Study on Seismic Behavior of Frame Structures Considering Effects of Variable Axial Loads

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SUMMARY:
The failure modes of the frame columns are largely influenced by axial loads that are imposed on the columns with unavoidable eccentricities. The effect of axial loads on the column behaviour under earthquake action is considered by mode superposition response spectrum method in the current seismic code of China. The maximum and minimum static axial loads and the corresponding bending moments at the ultimate stage are calculated respectively for the design of the columns. However, the most adverse combination of axial load and bending moment may not be captured by the maximum and minimum static axial loads due to the dynamic characteristics of the structural response under earthquake action. The previous strong earthquake records indicate that the ratio of the vertical component and the horizontal component of the ground acceleration at the near fault epicenter region is approximately one. The influence of vertical earthquake effect cannot be ignored. In this paper, a frame structure are designed and studied to investigate the relationship of the most adverse bending moment and axial load during the time history of the earthquake input using dynamic analysis. Comparing the internal force and bearing capability of the frame structure under horizontal ground motion with that under combined horizontal and vertical ground motion, showing that the variation of axial loads has a significant effect on the seismic performance of frame structures.

Keywords: Frame, Variable Axial Loads, Seismic Behaviour

1. INSTRUCTION

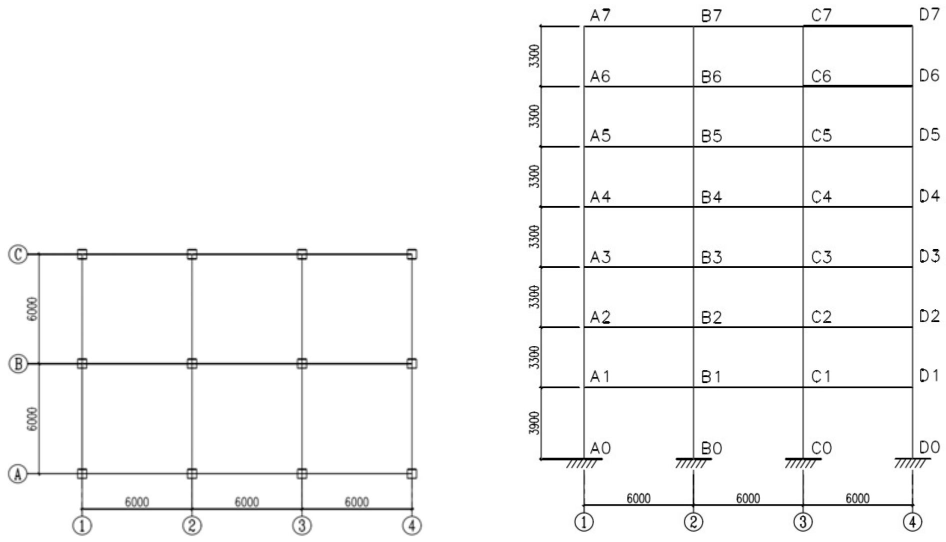
The veritable ground motion is three-dimensional spatial. For the convenience of analysis, it is normally regarded as a ground motion with orthogonal direction. Code for Seismic Design of China stipulates that all structures in earthquake resistance region should be analyzed of the affection of horizontal ground motion, but the vertical ground motion is considered only in high seismic intensity region (8, 9 degree) and the ratio of the vertical component and the horizontal component of the ground action is 0.65. According to 40 records of Wenchuan Earthquake at a distance of 120km from the fault, near-field vertical earthquake motion component was extremely significant, the ratio of the vertical component and the horizontal component of the ground acceleration was even as high as 1.4.The vertical earthquake motion could have a dramatic effect on the axial loads of the columns of the frame structure. Therefore, how the variable axial loads affect the behaviour and bearing capability of the frame structures is worthy to research and discuss. Taken a reinforced concrete frame structure as object of the research, this paper investigate the relationship of the most adverse bending moment and axial load during the time history of the earthquake input using dynamic analysis. By using the finite element software ABAQUS, a seven story plane frame model was built. In this paper, elasto-plasticity time history analysis was applied to compare the internal force and bearing capability of the frame structure under horizontal ground motion with that under combined horizontal and vertical ground motion and analyze the effect on the seismic performance of frame structures considering vertical ground motion.

2. ANALYSIS METHOD FOR SEISMIC RESPONSE

Previous study showed that the fiber model can simulate the coupling interactions of the bending moment and the variable axial loads in analysis of the seismic response analysis. The beams and columns were simulated by two-dimensional beam element using a fiber model based on the material and the nonlinear analysis is researched. The material model use a confined concrete model based on Scott-Kent-Park and a kinematics harding steel model based on Clough constitutive model. Use mean value of the material strength during the nonlinear analysis. The accurate simulating for floorslab has an important effect on the analysis results. Considering the influence of the slab on the bending capacity of the beams, the analysis model takes 6 times of thickness of the slab each side within the scope of the slab and steel to work together with the beam.

3. MODEL DESIGN

Design a reinforced concrete frame structure based on Code for Seismic Design 2010 version of China, as shown in Figure 1. The earthquake intensity is 8 degrees and the grade of anti-seismic is 3. The type of the site is II and design group 1(the characteristic period is 0.35s).The frame structure is 7 stories, x direction is 3-span and y direction is 2-span, the span is 6m.The ground floor height is 3.9m and the others are 3.3m, the height of the structure is 23.7m.The beam section is 250×500mm and the column section is 500×500mm. The floor dead load is 4.0kN/m^2, live load is 2.0kN/m^2. The roof dead load is 6.0kN/m^2, live load is 2.0kN/m^2.The concrete level is C30, the average yield strength f_y of the reinforcement is 388Mpa. Internal-force and reinforcement calculation of the structure element use software PKPM developed by China Academy of Building Research. Axial-load ratio and lateral displacement satisfy requirements of the design code. Take the middle frame (Axial B) as the calculating model. The mean value of the concrete strength is 26.1MPa and the elastic modulus is 3.24×10^4MPa in nonlinear analysis.



(a) Plan View (b) Elevation View

Figure 1. Plan View and Elevation View of the Structure

4. RESULTS OF ELASTO-PLASTICITY TIME HISTORY ANALYSIS

By using elasto-plasticity time history analysis we could find out that the internal force of the structure which is time varying and the actual mechanical behaviors of the structure under seismic action. During the analysis, the representative value of gravity load was applied to the structure first, then inputting horizontal seismic acceleration (the following marked as H) and combined horizontal and vertical seismic acceleration (the following marked as H+V). Take three near-field ground motion records, as shown in Table 1. The spectrum of the horizontal ground motion records is as shown in Figure 2. In order to research the seismic performance under rare earthquake, the peak value of the horizontal seismic acceleration is turned into 400gal according to seismic code of China and adjusting the vertical seismic in proportion to the horizontal seismic.

Table 1. Information of the Natural Ground Motion Records

Ground Motion Record	Magnitude /Mw	Fault Distance /km	V-PGA/gal	H-PGA/gal	V/H
Imperial Valley	6.9	20.2	292	243	1.2
San Fernando	6.6	29.1	215	192	1.12
Loma Prieta	7.1	26.9	82	126	0.65

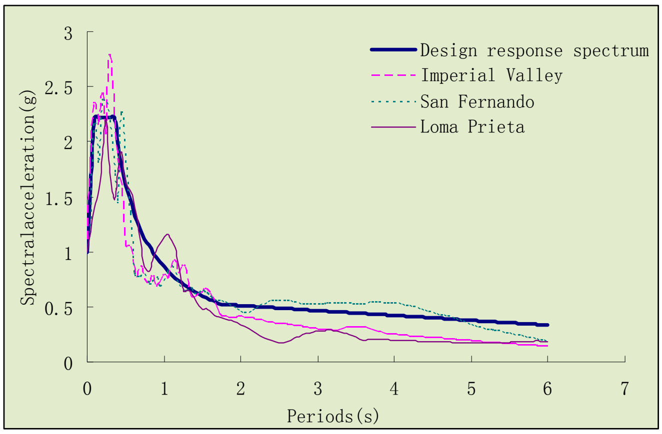


Figure 2. Spectra of the Ground Motion Records

4.1. The Variation of Axial Loads of Columns

The axial loads time-history of ground floor columns under San Fernando wave is shown in Figure 3. When inputting horizontal seismic acceleration only, the peak value of the axial loads of column B0B1 (interior column) changes significantly while the axial loads of column A0A1 (exterior column) are steady. When inputting combined horizontal and vertical seismic acceleration, the variation tendency of axial loads of the exterior column is generally consistent with the variation which inputting horizontal seismic acceleration only while the peak value of the axial loads increase. But both the variation tendency and the peak value of the axial loads of the interior column have changed significantly: The axial loads time-history changes from steady into acutely and the peak value of the axial loads is notably increased. The results of other ground motions was similar, We will not go further on this.

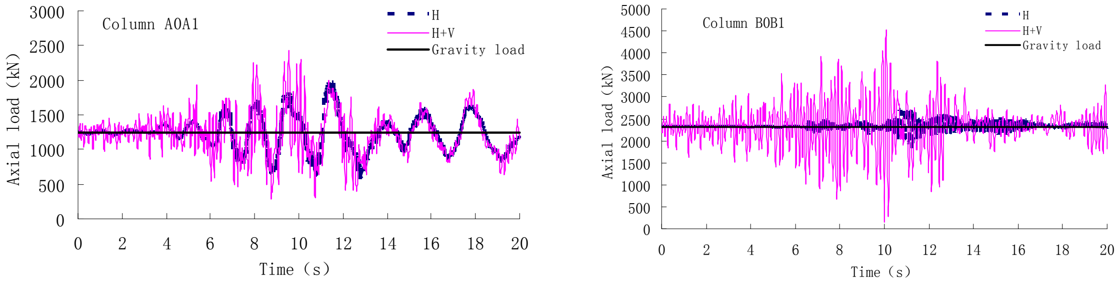


Figure 3. The axial loads time-history of ground floor columns

The maximum and minimum value of the axial loads of the columns on each floor under three ground motions is as shown in Figure 4. Compare the axial loads of the columns under inputting horizontal ground motion only with that under combined horizontal and vertical ground motion. As we can see, when inputting horizontal ground motion only, the axial loads of the interior columns had little change compare with the axial loads under gravity load, but the exterior columns change much. When inputting combined horizontal and vertical ground motion, the peak value of exterior columns increased evidently, while the variation of the peak value of interior columns was particularly significant. The tension force did not occur in all the exterior and interior columns under horizontal ground motion. But the action of vertical ground motion made the tension force occur in the columns and the maximum tension force mostly occurred in the middle and upper columns of the structure.

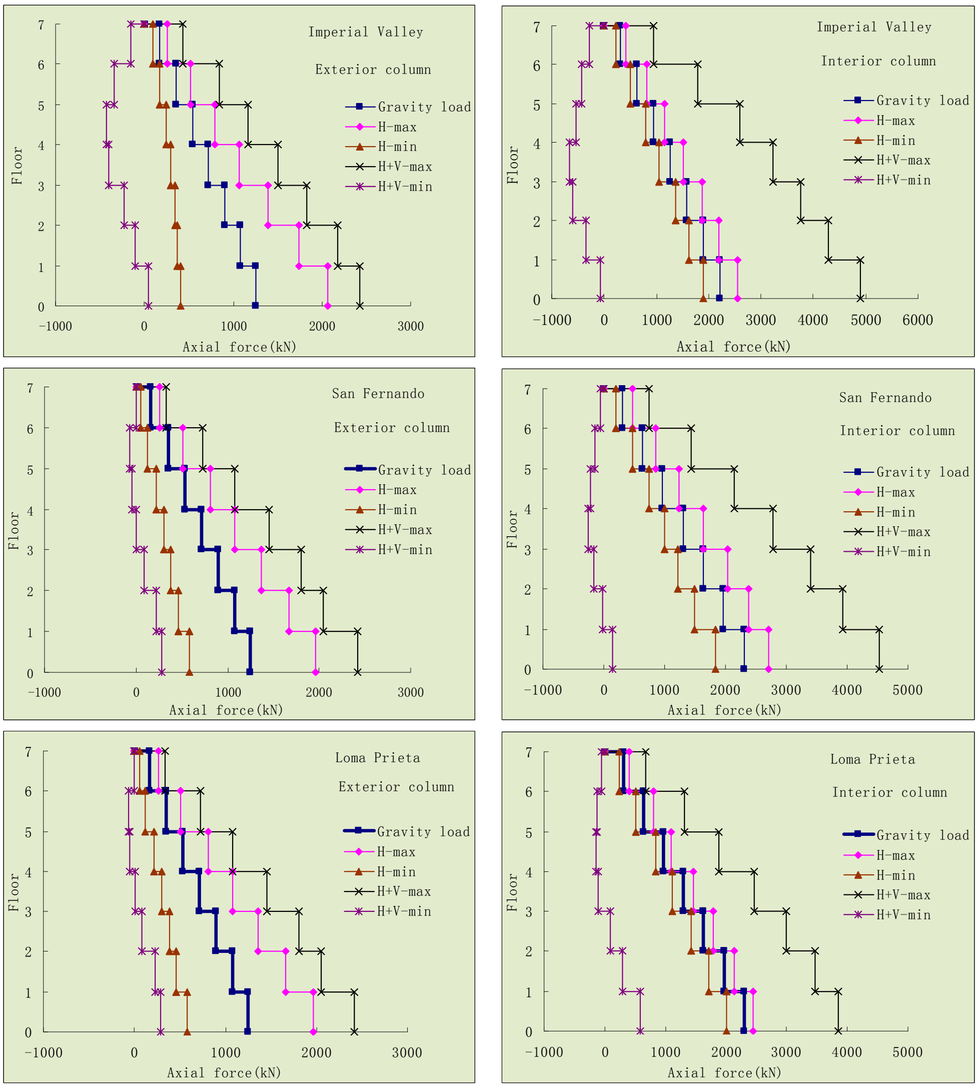


Figure 4. The peak value of the axial loads of the columns on each floor

Set the ratio of acceleration of vertical and horizontal ground motion of San Fernando to 0.65, 1.12 and 1.31 (V/H=0.65, 1.12, 1.31). Inputting horizontal ground motion only and combined horizontal and vertical ground motion which had different ratio of V/H. The maximum and minimum value of the axial loads of the columns is shown in Figure 5 and Figure 6. The maximum value of the axial loads increased with the ratio of V/H and the variation of the peak value of the interior columns was more significant than that of the exterior columns. The minimum value of the axial loads decreased as the ratio of V/H increased and the amplitude of variation of the axial loads of middle floor columns increased. The tension force did not occur in the columns at the ratio of V/H of 0.65. As the ratio increased, the vertical acceleration increased, even exceeded gravity acceleration. That would make the tension force occur in the columns and the maximum tension force mostly occurred in the middle and upper columns of the structure.

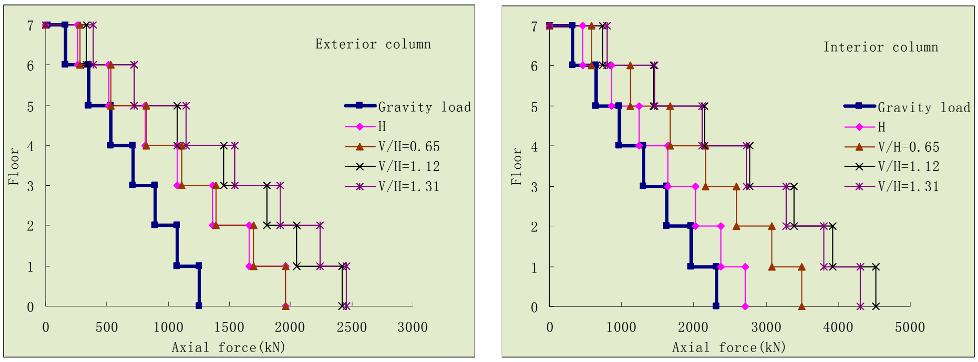


Figure 5. The maximum value of the axial loads of the columns on each floor under different ratio of V/H of San Fernando

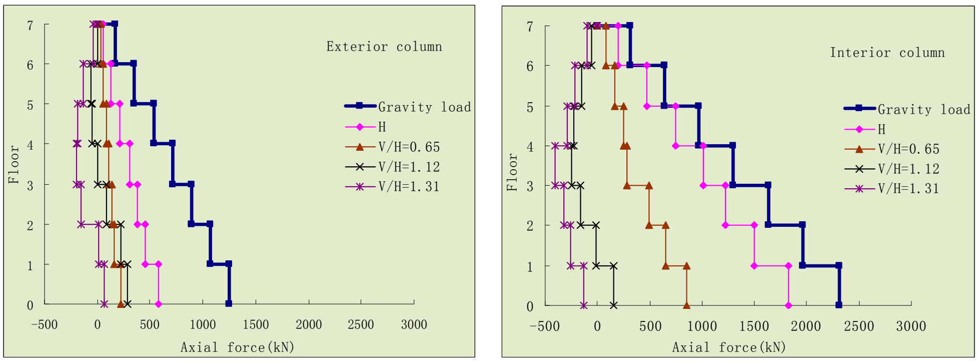
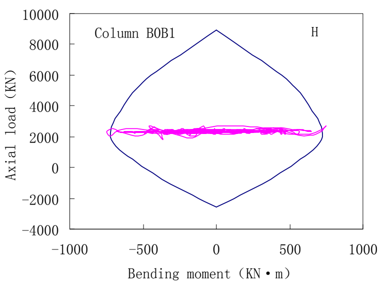


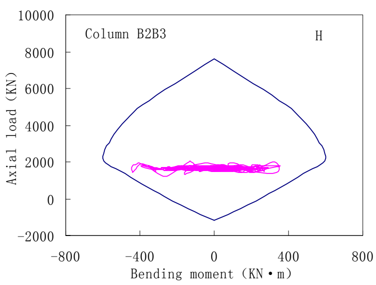
Figure 6. The minimum value of the axial loads of the columns on each floor under different ratio of V/H of San Fernando

4.2. The Bearing Capacity of the Columns

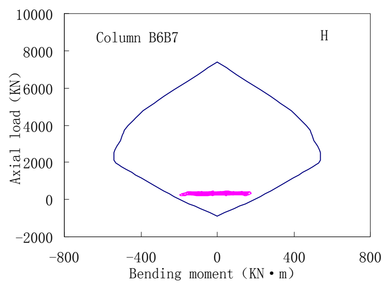
According to the M-N correlativity for cross-section of reinforced concrete, the bending capacity of the frame columns is influenced mainly by the axial loads. The bending capacity of the frame columns changes with the variation of the axial loads due to the vertical ground motion. Therefore, the M-N correlativity of the columns which is designed considering horizontal ground motion only, might not be able to contain the bending moment-axial load correlativity considering the action of combined horizontal and vertical ground motion. According to the analysis of variation of the axial forces in 3.1, the variation of the axial forces of interior columns was more significant than that of exterior columns. Present the M-N correlativity of the bottom cross-section of the interior columns as the ultimate envelope of the bearing capacity. And the bending moment-axial load correlativity of the bottom cross-section of the interior columns on the 1st, 3rd and 7th floor inputting San Fernando horizontal ground motion only and combined horizontal and vertical ground motion is present, as shown in Figure 7.



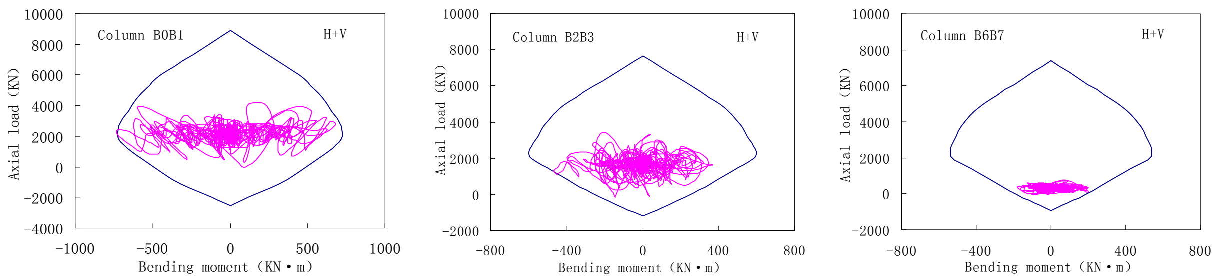
(a)M-N correlativity of column B0B1(H)



(b)M-N correlativity of column B2B3(H)



(c)M-N correlativity of column B6B7(H)



(d)M-N correlativity of column B3B4(H+V)

(e)M-N correlativity of column B2B3(H+V)

(f)M-N correlativity of column B6B7(H+V)

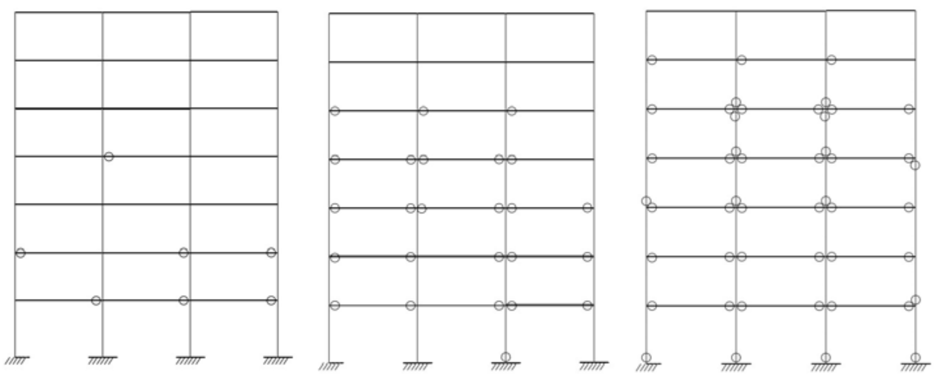
Figure 7. M-N correlativity of the bottom cross-section of the interior columns on the 1st, 3rd and 7th floor

As shown in Figure 7, when inputting horizontal ground motion only, the axial loads changed little. So the bending moment-axial load correlativity of the column was basically a horizontal line and also had little change. But the bending moment-axial load correlativity changed signally when inputting combined horizontal and vertical ground motion. The amplitude of variation of the correlativity curve toward longitudinal axis became larger and irregular due to significant variation of the axial loads. The bending moment-axial load correlativity curve of the bottom cross-section of the interior column on the 3rd floor had already touched the yield curve of the bearing capacity, it illustrated that the bottom of the column had failed. As shown in the figure of plastic hinge distribution of the frame (Figure 8), the plastic hinge occurred at the bottom of all the interior columns on the 2nd to 6th floor under combined horizontal and vertical ground motion. Since the bending capacity of large eccentric compression column decreases with the increase of the axial load, while the axial load of large eccentric compression column was remarkably decreased caused by the significant variation of the axial loads under combined horizontal and vertical ground motion, even tension force occurred. Therefore, the bending capacity of the columns was weakened, so the developing order and quantity of the plastic hinge changed greatly compared with that under horizontal ground motion only. That might had great impact on the seismic performance of the frame.

4.3. Developing and Distribution of the Plastic Hinge

Set the ratio of acceleration of vertical and horizontal ground motion of San Fernando to 0.65 and 1.31 (V/H=0.65, 1.31). Inputting horizontal ground motion only and combined horizontal and vertical ground motion which had different ratio of V/H. The developing and distribution of the plastic hinge of the frame under different action is shown in Figure 8. *A* represents beam hinge occurred for the first time, *B* represents column hinge occurred for the first time, *C* represents all the hinges occurred finally.

Horizontal Only :



A（8.82s） B（9.42s） C（11.90s）

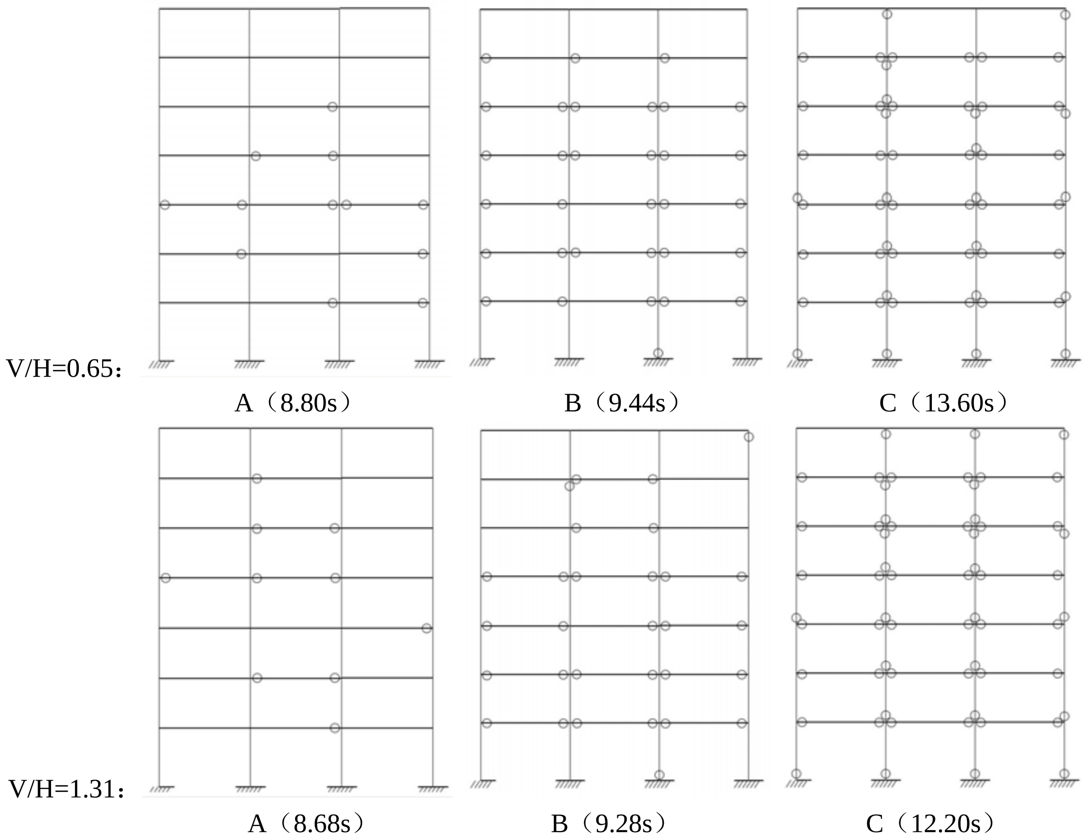


Figure 8. The developing and distribution of the plastic hinge of the frame

As shown in the Figure 8, when inputting horizontal ground motion only, the beam hinge occurred first at the beam-end of the 1st and 2^{nd} floor, then the beam hinge developed toward upper floor. The column hinge occurred first at the bottom of the column on the 1^{st} floor, then all bottom column hinges on the 1^{st} floor occurred and column hinge occurred at some column-end on the 4^{th} to 6^{th} floor. When inputting combined horizontal and vertical ground motion, the beam hinge occurred from the middle and upper floors first. The range of column hinge extended while the ratio of V/H increased. When the ratio of V/H is 1.31, all bottom column hinges on the 1^{st} to 6^{th} floor occurred and top column hinges also occurred on the 6^{th} and 7^{th} floor. When inputting horizontal ground motion only, the plastic hinges mainly occurred at the beam-ends of the frame. But under combined horizontal and vertical ground motion, the column hinges notably increased, especially the significant increase of plastic hinges at middle floor columns. And the column hinges concentrated at the interior columns while the hinges at the exterior columns were less. So, when inputting combined horizontal and vertical ground motion, the frame structure was more likely to form a mechanism of beam-column hinge of which the column hinge was principal. Thus the interior columns especially the middle floor columns of the frame might be the weak part which might cause more serious failures to the structure.

5. CONCLUSIONS

(1) By analyzing the frame structure designed based on the code of China, the axial loads of the columns especially the interior columns varies significantly considering the action of vertical ground motion under rare earthquake. When the ratio of V/H is 1.31, the axial force of the interior columns even decreased 1.3 times of the axial force under gravitational load; it indicated that tension force occurred. And the variation of the peak value of the middle and upper columns was particularly significant.
(2) Compare the bending moment-axial load correlativity of the bottom cross-section of the interior columns under horizontal ground motion only with that under combined horizontal and vertical ground motion. The correlativity curve changed signally when inputting combined horizontal and

vertical ground motion. Since the bending capacity of large eccentric compression column decreases with the increase of the axial load, and the axial load of the columns was remarkably decreased caused by the significant variation of the axial loads under combined horizontal and vertical ground motion, even tension force occurred on the middle floor columns. Therefore, the bending capacity of the columns was weakened and the middle floor columns of the frame might be the weak part comparing with that under horizontal ground motion only.
(3) When inputting horizontal ground motion only, the plastic hinges mainly occurred at the beam-ends of the frame. But under combined horizontal and vertical ground motion, the column hinges notably increased, especially the significant increase of plastic hinges at middle floor columns. For the frame structure, the variation of axial loads under combined horizontal and vertical ground motion might lead to the weakening of the bending capacity of the columns. So the distribution and quantity of the plastic hinge changed greatly and the frame structure was more likely to form a mechanism of beam-column hinge of which the column hinge was principal. Because the variation of the axial loads of the middle floor columns was particularly significant and the maximum tension force also occurred at the middle floor columns, the middle part of the structure was more likely to be the weak part.

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