Seismic Response Analysis of Single-Story Factory Buildings with Reinforced Concrete Columns

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ABSTRACT
The single-story factory buildings are the main structural type in various industrial areas in China. At present, the plane finite element models were mainly used on seismic response analysis of single-story factory building in the last researches. In this paper, a spatial finite element analysis model and a nonlinear model are established. Through free vibration characteristics analysis, the results of analysis are compared with those of both plane single-mass formula and empirical formula to verify the reliability of finite element model. The reliability of nonlinear model is also testified by analyzing an experimental model. The results of this paper have practical significance to ensure seismic safety and reduce earthquake damage of this kind of building.

Keywords: single-story factory buildings; reinforced concrete columns; spatial finite element model; seismic response analysis.

1. INTRODUCTION

At present, the single-story factory buildings are the main structural type in various industrial areas in China. When earthquake occurs, these buildings can suffer great damage, thereby the production or part of factory building can be at a standstill, which further affects the national economy. Many scholars in China has paid a lot of attention to the research of single-story factory buildings and obtained some results since 1950s, but it was found in previous earthquake damage investigations that seismic behavior of single-story factory buildings needed to be enhanced. So it is necessary to study on the seismic response analysis method of single-story factory buildings.

A single-story factory building with reinforced concrete columns (abbr. single-story factory building) is a kind of spatial structure constituted by longitudinal linking members, such as bent frame column, roof board system, gable wall, crane beam and linking beam etc. According to the main point of single-story factory buildings calculation provision in sections 9.1.7 and 9.1.8 of "Code for seismic design of buildings GB50011-2001", for seismic calculation in transversal direction of a factory building, the multi-mass spacious structure analysis considering the influence of transversal planar elastic deformation of the roof should be used generally. It should be analyzed as multi-mass spacious structures generally, considering the influence of longitudinal planar elastic deformation of the roof, effective stiffness of enclosure walls and partition walls. But in this code no specific spatial analysis method is provided. So at present the plane bent frame model is applied in the single-story factory building design and calculation. By plane bent frame model a real building is simplified, which the influence on the whole factory structure by roof deformation, bridge crane and gable is ignored or is considered by coefficient adjustment method. There are some differences between calculation results and actual situation, which causes some weak components were destroyed when earthquake occurred.

Because the single-story factory building composition and the connection of each member are relatively complex, there is not an accepted spatial calculation model at present. In this paper a practical spatial analysis model of single-story factory building is provided. The restoring-force model of nonlinear response analysis is selected. Using structural analysis software SAP2000, the spatial linear seismic response analysis and the nonlinear seismic response analysis are performed. The validity and reliability of model are verified by calculation example. The methods of this paper have practical significance to ensure seismic safety and reduce earthquake damage of this kind of building.

2. SPATIAL FINITE ELEMENT ANALYSIS MODEL OF SINGLE-STORY FACTORY BUILDING

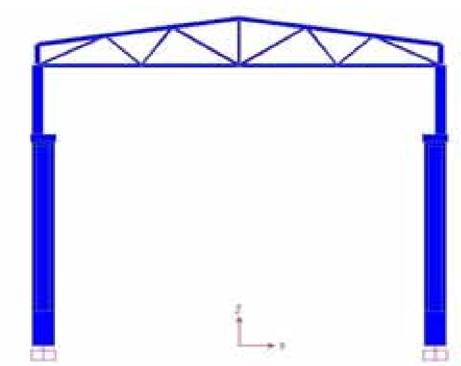
With the improvement of calculation ability of computer, the application of finite element method is used more and more widely, which is a powerful method on complex structural analysis. Through spatial finite element model, the physical and material nonlinearity and space mechanical problem of real structures are simulated really. By using finite element analysis software, the spatial finite element model is established, which is an ideal finite element calculation mechanics model. At present, the main analysis softwares are applied, such as ANSYS, ABAQUS, MSC-MARK, SAP2000, etc. In this paper, a spatial finite element analysis model of single-story factory building is established by using structural analysis software SAP2000 as the implemented tool.

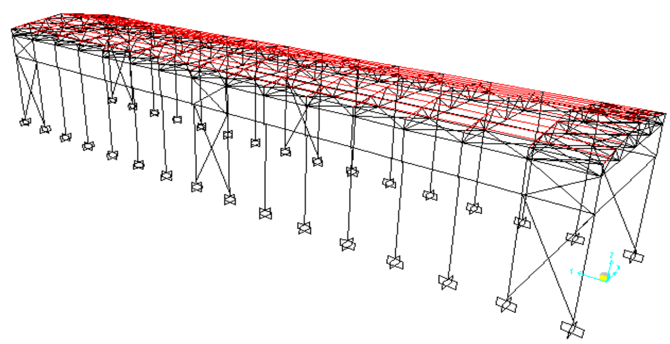
2.1. Establishment of spatial finite element analysis model

According to the real single-story factory buildings with reinforced concrete columns, the spatial finite element model of this kind of buildings is established by the method as following:

1) the joint of beam and column is simulated hinge joint, the connection joint of roof truss and top of column is simulated hinge joint;
2) the crane mass is forced on the structure by lumped mass without considering the action of crane hanger frame;
3) beam and column are simplified by beam element;
4) roof is simplified by shell element in order to consider two direction deformation, which confirms to the actual seismic response of roof;
5) enclosure wall is only forced on the beam, without considering the influence on structure stiffness;
6) if steel board is applied in gable wall of factory building, its influence is not considered.

From the above hypotheses, a single-span factory building model is established, which is shown in Figure 1. For this model, by using the calculation analysis software SAP2000, the spatial finite element analysis of single-story factory building is conducted.





(a) Plane model (b) Spatial integral model

Figure 1. Calculation model of single-story factory building with reinforced concrete columns

2.2. Verification of spatial finite element model

Structural analysis is the proper balance between calculation time and calculation precision, which is the key point of a successful analysis. However the calculation analysis is based on the right model established which is also very important for the real problem analysis of structures. In this paper the validity of model is verified by using the natural vibration characteristic.

In order to compare the calculation results obtained from SAP2000, the calculation are conducted by the natural period formula of plane single-mass of single-story factory building, which is deduced based on the single-mass system according to dynamic principle, and the empirical formula obtained by the practical measure regression of factory building natural period according to pulse method. Through compared the analysis result obtained by SAP2000 with the calculation results obtained by the two above formulas, the reliability of finite element model is verified.

As a calculation example, a factory building in Shifang city, Sichuan province is selected, which was built in 2006. In this building, two 20/5t heavy duty bridge-type cranes are installed inside. The altitude of top of track is 12.0m, the altitude of top of column is 15.9m, the span in transversal direction is 18.0m, the length in longitudinal direction is 90.0m, and the distance between columns is 6.0m. The seismic fortification intensity is VII; the classification of site is II. For the bent frame column, the rectangular section dimension of upper column is 500×400mm; the bracket section is 1150×400mm; the section shape of lower column above ±0.00 is H-section, whose section height is 1000mm, web thickness is 100 mm, flange thickness is 200mm; the section shape of lower column below ±0.00 is rectangular shape by 1000×400mm. The strength of column is C30. After the Wenchuan Earthquake, in this factory building, except buckling deformation of some individual supports and a slight shift of crane beam were found, there was no damage to other members. According to the damage level provisions of bent frame factory building with reinforced concrete columns in “Classification of earthquake damage to buildings and special structures GB/T24335-2009”, the damage classification of this factory building was between slight damage and moderate damage.

The natural periods of factory building are compared in Table 2.1, which are calculated by formulas of spatial and plane model using finite element software SAP2000, the plane single-mass formulas and the empirical formulas. From the table it can be seen the natural periods of the spatial model are between the natural periods from the empirical formulas and those from the plane single-mass formulas, which shows that the spatial model of this paper is reasonable, and the computation accuracy is reliable.

Table 2.1. Compared the natural period of model

Model	The first order	The second order	The third order
Spatial model by SAP2000	0.8889 (X)	0.7566 (T)	0.4322 (Y)
Plane model by SAP2000	1.0239 (X)	0.6728 (T)	0.4049 (T)
Plane single-mass formula	0.9570 (X)		0.1636 (Y)
Empirical formula	0.6437 (X)		0.4677 (Y)

Note: the transversal direction of factory is represented by X, the longitudinal direction of factory is represented by Y; the torsional direction of factory is represented by T.

3. NON-LINEAR ANALYSIS MODEL OF SINGLE-STORY FACTORY BUILDING

3. 1. Nonlinear restoring-force model selection of member

In software SAP2000, the restoring-force model of member is defined by free according to analysis need. When the hysteresis relationship of member is selected, if the complex restoring-force curve summarized by experiments directly is applied, it’s too complex and too difficult to realize that. Therefore the simplified calculation model is needed, which is similar to the real curve characteristic, expressed by mathematical formula, and applied easily. And this kind of actual model is called by restoring-force model. Nowadays many restoring-force models are present. To concrete members, some typical models are applied mainly at present: ideal elastic-plastic model, Clough model, and Takeda model. Because the stiffness degradation characteristic of concrete member could be simulated by Takeda model and nonlinear characteristic could be also simulated well, Takeda model is applied more widely in three models. Therefore Takeda model is selected as nonlinear restoring-force model of single-story factory building members, which is shown in Figure 2.

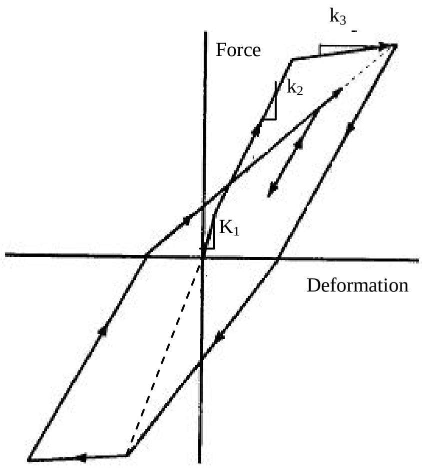


Figure 2. Takeda trilinear model

3.2. Definition and installation of plastic hinge

In software SAP2000, the plastic hinge model of frame structure is defined by rigid plastic model, whose constitutive model is shown in Figure 3. In the figure, the vertical coordinate stands for the bending moment, axis force and shear force; horizontal coordinate stands for the curvature or rotation, shear deformation, axial compressive deformation. There are four stages for the whole curves, elastic stage (AB), strengthen stage (BC), unloading stage (CD), and plastic stage (DE). B point stands for emergence of the plastic hinge, C point stands for collapse point which means bearing capacity of member is lost when plastic hinge is found. About the definition of B point related to yield force and yield displacement definition of member, there are two methods mainly: one is self-definition by inputting a specific value, the other method is calculated by a program automatically. When C, D, E point are defined, vertical and horizontal coordinates of each point are inputted by the ratio of force & displacement and yield force & yield displacement. There are two ways in SAP2000 program which one is self-definition, and the other one is obtained according to the Table 6-7 and Table 6-8 in American code FEMA356, or to the provision of concrete column based on Clatarans. In this paper, the way of definition of B, C, D, E point are all obtained by the first method, which is calculated by the program automatically.

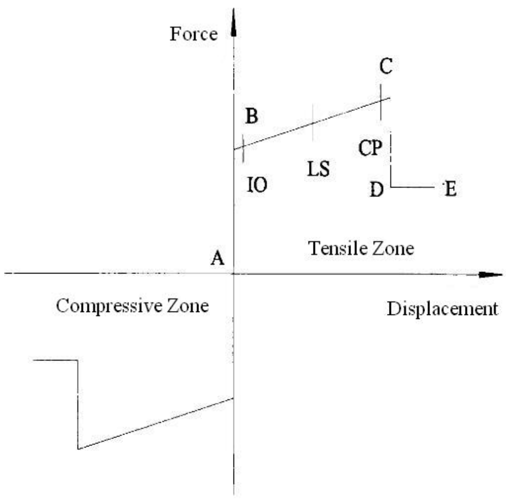


Figure 3. Constitutive model of plastic hinge model in SAP2000

Because plastic hinge is the first position to yield, the position of the plastic hinge is installed by the maximum inner force in elastic stage of member. To beam and column elements, for the maximum bending moment are located in two ends of member generally, the position of bending plastic hinge and the hinge combined flexure and axial force are set in two ends of member, and shear hinge is installed by the maximum shear force. In this paper the related hinges of the axial force and bending are set in root of upper column and lower column, and axial hinges are set in two ends of support where the crane is located.

3.3. Verification of nonlinear model of single-story factory building

The feasibility of single-story factory building nonlinear analysis model is verified by the test result of model obtained by Reference (FENG Ding-guo, 1984). In this reference, as a prototype, a bent frame of Tangshan cement machine factory workshop was tested. This factory building was built by a reinforced concrete bent frame with double span and same height, which is shown in Figure 4. During 1976 Tangshan Earthquake, it was located on the zone of the seismic intensity X. After earthquake, there were many cracks in most of columns, which is shown in Figure 5. The 1:4 model tests of bent frame column in transversal direction of factory building were performed, and single column test and bent frame column static test were conducted. From the tests some conclusion were obtained that the plastic hinge position of bent frame column were root of lower column of middle columns, and root of upper column of side columns.

By using the nonlinear model above mentioned, the experiment model is analyzed and the plastic hinges are shown in Figure 6**.**

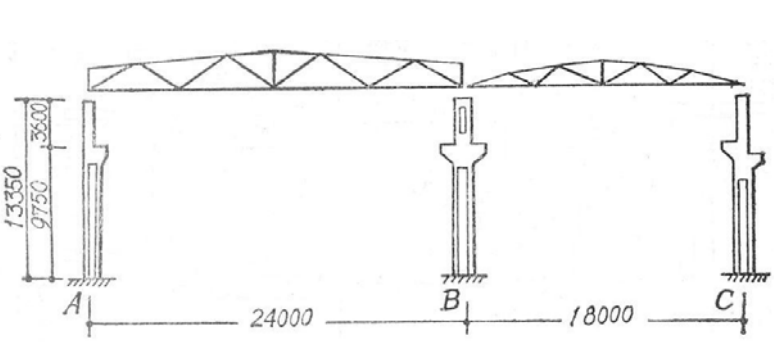


Figure 4. Bent frame of Tangshan cement machine factory workshop

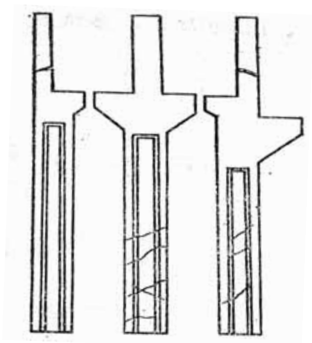
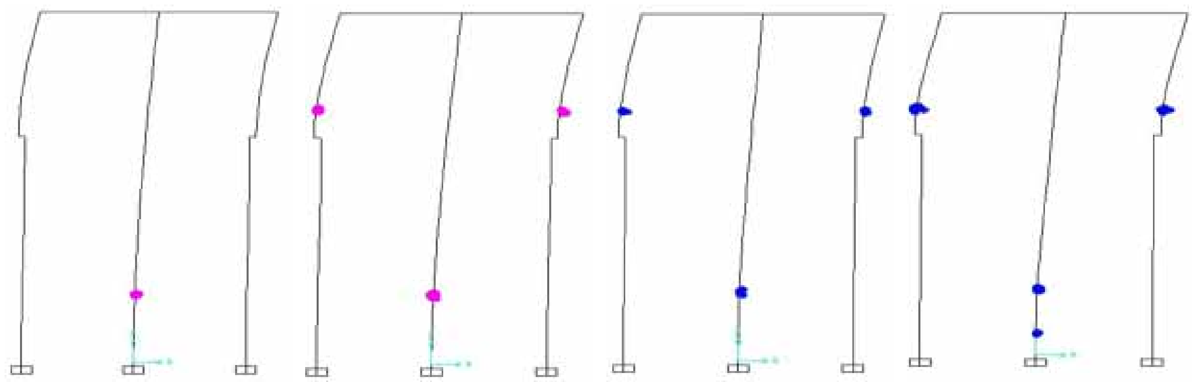


Figure 5. Cracks of bent frame columns



(a) Root of lower column of middle column (b) Root of upper column of side column (c) Variable section in root of middle column (d) Root of upper column of side column

Figure 6. Plastic hinge development of nonlinear model under lateral loading

From Figure 6, it can be seen that the plastic hinge sequence and final situation are obtained: the plastic hinges appear in the root of upper column of side column, and the root and variable section of lower column of middle column. The plastic hinge sequence and position are in accord with those of the test results. It shows that the nonlinear analysis model of single-story factory building in this paper is reasonable.

4. CONCLUSION

By using structural analysis software SAP2000, the spatial finite element model and nonlinear analysis model of single-story factory building are built and the methods are mainly introduced in this paper. The main researches are shown in the following part.

1. By using structural analysis software SAP2000, the spatial finite element model and nonlinear analysis model of single-story factory building are built. The natural vibration characteristic of spatial finite element model is analyzed, whose analysis result is compared with the results of theoretical deduction period formula and empirical formula. The results show that the natural period of the spatial model are between the natural periods from empirical formulas and those from plane single-mass formulas, which verifies that the spatial finite element model is reliable.

2. Using structural analysis software SAP2000, the nonlinear analysis model is built, and verified by combining with the test results. The plastic hinge sequence and position obtained by nonlinear model of test model structure are in accord with the test results. The results show that the nonlinear analysis model of single-story factory building in this paper is reasonable.

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