Study on Damage Law of Multistory and High-rise Steel Frame Structures under Strong Earthquake

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Abstract. In order to study the seismic performance of steel frame structures of multistory and high-rise buildings under strong earthquake, six and nine story steel frame structure models are established. In this paper, based on the peak acceleration of frequent earthquakes with 8 degree (0.2g) seismic effect and the finite element calculation of artificial seismic wave, the damage law of multi-storey and high-rise steel frame structures is studied under strong earthquakes, such as Taiwan CHICHI earthquake and the MENDOCINO earthquake in the United States. The results suggest that: under the strong earthquake, the inter-storey drift angle is obviously concentrated when the cross-section size of column and beam changes, so that the rational control of the inter-storey drift angle is conducive to reducing the concentration of structural damage.

1. Introduction
Reviewing the major destructive earthquakes in the world, the seismic intensity is often higher than the design intensity. The concentration of structural damage of steel frame structure under strong earthquakes is mainly influenced by the floor displacement and the change of structural element size. There are some researches on the damage of steel frame structure under strong earthquakes at home and abroad. Reference [1], which studies the general law between the deformation of steel frame joint and the deformation of column, beam and joint domain by the means of the Elastic analysis method. Reference [2], the influence of the mechanical properties of the exposed steel column base on the dynamic response mechanism of the multistory steel frame is studied by defining the sliding-mode hysteretic curve model of the exposed steel column base and taking the shear-weight ratio of the first floor and the strength coefficient of the steel column base as the main research parameters. Through the dynamic time-history analysis under strong earthquake, the influence of strong column coefficient on the dynamic response of multistory steel frame structure is studied in reference [3]. In reference [4-5], the method of non-linear dynamic time-history analysis is used to study the dynamic response mechanism and optimal design of multistory or high-rise steel structures with rigid or hinged steel column bases. In reference [6-7], the failure mode and failure control method of high-rise steel structure with strong column and weak beam are studied; in reference [8], the damage model of steel is established by using the plastic strain and energy loss theory, and the seismic analysis of a 9-story Benchmark structure considering the damage accumulation effect is carried out. Based on the above, it can be seen that the comprehensive analytical researches about the damage concentration rule of multistory and high-rise steel frame structure under strong earthquake are still rare at home and abroad. Therefore, this paper analyzes the general rule of damage of steel frame structure under strong earthquake by taking multistory and high-rise steel frame structure as the research object.
2. Finite Element Analysis of Research Model

2.1. Structural Model Building
The multi-layer steel frame structure model (6 layers) and the high-rise steel frame structure model (9 layers) were established respectively. The steel is used as shown in table 1 by calculating. Both columns and beams are made of Q235 Grade H steel. The model diagram is shown in Figure.1, referring to the six-layer model, the steel used in 1-3 layers is the same, the steel used in 4-6 layers is the same, and the steel used in nine-layer model is different from the six-layer model. The steel used in each three layers is different, and the steel size every three layers is reduced with the increase of height.

2.2. Seismic Wave Selection
Frequent occurred earthquakes with an earthquake effect of 8 degrees and the maximum time range of seismic acceleration of 70 cm/s² is adopted. Selecting representative artificial seismic waves, such as MENDOCINO seismic waves in the United States and CHICHI seismic waves in Taiwan as shown in Figure.2, and the selected amplitude-modulated seismic wave is adjusted to the one with corresponding acceleration time history of 70 cm/s². The main direction, the secondary direction and the vertical direction are loaded, in which the main direction acceleration is equal to the secondary direction acceleration, and the vertical direction acceleration is 1/2 of the main direction acceleration.

3. Results analysis

3.1. Structural quality analysis
Table 2. Quality Distribution

| Number of layers | 6-story model | 9-story model |
|------------------|---------------|---------------|
|                  | Layer mass (t) | Quality ratio | Layer mass (t) | Quality ratio |
| 9                | -              | -             | 126.6         | 79.8%         |
| 8                | -              | -             | 158.7         | 100.0%        |
| 7                | -              | -             | 158.7         | 95.7%         |
| 6                | 128.9          | 75.3%         | 165.8         | 100.0%        |
| 5                | 171.1          | 100.0%        | 165.8         | 100.0%        |
| 4                | 171.1          | 98.4%         | 165.8         | 96.6%         |
| 3                | 173.8          | 100.0%        | 171.6         | 100.0%        |
| 2                | 173.8          | 99.5%         | 171.6         | 99.2%         |
| 1                | 174.6          | 100.0%        | 173.0         | 100.0%        |

In light of the quality of the steel used in Table 1, the layer height of the actual model, and the mass distribution of each layer of the model calculated by the mass generated by the combined load are shown in Table 2. It can be seen from Table 2 that the layer mass of the 6-layer model is close except for the layer mass of the top layer affected by the less live load, but the mass ratio between 4~3 layers and 4~6 layers is only 98.4% because the steel cross section size is adjusted and reduced. While for the model with 9 layers, the mass of 1~3 layers and 4~6 layers is close, and the mass ratio between 4 layers and 3 layers is only 96.6%. Meanwhile, the steel section size of 7~9 layers is further reduced with respect to 4 and 6 layers, and the mass ratio between 7 layers and 7 layers is only 95.7%.

3.2. Analysis of Floor Shearing

Under the seismic wave of 8 degrees (0.2g), the floor shearing force of the 6-story steel frame structure and the 9-story steel frame structure in the x direction and y direction is shown in Figure 3.

![Figure 3. Floor Shearing Forces Calculated by Seismic Waves (kN)](image)

We can see from Figure 3.(a) and (b) that, under the action of three kinds of seismic waves, the floor shearing force of 6-story steel frame model increases with the decrease of floor height, and the maximum value of floor shearing force in y direction is larger than that in x direction. The variation law of floor shearing force of 9-story steel frame model is basically the same as that of 6-story steel frame model, but the maximum shear force value increases with the increase of floor height, as shown in Figure 3.(c) and (d); Meanwhile, under the action of CHICHI seismic wave, the shearing force at the connection of 3 and 4 layers changes slightly in the x direction, the shear force at the connection of 6
and 7 layers appears obvious turning point, the 468kN, at the 6 floor shearing force is suddenly smaller to 389kN at the 5 floor; in the y direction, the floor shearing force at the connection of 6 and 7 floors changes under the action of CHICHI seismic wave and MENDOCINO seismic wave. The results show that under the action of seismic wave, for multistory and high-rise steel frame structures, the reduction of floor steel section size, that is, the change of floor mass ratio, will lead to the sudden change of floor shear force.

### 3.3. Analysis of floor displacement

The 6-story steel frame model and 9-story steel frame model are calculated for storey drift. The results are shown in table 3.

| Model          | Layers | x direction | y direction |
|----------------|--------|-------------|-------------|
|                |        | Artificial  | CHICHI      | MENDOCINO   | Artificial  | CHICHI      | MENDOCINO   |
| 6-story model  | 6      | 18.6        | 31.6        | 49.5        | 12.7        | 26.5        | 40.7        |
|                | 5      | 17.5        | 29.3        | 46.0        | 11.4        | 24.0        | 36.6        |
|                | 4      | 15.2        | 24.8        | 39.1        | 9.8         | 19.9        | 30.1        |
|                | 3      | 11.9        | 18.5        | 29.4        | 7.5         | 14.6        | 22.0        |
|                | 2      | 8.1         | 13.1        | 19.9        | 4.7         | 8.9         | 13.3        |
|                | 1      | 3.8         | 6.7         | 9.3         | 1.8         | 3.4         | 5.1         |
| 9-story model  | 9      | 26.2        | 49.4        | 80.9        | 21.8        | 35.1        | 53.7        |
|                | 8      | 23.4        | 41.0        | 73.5        | 19.4        | 32.3        | 48.6        |
|                | 7      | 21.0        | 33.4        | 65.7        | 17.8        | 28.5        | 41.3        |
|                | 6      | 18.8        | 28.3        | 55.8        | 15.6        | 24.0        | 33.8        |
|                | 5      | 16.7        | 24.4        | 47.7        | 13.0        | 20.6        | 28.1        |
|                | 4      | 13.7        | 19.3        | 37.9        | 10.1        | 17.3        | 22.3        |
|                | 3      | 10.7        | 15.3        | 27.9        | 7.0         | 12.5        | 16.2        |
|                | 2      | 7.1         | 10.2        | 18.4        | 4.1         | 7.6         | 9.9         |
|                | 1      | 3.1         | 4.5         | 8.1         | 1.6         | 2.9         | 3.7         |

It can be seen from table 3 that for the 6-story steel frame model, the storey drift produced by artificial seismic wave action is less than that produced by CHICHI seismic wave action, and the displacement produced by CHICHI seismic wave action is less than that produced by MENDOCINO seismic wave action. Meanwhile, the storey drift in the x direction of the same floor is larger than that in the y direction, and in the same direction, the storey drift increases with the height of the floor. For the 9-layer model, it presents the same storey drift change trend as the 6-layer model, and when the same seismic wave acts, the storey drift of the 9-layer model at the 6th floor is similar to that of the 6-layer model at the 6th floor.

### 3.4. Interlayer Displacement Angle Analysis

The inter-storey drift angle of each model x direction is calculated according to the characteristics that the upper floor displacement in each model x direction is larger than that in the y direction. The calculation results are shown in figure 4.
Overall, the inter-storey drift angle of the calculated model increases first and then decreases as the layer height increases. For the 6-layer frame model, the inter-storey drift angle under the action of artificial seismic wave is smaller than that under the action of CHICHI seismic wave, and less than that under the action of MENDOCINO seismic wave. Under the action of artificial seismic wave, the 6-layer model obtains the maximum inter-storey drift angle at 2 layers, which is 1/802, and then the interlayer displacement angle decreases at 3~4 layers. CHICHI the action of seismic wave and MENDOCINO seismic wave, the inter-storey drift angle also appears in 3~4 layers, which decreases first and then increases. The maximum inter-storey drift angle appears in 4 layers, which are 1/319 and 1,482, respectively. For the 9-layer frame structure, under the action of three kinds of seismic waves, where the size of two columns and beams cross section of 3~4 and 6~7 layers change, the inter-storey drift angle shows the law of first decrease and then increase, and the maximum drift angle basically appears in the seventh layer after the second cross-section size change. The results show that in the multi-layer and high-rise frame structures, the inter-storey drift angle increases first and then decreases with the increase of the height of the layer.

4. Conclusions

a. For multi-story and high-rise steel frame structures under strong earthquake, when the cross-section size of columns and beams is changed, that is, when the mass ratio is changed, the floor shear force will change and even change.

b. In the multi-layer and high-rise frame structures under strong earthquake, the inter-storey drift angle shows salient law of first decrease and then increase when the cross-section size of column and beam changes (that is, the change of floor mass ratio). Reasonable change of the cross-section size of columns and beams is beneficial to reduce the damage concentration of inter-storey drift angle.

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