Application of viscous dampers in collapse resistance of truss structures

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Abstract. With the benefits of variable shape and large scale, the long-span space structure can realize the concept of the building appearance by the designer. However, China is in the area where earthquakes occur frequently, with more than one hundred reported occurrences of earthquakes in the past 100 years. This type of building has the characteristics of big importance, high people density, and great influence. During the time of the disaster, it also functions as a temporary evacuation site. It is required that it not only satisfies safety requirement by the code, but also that it meets the demand of resisting continuous collapse under the action of a strong accidental load to guarantee the safety of people's lives and property. In this paper, a numerical study is conducted on an actual grid structure using the method of incremental dynamic analysis (IDA), which locates the weak spots of the structure. Viscous dampers are added to the structure for studying their damping effect on the large span truss structures under seismic waves. And the rational arrangement of the damper in the truss structures is proposed, which provides a reference for collapse-resistant design.

1. Introduction

The number of large span spatial structures has become one of the symbols of a country's comprehensive national strength. It is generally believed that the grid structure has the advantages of excellent stability, large load-resisting capacity, relatively uniform load distribution and high structural strength, which leads to the belief that the failure of a certain rod will not influence the ability of the whole structure to resist the external force. In fact, it is found that when part of the rod in the structure is dismantled[1][2], a chain reaction will occur, thus causing irreversible damage to the whole structure. Some scholars have studied[3] through experiments. It is found that initial damage to important members is the main cause of structural failure during collapse.

The incremental dynamic analysis method is used in this paper. This method is often used to evaluate the performance and safety stability of reinforced concrete, bridge and other structures when they encounter earthquakes. The principle of incremental dynamic analysis is based on the dynamic elastoplastic time history analysis, which can be used to reflect the ability to resist earthquakes during earthquakes with different intensities, and to evaluate the seismic capacity of the structure more comprehensively. From this analysis, the weak links of the structure can be located. As a result, the rational arrangement of the damper in the truss structures is proposed providing reference for collapse-resistant design.
2. Incremental dynamic analysis

Incremental dynamic analysis is an analytical method for evaluating the seismic performance of structures proposed by Vamvatsikos and Cornell et al [4]. In recent years, more and more scholars have introduced this method into the seismic evaluation of structure and performance in different forms. This method has become an important means of analyzing the anti-collapse ability of the structure after the earthquake.

The IDA analysis is based on the nonlinear time history analysis. By gradually increasing the acceleration amplitude IM (Intensity Measures) of each seismic motion to the complete collapse of the structure, the corresponding structural performance results DM (Damage Measures) are obtained in turn, and the corresponding IM and corresponding DM values of the critical damage point of the structure are obtained in the process. These values are used to evaluate the seismic performance of the structure.

Compared with the traditional static elastoplastic analysis method, the IDA method solves the error caused by the transformation of the dynamic problem into the static problem in the past operational analysis. And in the current dynamic analysis method, the IDA method is enriched on the basis of the time history analysis method. By increasing the amplitude, the dynamic response of the structure under the action of different intensity earthquakes is obtained, and the critical amplitude is found. This method can better reflect the seismic performance of the structure, and in the process of simulation, the weak parts and key links related to the bearing capacity in the structure can be found through the results of each dynamic response. This provides a basis for the safety performance evaluation and anti-collapse design of the structure, and is often used in practical engineering.

3. Structure example

3.1 Structure condition

In this paper, a practical grid structure is taken as an example: the structure is 6 degrees (0.10g) fortified, II ground, the seismic grouping is second groups. The longitudinal length of the truss structure is 90m, the transverse length is 58.1m, and the height of the grid is 20.6m. The grid frame is composed of 6277 round steel tube members, as shown in Figure 1. In SAP2000, the characteristic [5] of a member after entering the plastic state is defined by a discrete plastic hinge. For the structure in this paper, the bars are pinned in three directions, only subjected to axial force [6], and the relationship between generalized forces and generalized displacements of plastic hinge in SAP2000 is shown in Figure 2.

3.2 Modal analysis

First, the static analysis of the calculation model is carried out by software SAP2000 to ensure that the deflection of the grid structure meets the requirements. It is required that the deflection of the grid
structure is less than the 1/250 of the short span. Then the self-vibration characteristics of the grid structure are analyzed. Modal analysis of truss structure is the basis of seismic response calculation and seismic design of truss structure, and it can be judged whether the calculation model is reasonable according to the mode of structure. The modal analysis of the structure consists of the analysis of the structural self-vibration mode and the analysis of the structural vibration frequency. The structural vibration is closely related to the state of the dynamic response of the structure. The structural natural frequency is the response of structural rigidity index, and is also used as a basis for judging whether the structure will have resonance. Therefore, before the classification of the grid structure, we must first grasp the dynamic response characteristics of the truss structure.

In this example, the first ten frequencies of the structure are calculated by subspace iteration method, and the modal analysis of the structure is performed. The self-vibration period of the truss structure is shown in Table 1. According to the data in the table, it can be seen that the first 10 order modes of the structure are smaller, with the uniform frequency distribution and the frequency of the vibration mode increasing gradually, which reflects the characteristics of the vibration frequency of the large span space structure.

Table 1. The self-vibration period of the structure (unit: second).

| Mode of vibration | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-------------------|----|----|----|----|----|----|----|----|----|----|
| Cycle             | 0.84 | 0.81 | 0.49 | 0.48 | 0.40 | 0.33 | 0.31 | 0.27 | 0.26 | |

The modal analysis of the structure shows that the mainly vibration mode of the truss structure is vertical vibration mode. The natural frequency of the structure can be obtained from the data in the table. The natural frequency reveals the characteristics of the free vibration of the system. It is an important parameter for the structural design to bear the dynamic load, which lays a foundation for the time history analysis of the structure of the truss structure.

4. Seismic waves with three phase input

According to the provisions of the code for seismic design of buildings (GB50011-2010), the time history analysis of the actual strong earthquake record and the artificial simulated acceleration time history curve is selected according to the classification of the building site and design earthquake. The number of actual strong earthquake wave records is 2/3 of the total number of waves at least. Therefore, using the EL-Centro seismic wave input, the step length of the time history analysis is 0.02s, with a total of 2688 time points and the holding time is 53.76s; the step length of the time history analysis is 0.01s with the Tangshan wave input, a total of 4922 time points and the holding time is 49.22s; the step length of the time history analysis is 0.02s, with a total of 1000 time points with the selected artificial wave input, the holding time is 20s.

4.1IDA Curves

The three - direction seismic input of the truss structure is carried out, and the three waves selected in front of the structure are input according to the coefficient of 1.0X+0.85Y+0.65Z, and the maximum node displacement values of the structures under different acceleration peaks are recorded. After the data were statistically analyzed in three directions, the structural collapse vulnerability curves with three inputs were obtained, as shown in Figure 3. In the IDA curve, the decline of the structural carrying capacity can be initially obtained according to the change of the slope of the curve. According to the Budinskay-roth criterion, for the stress-strain curve of the structure, when the slope of the curve is increased significantly, the load at the inflection point can be defined as the critical value, and the critical acceleration peak value of the structure under three seismic inputs can be obtained with the development of the plastic hinge.
Figure 3. Structural collapse vulnerability curve under three direction input.

4.2 The development of plastic hinge
The development degree of plastic hinge reflects the plastic development degree of single rod. The number of plastic hinge and the location and development degree of the plastic hinge reflect the plastic development degree of the structure. The analysis shows that the above parameters will directly affect the deformation form and failure form of the structure. Therefore, it is of great significance to make statistical measures of the number of plastic hinge corresponding to the results of each dynamic response. Because the damage position of the structure is approximately the same under the action of three seismic waves, it is only showing the plastic development of the rod and the whole structure deformation map under the action of artificial wave in Figure 4.

According to the results, the number of plastic hinges in the structure rises with the increase of peak acceleration under the action of three direction seismic waves, and the number of rods entering the plastic state increases gradually. The plastic deformation becomes increasingly obvious. In elastic-plastic junction state, the plastic hinge first appears at the 1/4 span of the structure. When the critical failure state of the structure is reached, the plastic hinges are concentrated in the 1/4 span and the midspan area on both sides of the structure, which is the weak seismic part of the truss structure.

(a) Artificial wave 150gal (b) Artificial wave 320gal
Figure 4. Plastic development and structural deformation of members under artificial waves.

5. Application and optimal layout of viscous dampers

5.1 The example of structural energy dissipation and shock absorption
In this section, the dynamic time history analysis of EL-Centro wave is used to analyze the dynamic time history of the structure. The dynamic response of the damper before and after the arrangement of the damper is compared. The viscosity damper index is selected to be 0.3 and the peak acceleration 220gal. A reasonable damper placement scheme is selected to optimize the layout of the dampers.
Then, according to the structure condition, the control nodes are selected, respectively NO.814 node located in the middle span and NO.769 node located at the 1/4 cross position. The selected control rods are NO.3272 located at the 1/4 cross position and NO.1084 located in the middle span, respectively. After that, the above control rods and control nodes are mainly analyzed, and the effect of viscous dampers on large-span truss structures is obtained. The position of the control node and the control rod in the structure is shown in Figure 5. Three different damper layout schemes are shown in Figure 6~Figure 8.

Figure 5. The position of the control node and the control rod in the structure.

Figure 6. The damper is arranged in a square shape in the middle span area of the grid and the 1/4 span of the grid.

Figure 7. The damper is arranged along the long span direction in the middle span and the 1/4 span of the grid.

Figure 8. The dampers are crisscross arranged in the middle span and the 1/4 span of the grid.

5.2 Simulation results

Table 2. The shock absorption rate of each control target

| working condition | Z displacement damping ratio (%) | Z acceleration shock absorption rate (%) | Damping ratio of axial force (%) |
|-------------------|---------------------------------|----------------------------------------|---------------------------------|
|                   | node769    node814   node769    node814    rod1084   rod3272 |                                       |                                 |
| 1                 | 63.97       64.20       63.23       62.86       65.95       63.77 |
| 2                 | 52.11       52.40       54.98       57.28       49.59       51.51 |
| 3                 | 74.14       73.63       74.62       76.30       87.90       88.02 |

It can be found that, without changing the input of the structure itself and the ground motion, the method of adding viscous dampers to the key parts can reduce the seismic effect of the space structure. And it can be seen that the working condition of 2 achieves the most reduction effect among the three conditions.
6. Conclusion
(1) Before the final destruction, the acceleration – deformation curve began steepening. At this stage, the plastic hinge began developing rapidly and the structural stiffness declined significantly. Finally, with the gradual accumulation of plastic hinge, the structural members completely lost the bearing capacity and the structure collapsed.

(2) Through the simulation of the collapse of the structure under earthquake, the development trend of plastic hinge is summarized, and the weak links of the structure are found to be concentrated in the 1/4 span of the structure and the middle span of the structure. Therefore, it is suggested to focus on the members of this kind of position in the process of structural design.

(3) Without changing the structure itself and the input of ground motion, the use of viscous dampers is conducive to the study of collapse resistance of truss structures, and the effect is remarkable. The viscous damper can be arranged straight along the chord of the lower part of the structure along the key cross section direction, and the damping effect is found to be optimal by this arrangement.

Acknowledgments
First of all, I want to thank my mentor, Professor Wang Menghong, who has given me a lot of guidance in scientific research. I also want to thank my elder sister for helping me patiently. Thank the National Natural Science Foundation for their support. Finally, I want to pay my highest respect to my alma mater, and I thank my alma mater for training me.

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