Study on Collapse Mechanism of Steel Frame Structure under High Temperature and Blast Loading

Qi Baoxin1, Shi Yan1, Jialiang Bi1

1School of Civil Engineering, Shenyang Jianzhu University, No.9 Hunnan East Road, Hunnan New District, Shenyang Liaoning, 110168, China

Abstract. Numerical simulation analysis for collapsing process and mechanism of steel frame structures under the combined effects of fire and explosion is performed in this paper. First of all, a new steel constitutive model considering fire (high temperature softening effect) and blast (strain rate effect) is established. On the basis of the traditional Johnson-Cook model and the Perzyna model, the relationship between strain and scaled distance as well as the Eourocode3 standard heating curve taking into account the temperature effect parameters is introduced, and a modified Johnson-Cook constitutive model is established. Then, the influence of considering the scaled distance is introduced in order to more effectively describe the destruction and collapse phenomena of steel frame structures. Some conclusions are obtained based on the numerical analysis that the destruction will be serious and even progressively collapse with decreasing of the temperature of the steel column for the same scaled distance under the combined effects of fire and blast; the damage will be serious with decreasing of the scaled distance of the steel column under the same temperature under the combined effects of fire and blast; in the case of the combined effects of fire and blast happening in the side-spans, the partial progressive collapse occurs as the scaled distance is less than or equal to 1.28; six kinds of damages which are no damage, minor damage, moderate damage, severe damage, critical collapse, and progressive collapse.

1. Introduction

Steel structure is a new kind of steel structures, and it has been developed and applied in industrial, residential and public buildings. However, there is insufficient of the steel structure with the disadvantage of small lateral stiffness, weak fire resistance performance. It can be seen, fire and blast often occur in combination, therefore, it is significance of researching the progressive collapse of building structures under fire and blast. In abroad research field, Izzuddin (Izzuddin., 2000) first attempted to take blast and fire into account at the same time. They made use of adaptive mesh finite element analysis software to develop a comprehensive analysis of the steel frame under the fire and blast loading. Liew3-6 performed an implicit dynamic analysis using ABAQUS software on a two-dimensional steel framework under the combined effects of the blast and fire. They found that the cause of the collapse of the steel frame structure was due to the failure of the key pillar of under fire. In domestic research field, Li7 took a numerical analysis, using ABAQUS finite element analysis software and considering the influence of the high strain rate effect on the material cumulative damage, on the dynamic response and failure modes of both a steel column and a steel plane frame under blast loadings according to typical blast overpressure curve in the case of the diffusion limited gas. Qian8 studied the dynamic effect resulted from the initial damage of the structure during progressive collapse, and the lumped plastic hinge model and the instantaneously applied load method were adopted to perform the elasto-plastic dynamic response analysis of a multi-story plane steel frame and a multi-
story spatial steel frame corresponding to various demand capacity ratios (DCR) respectively. Ma9 studied the fire assistance performance of steel structures by numerical simulation method after shocking loads, and the study showed that an increase in fire protection through appropriate thickness can effectively control the internal temperature of the steel components, so that the critical temperature can effectively increase structural fire assistance. Fang10 studied the resistance fire limit problem under the combined effect of fire and blast, proposed that the blast loads will reduce the resistance fire of beams. He11 also used ABAQUS software on the deformation and failure characteristics of steel columns under the combined effects of fire after the blast, results showed that the blast reduced the refractory limit of steel columns. Xu12 used ANSYS software on reasonable failure mode of steel beams in separate fire, separate blast and fire and blast, discussed influences of the different rotational constraint, axial constraint, load ratio and high span ratio of several parameters effects of interaction of steel beams under fire and blast. Tan13 applied ABAQUS finite element software for numerical simulation analysis to determine the failure criterion of steel beams and portal frame, and discussed the impact of temperature on the P-I curve, and pulse peak load impact on Tcr-I curve. However, there are few researches in this area, which research on the mechanism of steel frame structure collapsed under fire and blast. Through the establishment of a new steel constitutive relation of considering the thermal effect and high-speed strain rate effect, damage assessment methods to establish the role of the steel frame structure under high temperature and blast loading is established for the research of the collapse process the frame structure.

2. Constitutive relation model of steel under high temperature and blast loading

Based on JC model and Perzyna model, an improved constitutive model combined with the results of this paper which the relationship between the scaled distance and strain rate, and the relationship between time and temperature are taken into account is established in this paper. The modified model is showed in Equation 6.

\[
\sigma_y = \left( \sigma_0 + B \frac{\varepsilon^N}{K^N + \varepsilon^N} \right) \left[ 1 + \ln \left( \frac{\varepsilon(t)}{\varepsilon_0} \right) \right] \left[ 1 - (T^*(t))^m \right]
\]

where \( \sigma_y \) is the yield strength after high temperature and blast loading effects; \( \sigma_0 \) is the initial yield strength; \( \varepsilon \) is the strain; \( B, n, K \) are the strain hardening coefficients, respectively; \( m \) is temperature coefficient of softening; \( \varepsilon(t) = 1241 \exp(2.065z) \) is the strain rate under different scaled distance; \( \varepsilon_0 \) is the reference strain rate, in this paper \( \varepsilon_0 = 0.0001s^{-1} \); \( T^*(t) \) is the dimensionless temperature, determined by Equation 7.

\[
T^*(t) = \frac{T_g(t)}{T_m} \frac{T_r}{T_r}
\]

where \( T_r \) is the room temperature; \( T_m \) is the material melting temperature; \( T_g(t) \) is different time temperature, determined by \( T_g(t) = 345 \log_{10}(8t + 1) \).

Tanking parameters of Q235-B steel as an example, the modified J-C constitutive model can be expressed by Equation 8.

\[
\sigma_y = \left( \sigma_0 + 35677.019 \frac{\varepsilon^{1.686}}{0.029^{1.686} + \varepsilon^{1.686}} \right) \times \left[ 1 + \ln \left( \frac{\varepsilon(t)}{\varepsilon_0} \right) \right] \times \left[ 1 - (T^*(t))^{0.05} \right]
\]

3. The finite element model of steel frame structure

3.1. Spatial finite element of steel frame structure

The plane layout of the frame structure is shown in Figure 1, in which, the distance between columns are 6mx8m, and the story height is 3.6m; The dimensions of the steel column and beam are showed in Table 1.
The steel grade is Q235-B with the density of 7.8kg/m³. The modified J-C constitutive model is used by changing the parameter of the Cowper-Symonds model of the ANSYS/LS-DYNA finite element software to realize the influence of the high temperature softening and high strain rate on the yield stress and elastic modulus. In order to simplify the calculation and save the computational time, the Beam 163 element is used for the steel column, girder and beam, respectively. Frame nodes are connected by a common node, and fixed to the foundation at the bottom of column. As Figure 2 shown, the finite element software ANSYS/LS-DYNA is used to establish four layers of steel frame structure model.

Table 1. Section sizes of columns and beams

| Component type | Serial number | Sectional dimension/mm |
|----------------|---------------|------------------------|
| Frame column   | BZ            | 400×300×12×16          |
|                | ZZ            | 500×300×12×16          |
|                | BL            | 300×200×10×14          |
| Frame beam     | ZL            | 350×200×12×16          |
|                | HL            | 250×200×10×14          |

Based on the four-story of steel frame structure, the loading are divided into two conditions: one condition is that fire and blast occurred in the side spans; the other condition is that fire and blast occurred in the mid-span. For the two different cases, the numerical simulation analysis of steel frame collapse and the damage degrees are performed. As shown in Figure 2, the isothermal temperature field is generated after exposure to fire, and the blast loadings are applied in the middle of building and the simulation is performed.

3.2. Spatial steel frame calculation assumption

As simulating the steel frame structure under high temperature and blast loading, the following basic assumptions are made.(1) For the light steel frame structure (LSFS), the fire is happening in one room and the thermal effects are considered for the element related to the room; for each cross section of the element, the same temperatures are supposed.(2) The steel frame structure is considering the local high temperature and blast effect, and the other part is passively vibrating. As shown in Figure 2, the blast load is applied at the given position.

The blast happened in an instant, the action time is only a millisecond level, the air blast wave propagation in the form of a spherical wave propagation, due to the high temperature and blast loading occurred inside the building structure, so the role of blast loading in steel columns, primary beam, secondary beam simplify the uniform distribution of the column, pillar, secondary beams welcome burst surface.

3.3. Fire loading method

The proposed steel constitutive model expressed as Equation 8 considering softening and strain rate effect is used for the numerical simulation. The yield strengths of steel under different temperature conditions are calculated and the results are shown in Table 2. According to the European standard, the modulus of elasticity under high temperature may reduce and express by the reduction coefficient.
The calculated modulus of elasticity of steel under different temperature conditions is shown in Table 3.

| Temperature/℃ | 200 | 300 | 500 | 600 | 700 |
|---------------|-----|-----|-----|-----|-----|
| $f_{y,T}$/MPa | 388 | 306 | 194 | 156 | 101 |

| Temperature/℃ | 200 | 300 | 500 | 600 | 700 |
|---------------|-----|-----|-----|-----|-----|
| $E_T$/MPa     | 189 | 168 | 126 | 0.065 | 0.027 |

3.4. Blast loading method

The time curve of blast loading is calculated by the finite element software ANSYS/LS-DYNA, in order to quantify the effect of blast loading, the introduction of scaled distance $z$, expressed as Equation 3. According to the conditions, numerical simulation of the blast load-history time curve when the scaled distances were 2.11,1.67,1.46,1.33,1.28,1.23, 0.98, 0.95, 0.92, 0.90, 0.87, 0.85, 0.84, 0.80. The scaled distance $z$ is calculated, used numerical simulation method. Respectively, blast load curve is calculated by finite element AYSYS/LS-DYNA software, when the scaled distance are 2.11,1.67,1.46,1.33,1.28,1.23, 0.98, 0.95, 0.92, 0.90, 0.87, 0.85, 0.84, 0.80. According to the condition I and condition II as shown in Figure 3, the blast load curve of steel frame column and beam in different scaled distances can be obtained.

4. Analyses on damage and collapse of LSFS under high temperature and blast loading

4.1. Condition I describe damage and collapse analysis on the LSFS

When $z=1.46$ and temperature is 200 ℃, high temperature and blast occurred, the failure mode of steel frame structure is shown in Figure 3, cross border bottom column and two column are plastically deformed. The steel column BZ(2) breaks from the connection point between the edge beams and longitudinal beam. Side column BZ (1), BZ (3) bears internal force passed by steel frame structure after removing the steel column BZ(2).

When $z=1.33$ and temperature is 200℃, fire explosion occurred, as shown in Figure 4, steel frame structure crosses border bottom frame node, finding local cracking and damaged. Beam ZL (1), HL (3), ZL (3), ZL (2) are bending and damaged seriously. BL (1) and B (2) plastically deform centered on the bottom column BZ (2) along the X direction. Across the floor while column BZ (1), the beam-column joints of the BZ (3) bottom are pulled by the underlying beam ZL (1), ZL (3), BL (1), BL (2) and produce plastic hinge at the top of the column.

![Figure 3](image1.png)  ![Figure 4](image2.png)

4.2. Assessment level of the steel structure under high temperature and blast loading

As Figure 6 (a) ~ (c) shown, it describes the steel frame structure destructs and collapses because of fire blast, when $z$ is 1.33 and the temperature is 700 ℃. Firstly, under the blast load, the joints point between the bottom side span column BZ (3) and beam BL(1)、BL(2) tears. Secondly, under the blast...
load, cross border bottom side column BZ (1), BZ (2) topples, causing the beam column node tearing. That makes bottom side column of the steel frame structure removed. Finally since the bottom side span does not have the carrying capacity; it will make steel structure collapse along the side span.

As Figure 5 (d) ~ (f) shown, it describes damaged and collapsing process of the steel frame structure under fire blast when the z is 1.28 and the temperature is 200 ℃. Under the blast load, firstly the joints point between the bottom side span column BZ(1) 、 BZ(2) 、 BZ(3) and beam BL(1) 、 BL(2) tears. Secondly, as side span two storey side column BZ (1), BZ (2), BZ (3) column are pulled by the joints point between bottom side beam BL (1), BL (2) and stringer ZL(1) 、 ZL(2) 、 ZL(3), two layers side column overturns, which makes two layers side column removed. That causes three layers column bottom of steel frame structure doesn’t have load-bearing elements. Finally that causes the three floor and four floor of the steel structure, along the side span partially collapse.

Through the simulation numerical analysis on damaging and collapsing process of edge across the bottom of steel frame structure under the effect of fire blast, the proportion of the distance is the key factor to affect steel frame structure under fire blast, as shown in Table 4. After a fire, the steel frame structure within forms the temperature field with a certain temperature. Blast in such temperature field will cause the beam - columns nearby to be under the effect of blast loads. From the above analysis, collapsed process of the steel frame structure under the effect of fire blast is: firstly, secondary beam and girder connection point fault caused the floor crushing destruction. Secondly, the column and beam column connection point fracture, finally removed from the overall steel frame, leads to the redistribution of steel frame structure internal force. Finally, because the bottom column load capacity weakens, it causes the collapse of steel frame structure. Therefore, based on the numerical simulation results, the main reason for the collapse of the steel frame structure is that the underlying string bends, shears and deforms under explosive load. Steel column and beam connection point shears and cracks under explosive load, which leads to the loss of carrying the upper structure capacity of steel column.
The axial stress distribution of steel structures (z=1.28, temperature is 200°C, time is 0.299s)

The axial stress distribution of steel structures (z=1.28, temperature is 200°C, time is 3s)

Figure 5. The axial stress distribution of steel structures

| Scaled distance z | When the blast temperature/°C | Degree of injury |
|-------------------|-------------------------------|-----------------|
| z>1.46           | 200~700                       | Minor damage    |
| z=1.46           | 200~700                       | Moderate damage |
| z=1.33           | 200~600                       | Severe damage   |
| z=1.28           | 700                           | The partial progressive collapse |
| z≤1.28           | 200~700                       | The partial progressive collapse |

5. Conclusions
According to the above, this paper used numerical simulation of progressive collapse of steel frame structures under high temperature and blast loading, exploring at different temperatures, damage assessment under blast loading level of steel frame structures. Draw the following main in conclusion: (1) Some conclusions are obtained based on the numerical analysis that the destruction will be serious and even progressively collapse with decreasing of the temperature of the steel column for the same scaled distance under the combined effects of high temperature and blast loading. (2) The damage will be serious with decreasing of the scaled distance of the steel column under the same temperature under the combined effects of high temperature and blast loading.

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