earthing beam [J]. *Journal of Building Structures*, 40(12) :61-67.

[4] S.J. Welsh-Huggins, J. Rodgers, W. Holmes, A.B. Liel(2017): Seismic vulnerability of reinforced concrete hillside buildings in Northeast India[J]. *16WCEE*, Santiago Chile, January 9th to 13th 2017, Paper No.2998.

[5] SURANA M, SINGH Y, LANG D(2017): Seismic characterization and vulnerability of building stock in hilly regions[J]. *Natural Hazards*,19(1) : 04017024.

[6] Tamboli Nikhil Vinod, Ajay Swarup(2017): Study of seismic behavior of multi-storied R.C.C. buildings resting on sloping ground and bracing System [J]. *IJARIIE*-ISSN(O)-2395- 4396, Vol3(4):317-324.

[7] GB50010-2010, Code for design of concrete structures [S]. Beijing: *China Architecture & Building Press*.

[8] GB50010-2010, Code for seismic design of buildings [S]. Beijing: *China Architecture & Building Press*.

[9] SCOTT B D, PARK R, PRIESTLEY M J N(1982): Stressstrain behavior of concrete confined by overlapping hoops at low and high strain rates [J]. *ACI Journal*, 79(1): 13-27.

[10] MOHLE, J, KUMNATH, S(2007): Reinforcing steel material: OpenSees command language manual [Z/OL]. *Berkeley, CA: University of California, PEER.*