ISSN:2790-1688 DOI: 10.56028/aetr.3.1.39

Temperature field simulation and collapse analysis of steel frame factory under fire

Xi Liu*, Junjun Wang, Lei Zhang, Gaowen Liu, Shiyi Hong, Sinian Gu

Shanghai Fire Science and Technology Research Institute of MEM, Shanghai, China

*Corresponding author e-mail: 866524798@qq.com

Abstract. Building collapse is fire-induced secondary disasters. Because of many combustibles, fire-induced collapse accidents occur frequently in the steel frame factory. It causes the economic property and firemen casualties. So this paper carries out the temperature field simulation and collapse analysis of the steel frame factory under fire. The analysis module of ABAQUS is used for simulation in this paper. By comparing room temperature with high temperature, the Mises stress nephogram and displacement nephogram of the steel frame factory are analyzed. It is found that the beams and columns are greatly deformed under fire, especially the steel beams of the bent frame. The local plastic damage is occurred in the fire area of the frame, which may lead to the danger of local collapse. On the other hand, the stress of the column and beam is studied under high temperature. It shows that the stress of them increases first and then decreases.

Keywords: component; steel frame; building collapse; numerical simulation

1. Introduction

Building collapse is fire-induced secondary disasters. Because of many combustibles, fire-induced collapse accidents occur frequently in the steel frame factory. According to USFA statistics, the number of firefighters killed by fire-induced collapse has tripled compared to the 1980s[1]. At home and abroad, there are many cases of firefighter casualties caused by fire-induced collapse. For example, the World Trade Center in the United States collapsed on September 11, 2001, which caused 2830 deaths, including 343 firefighters and police [2]. The steel structure column was failed by high temperature, and the steel frame in the west of the workshop collapsed in Xincheng Plastic Company on April 7, 2010, which caused the sacrifice of one firefighter and the injury of two [3] . The steel structure workshop collapsed under fire in Hangzhou Youcheng Machinery Company on January 1, 2013, which led to the sacrifice of 3 firefighters.

2. Simulation of temperature field of steel frame and analysis of collapse

2.1 Structure overview

The steel frame is a three-story steel structure frame workshop. The long axis of the frame has 5 frames in the longitudinal direction with a total of 4 spans. The structure has 3 frames in the horizontal direction with a total of 2 spans. And its elevation is shown in Figure 1.1. Rooms 1-1 to 1-6 are possible fire areas among them. In order to highlight the fire performance of the main structure, light steel roof trusses are configured for the frame of the project. It means that the single roof truss is controlled within 1t and the height is 1m. The steel plarfvb ctes are used by steel roof trusses.

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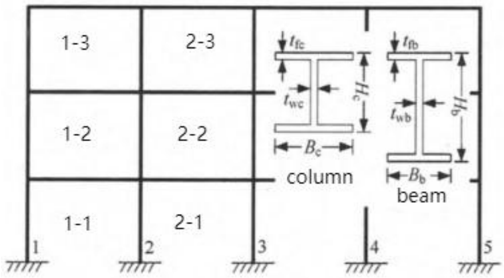

Figure 1.1 The elevation of steel frame

The floor height is 4.8 m. A single span is 10 m. The beams and columns are all I-beams. The cross-section dimension of all columns is 400 mm × 400 mm × 20 mm × 16 mm. The cross-section dimension of all beams is 600 mm × 300 mm × 16 mm × 12 mm. The ratio of the applied vertical load is P:Q=8:1. In other words, if each applied uniform load on the beam is 1 kN/m, the concentrated load on the column is 8 kN. It can be simulated the proportional relationship between the column's concentrated load transmitted from the beam and the uniform load on the acting beam.

2.2 Finite element model and meshing

According to the above-mentioned design scheme of the steel frame factory, the explicit dynamic analysis module of ABAQUS was used to establish the temperature change finite element model of the steel frame structure factory. Meshing, load setting and boundary conditions were added. The parameters related to the temperature field were used to perform the static analysis under normal temperature and high temperature. First, the I-beam beam-column members of the shell plate were assembled. Then, the beam-column members started to perform Boolean operations. In addition, the main frame structure was assembled and performs Boolean operations. Finally, the main frame was bound to the light roof truss. The fixed support constraints were imposed on the bottom of the bottom column. The finite element model was shown in Figure 1.2. The columns and roof trusses of the steel frame were all adopted by the S4R shell element model. The grid width was uniformly taken as 150 mm. The neutral axis algorithm was adopted, and the model mesh was divided as shown in Figure 1.3.

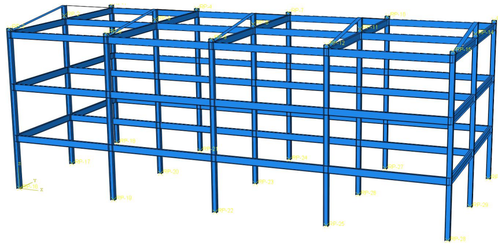

Figure 1.2 Finite Element Model

Figure 1.3 Meshing

2.3 Material constitutive and temperature field load cases

The steel in the model was all grade 3 steel with HRB400, the yield strength of the steel was uniformly taken as 400 MPa, and the ultimate load was uniformly taken as 600 MPa.

My country adopted the standard fire heating curve of the international standard ISO834 for the protection specification design. It was assumed that the cause of the fire was caused by fibrous materials. According to Section 6.1.1 of the "Code for Fire Protection Design of Building Steel Structures[4]" GB51249-2017, the heating curve formula could be determined as follows:

$$T = T_0 + 345\lg(8t+1) \tag{1-1}$$

Among them, t is the fire time, T is the temperature when the fire time is t, T0 is the initial temperature, and the initial temperature is set to 20 °C. The fire temperature curve is shown in Figure 1.4. 770℃ is adopted in this paper, because the steel structure fails at this temperature.

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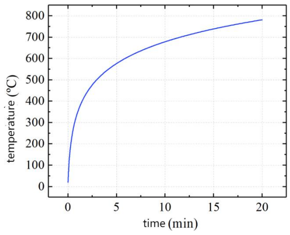


Figure 1.4 Fire heating curve

3. Analysis of simulation results of steel frame factory under room temperature

It cauld be seen from Figure 2.1 that the frame stress is mainly concentrated in the beam end and the core area of the node. The column stress was tiny, and there was no stress concentration phenomenon. The main structure had not yielded. From Figure 2.2 (a) to Figure 2.2 (d), it could be seen that the deformation of the steel structure frame factory at room temperature was mainly caused by the compressive strain of the inclined steel plate of the roof. The Mises stress nephogram and displacement nephogram showed that the vertical deformation of the steel frame was tiny and the distribution was relatively uniform. So the frame was in a normal stress state.

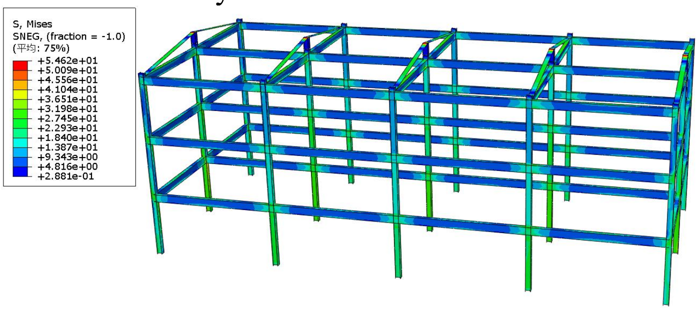
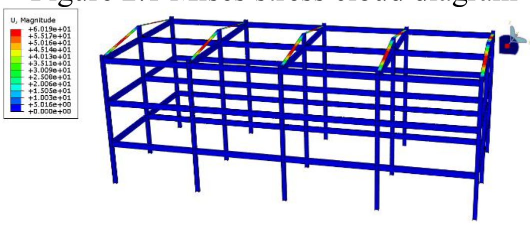
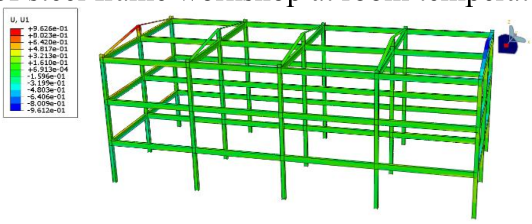
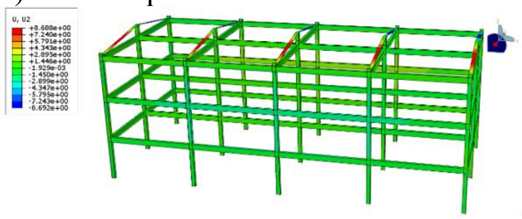
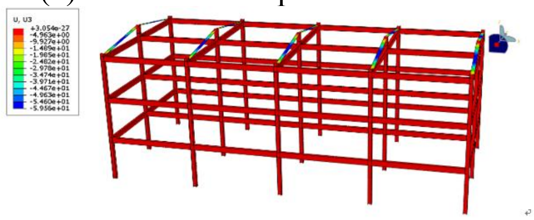


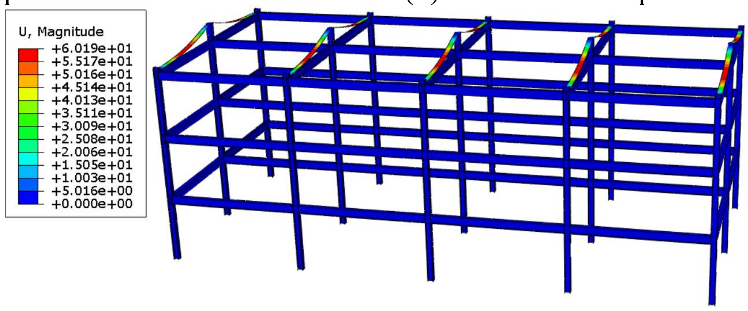
Figure 2.1 Mises stress cloud diagram of steel frame workshop at room temperature


(a) Total displacement deformation


(b) X-direction displacement deformation


(c)Y-direction displacement deformation


(d) Z-direction displacement deformation



(e) Cloud map of total deformation of steel frame

Figure 2.2 Displacement cloud diagram of steel frame workshop under room temperature

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4. Analysis of simulation results of steel frame factory under room temperature

4.1 Finite element cloud map results

It could be seen from Figure 3.1 that the frame stress was mainly concentrated in the inner bents of the fire area, and the stress concentration phenomenon appeared at the column and beam ends. It cauld be found that the Mises stress of the frame columns on the first and second floors of the second frame subjected to fire was obvious. Therefore, this fire frame was taken as the research object of the stress curve in the following paper.

From Figure 3.2 (a) to Figure 3.2 (e), it could be seen that each beam and column in the fire zone had a larger deformation. The steel beam in the top fire zone had the maximum deformation, and it was 540 mm. The deformation was about 90 times that of the normal temperature state. Plastic damage had locally appeared in the fire area of the frame, and it still maintained a basically stable state. But the structure was in danger of local collapse. Local reinforcement and fire prevention treatment shall be carried out in the fire area. The fire area had obvious the deformation of displacement, and the area affected by the fire has minor deformation. The largest deformation of the X axis was 61.3mm. The largest deformation of the Y axis was 66.9mm. The largest deformation of the Z axis was 75.6mm. So it could be seen that the high temperature had a great influence on the deformation of displacement of the steel structure, and the deformation of vertical displacement was the largest.

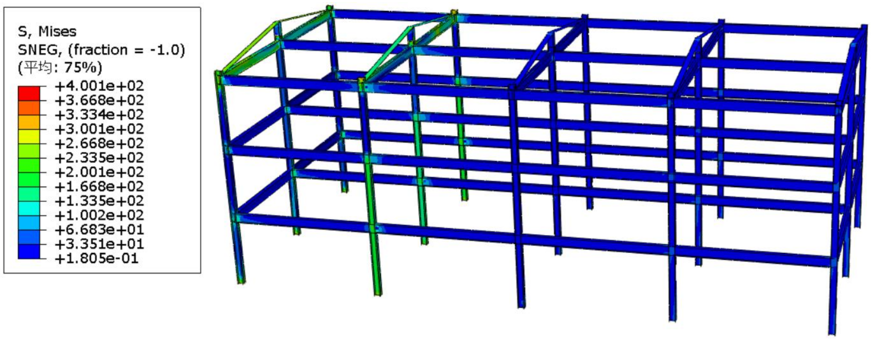
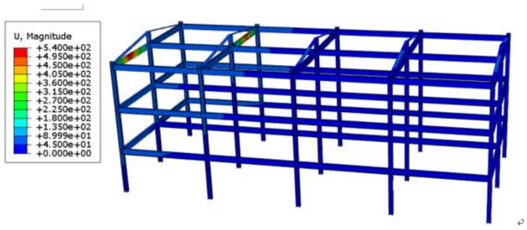
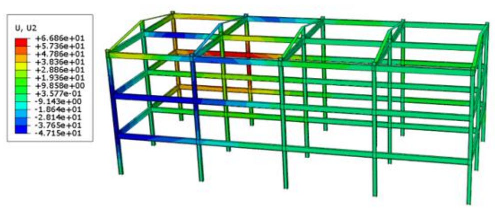
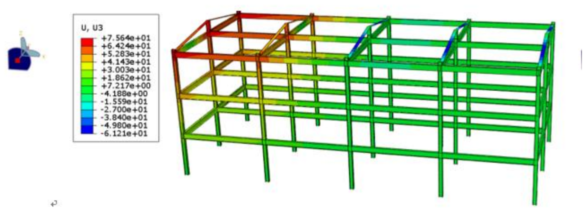


Figure 3.1 Maximum Mises stress cloud diagram of steel frame workshop at high temperature




(a) Total displacement deformation (b) X-direction displacement deformation

(c)Y-direction displacement deformation (d) Z-direction displacement deformation

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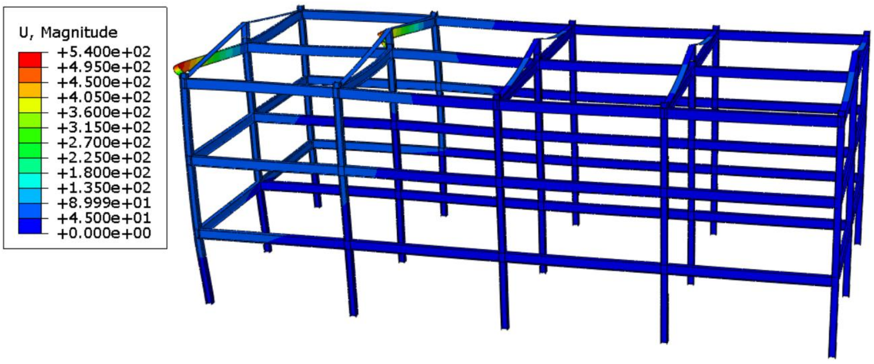
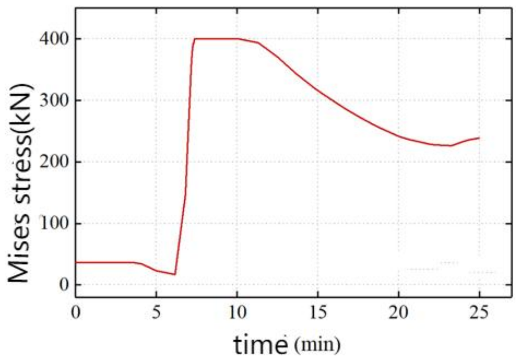


(e) Cloud map of total deformation of steel frame under high temperature (5x magnification)

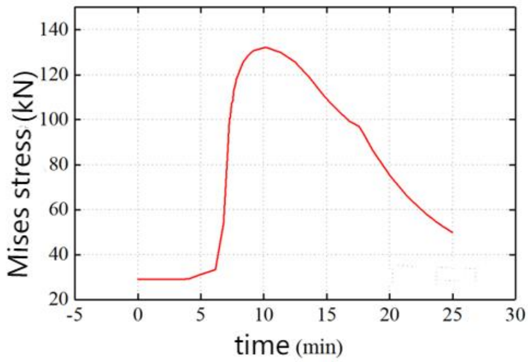
Figure 3.2 Displacement cloud diagram of steel frame workshop under room temperature

4.2 Mises stress curve analysis of key parts

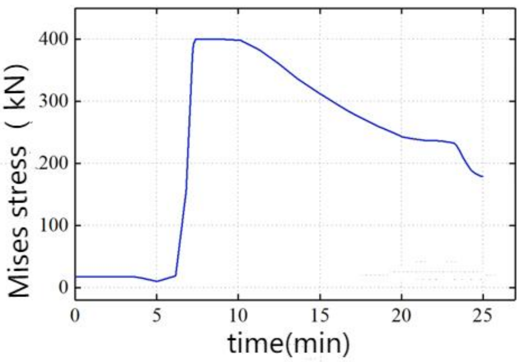
In order to study the strain change of the steel frame, the Mises stress change curves of the beam ends and column ends of the 1st to 3rd floors of the second fire frame were selected for analysis, as shown in Figure 3.3. It could be seen that the change trends of the column top and beam end of each layer were basically the same. And it was divided into three stages: the first stage, due to the low temperature in the early stage, the elastic modulus and strength of the steel was not obvious, so the stress of each layer basically remained unchanged. In the second stage, the steel frame was deformed by the high temperature due to the rapid increase in temperature, so the stress was increasing rapidly. In the third stage, the structure had been damaged, so the stress was decreasing gradually. To ensure the total strain remain unchanged under high temperature, the part of the elastic deformation of the steel gradually changed into plastic deformation as time increased. Because stress relaxation was produced, so the stress gradually decreased.



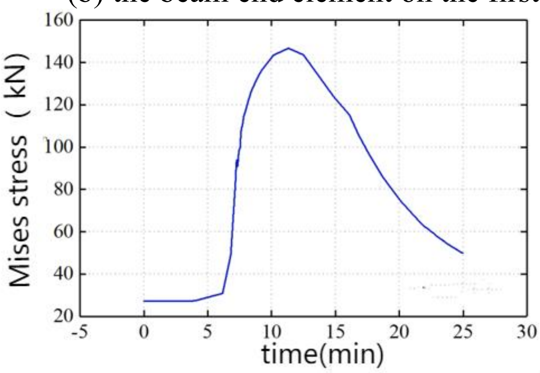
(a) the column top element on the first floor



(b) the beam end element on the first floor



(c)the top element of the second-story column



(d) the end element of the second-story beam

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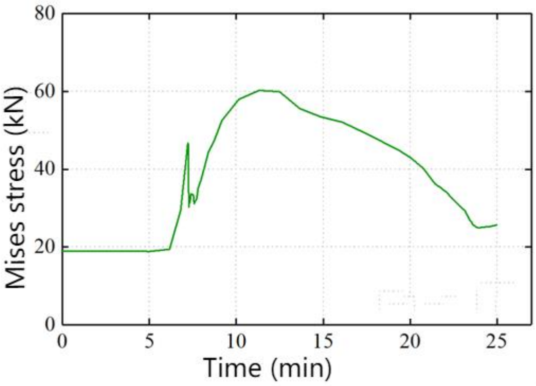
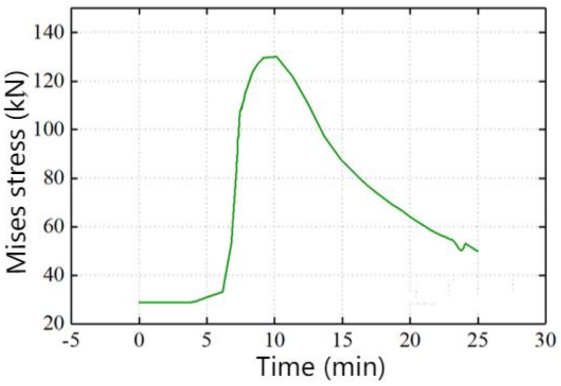


(e) the top element of three-story column



(f) the top element of three-story beam

Figure 3.3 Mises stress curve at key points of beam and column

5. Conclusion

Through the temperature field simulation and collapse analysis of the steel frame factory under fire, it could be seen that the vertical deformation of the steel structure was tiny and uniform under normal temperature. The frame was in a normal stress state. The beam and column had a larger deformation under 770℃. The steel beam in the top fire zone had the maximum deformation, and it was 540 mm. The deformation was about 90 times that of the normal temperature state. Plastic damage had locally appeared in the fire area of the frame. But the structure was in danger of local collapse. Local reinforcement and fire prevention treatment shall be carried out in the fire area. The stress of the top of the column and the end of the beam increased first and then decreased under 770℃, which was the occurrence of stress relaxation.

Acknowledgments

This work was financially supported by The National Key Research and Development Program of China (2021YFC3001901-03).

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