Analysis on seismic behavior of different structural systems of small high-rise buildings

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Abstract. In order to study the seismic performance of small high-rise building under different structural systems, an ordinary residential tower building of 11 floors in 7 degree area was designed as a frame structure, frame-shear wall structure and shear wall structure respectively. Elastic calculation of all structures was conducted based on FE model built by the software of YJK and elasto-plastic time-history analyses were conducted by the software of PERFORM-3D. The numerical results confirm that all of the three kinds of structure system can meet the requirement that the beam yield firstly, but vertical force component dose not yield in rare earthquake. On the frame-shear wall structure, the inter-story drift angle can be controlled better. The proportion of plastic energy dissipation of the frame structure is the highest and of the shear wall structure is the least among the three structures. All kinds of structure systems show good seismic behavior.

1. Introduction
Tower dwelling is a common building form in the market due to its flexible spatial structure, compact layout and saving land resources. Frame structure, frame-shear wall structure and shear wall structure are the three most widespread structural systems in common residential structural design, while these three structural systems are all suitable for the height of small high-rise buildings (7-12 floors). At present, less scholars compare the mechanical behavior of structures under different structural systems. Only a few scholars have made conceptual discussions and calculations within the elastic range of frequent earthquakes[1-2]. Some scholars only compare different types of buildings from the economic benefits[3-6]. Xie Jun[7] has carried out Elasto-Plastic analysis on different structural systems of super high-rise buildings in high intensity regions. However, the systematic comparative analysis of high-rise building has not been reported. Until now, the conventional structural design is only calculated within the elastic range, in which the state cannot be considered after entering the elasto-plasticity under rare earthquakes. Therefore, it is particularly important to carry out Elasto-Plastic analysis on different structural systems of the same building under the same site. It provides a more reasonable basis for structural selection and design of high-rise buildings.

2. General situation of engineering
2.1. Structural scheme
The seismic precautionary intensity of structure is 7 degrees (0.15g). The site classification is II. The classification of design earthquake is the first group. The basic wind pressure is 0.5kN/m² and the ground roughness is Class B. The total height of the building is 34.5m. The total number of floors is 11, each of which is 3m. The height of the top elevator and small tower of staircase is 4.5m. The area of the standard floor is 581.88 mm². The size of the frame beam is 200mm×400mm, 200mm×500mm, 200mm×600mm. The frame column size is 500mm×500mm, 700mm×700mm and the shear wall thickness is 200mm. The structural arrangement is shown in figure 1.

![Frame structure](a) Frame structure ![Frame-shear wall structure](b) Frame-shear wall structure ![Shear wall structure](c) Shear wall structure

Figure 1. structure layout.

2.2. results of Elastic analysis
The building is relatively regular and meets the rigid floor assumption. The structure has no abrupt change in stiffness. The ratio of storey stiffness and bearing capacity meet the requirements. Parameters such as period ratio, displacement ratio and inter-story drift angle of the structure under elastic calculation control are within the range specified in the code[8-11]. The main calculation results are shown in table 1.

| Structural system     | Period ratio (%) | Inter-story drift angle | Displacement ratio |
|-----------------------|------------------|-------------------------|--------------------|
| Frame                 | 79.58            | 1/900                   | 1.16               |
| Frame-shear wall       | 70.59            | 1/1118                  | 1.16               |
| Shear wall            | 75.67            | 1/1338                  | 1.20               |

2.3. results of model analysis
The elastic model is also established in Perform-3D software. In order to ensure the correctness of the model, the modal analysis is carried out firstly. The calculation results are close to those in YJK. The mass error and first and second period error are very small. The maximum error is 1.6%. Because of the existence of shear walls in frame-shear wall structure and shear wall structure and the simulation of shear walls by the two sorts of software which has somewhat difference, the error of the first torsion period is slightly larger than that of the first translation period. However, both are within a reasonable error range. It shows that the models established in the two sorts of software are consistent.

3. Selection of seismic waves
Five natural waves and two artificial waves are respectively selected for elasto-plastic time-history analysis from different structural systems through spectrum analysis and meeting the requirements of base shear force under frequent earthquakes. The peak acceleration of the seismic waves is 220 cm/s². It is applied to the weak axis (the first mode direction) in one direction. The seismic waves are transformed into response spectra and compared with the target response spectra in the code. Then select the seismic waves with good fitting and relatively close location at the first period of the structure. Spectrum analysis results are shown in figure 2. The seven seismic waves all fit well with the target spectrum, and the error of the influence coefficient at the first period is 0.01% minimum and 18.18% maximum, which can meet the requirements.
4. Dynamic elasto-plastic analyses

4.1. Elasto-plastic model
The elasto-plastic models of beams, columns and walls all adopted fiber cross-section models. Some studies[12] show that masonry filler walls have an important influence on the elasto-plastic analysis of the structure. In this study, because the filler walls are uniformly arranged and the stiffness distribution is uniform, the influence of masonry filler walls is not considered in elasto-plastic analysis. It will simplify the analysis model. The steel bar fiber of each component is input by the actual design results. The recommended formula of the code was adopted for the concrete constitutive relation of beam and shear wall, and is fitted as a degraded trilinear model. For the confined concrete the model of Mander was adopted to define constitutive behaviour of the concrete in the column[13], and bilinear constitutive model was adopted for the steel reinforcements.

4.2. Storey shear
Take the average values of the seven seismic waves’ calculation results for comparison and the results are shown in figure 3. As the number of storey increases, the storey shear decreases. The curves of the frame structure and the frame shear wall structure are relatively gentle. The bottom shear forces of the three structures are close, and the trend of storey shear force curves is similar.

4.3. Story drift angle
Same as the floor shear force, the average values of the seven seismic waves’ calculation results are taken for comparison and the results are shown in figure 4. The three structures all meet the elasto-plastic story drift angle limit specified in the code. The maximum story drift angle of frame structure is 0.0048 on the third floor. The maximum value of the story drift angle of the frame-shear wall structure appears on the fourth floor, which is 0.004, while the maximum value of the story drift angle of the shear wall structure appears on the seventh floor of the structure, which is 0.0044. It can be seen that the story drift angle curve of the frame-shear wall structure and the shear wall structure is relatively flat. The frame-shear wall structure is a combination of two different lateral force-resisting members. Through reasonable structural arrangement, the story drift angle can be controlled well.

Figure 3. Storey shear comparison.  Figure 4. inter-story drift angle comparison.
4.4. Member entering elasto-plastic state

Limit strain of concrete and yield strain of steel bars are defined as performance points. When the strain exceeds the performance point, the steel bars is in the yield stage or the concrete exceeded the peak value. Taking LOMA PRIETA wave as an example, the final states are shown in figure 5.

The plastic development of the three structures is very similar, which is shown as follows. (1) A few frames beam steel bars yield. (2) Some columns or walls reach 30% of the yield point. (3) More frame beam steel bars yield and some of their columns or core walls reach 50% of the yield point. (4) A majority of frame beam steel bars yield and some frame columns and core walls reach 50%-100% of the yield point. (5) Peripheral frame columns and walls reach 30%-50% of the yield point.

![Figure 5. The structural member entering plastic state.](image)

4.5. Energy dissipation

The energy forms of the structure include kinetic energy, elastic strain energy, plastic energy, mass damping energy and stiffness damping energy. This paper mainly analyses inelastic energy dissipation of structures. Take LOMA PRIETA wave as an example to illustrate the energy dissipation of three structures. The plastic energy dissipation of the frame structure is 186070kJ, the damping energy dissipation is 648150kJ (mass damping energy and stiffness damping energy). The plastic energy dissipation accounts for 22.30%. The plastic energy consumption of the frame-shear wall structure is 222640kJ, the damping energy dissipation is 887150kJ. The plastic energy dissipation accounts for 20.06%. The plastic energy dissipation of shear wall structure is 141790kJ, the damping energy dissipation is 1045650kJ. The plastic energy consumption accounts for 11.94% (as shown in figure 6). It can be seen that the inelastic energy dissipation of shear wall structure is the highest while energy dissipation in frame structure is the lowest. Plastic energy dissipation accounts for the highest proportion of frame structure and the lowest proportion of shear wall structure. In damping energy dissipation, mass damping energy is much higher than stiffness damping energy consumption.

![Figure 6. Proportion of plastic energy dissipation of structure.](image)
5. Conclusions
(1) The inter-story drift angle of the three structures can meet the requirements of the code. The story drift angle of the frame structure is the largest, and the maximum value appears on the third floor of the structure. The inter-story drift angle of frame-shear wall structure is the smallest, and the maximum value appears on the fourth floor of the structure. The maximum inter-story drift angle of shear wall structure appears on the seventh floor of the structure.

(2) The three structures all meet the seismic concept requirement that frame beams yield first. The development process of the three structures entering plasticity is the same. They are all carried out in the direction of frame beams, bottom core wall and column, middle core wall and column and outer wall and column. The number of frame beams that enter plastic for shear wall structures is relatively small.

(3) The inelastic energy dissipation of frame structure is the smallest and of shear wall structure is the largest. The plastic energy dissipation of frame structure is the largest, accounting for 22.30%. The plastic energy dissipation of shear wall structure is the lowest, accounting for 11.94%. The plastic energy dissipation of frame-shear wall structure is 20.06%. Mass damping energy dissipation is much greater than stiffness damping energy dissipation.

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