Stability Study on Steel Structural Columns with Initial Blast Damage under High Temperatures

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Abstract. Blast may bring light-weight steel columns with initial damages, resulting in lowering its critical fire-resistance temperature whose reduced amplitude is relevant to the form and degree of the damages. Finite element analysis software ANSYS was used in the paper to analyze the issue of the fire-resistance temperature of the column with the blast damages, and the coupling method for heat and structure was applied during the simulation. The emphasis was laid on parametric factors of axial compression ratio, the form and the degree of the initial damages, as well as the confined condition at the ends of the columns. The numerical results showed that the fire-resistance temperature will lower as increasing of the axial compression ratio, the form and the degree of the initial damages and it will be also affected by the restraint conditions at the ends of the columns. The critical stress formula with initial bending damage under elevated temperature was set up under flexural small deformation condition, then the stability coefficient was determined and the method for evaluating the limit temperature of the column was put forward. The theoretical result was also compared with that of the finite element method (FEM). The results both showed that the stability capacity for the damaged columns was dramatically reduced as increasing the temperature and the initial damage level.

1. Introduction

In certain conditions, explosion of explosive materials in a building may cause a fire. The structure under the blast load may generate some degree of residual deformation defined as initial one which will reduce the critical fire-resistance temperature of the structure. The refractory performance of steel components with the initial damages is relatively weak. When the temperature reaches 600 °C, the steel will basically lose all the strength and stiffness, and the general temperature of fire scene is usually from 800 °C to 1000 °C. Therefore, when the light-weight steel column with certain initial damages is in the fire, it will be more vulnerable to be failed.

The initial damage of a light-weight steel column caused by explosion is more complicated, and typical damage patterns can be roughly divided into three types: 1) bending failure, which had damages distributed along the overall column, 2) direct shear failure, which had shear slips occurred at both ends of the column, 3) shear-bend combine failure, which had shear slips occurred at both ends meanwhile the bending damage is distributed along the rest. With a certain initial damage, the fire-resistant capacity of the light-weight steel column will decline significantly. Many researchers had made the parametric analysis on critical temperatures of steel columns under fire, such as Franssen (Franssen J. M., 2000) and Neves (Neve I. C., 2002), etc. who proceeded parametric analysis of critical temperatures with the condition of axial restraint and force on the steel columns; Huang (Huang Z. F., 2006), Valente and Neves (Valente J. C., 1999) analyzed the critical temperature of constrained steel column which the axial and rotational were both restrained in fire. However, these researchers studied the fire-resistance only about non-destructive straight column or steel column with...
a certain initial defect, and it did not reflect the initial damage of the explosion characteristics. The explosion caused the failure of light-weight steel columns and induced a fire, and the critical temperature of the damaged column in this situation will be complicated and affected by several factors. In this paper, the critical temperatures of the light-weight steel columns with typical blast initial damages were analyzed by using finite element method (FEM) and the stability analysis formula under elevated temperature were also derived by selecting the bending damage models for different degrees.

2. Parameters and Basic assumptions

By using finite element analysis software ANSYS, the refractory critical temperature of the light-weight steel column with an initial damage was simulated and analyzed under fire. According to light-weight steel design manual of China (Light-weight Steel Design Manual Editorial Board, 2006; China National Standard GB 50017-2003, 2003), the steel section of Q235 was chosen. In elevated temperature condition, steel material model of EC3 was adopted (European Committee for Standardization, 2005), and the value of convection heat transfer coefficient is 25W/(m²·℃), Stefan-Boltzmann constant is 5.67×10⁻⁶W/(m²·℃). When the analysis on the critical temperature of fire-resistance was performed, the damage models may be divided into bending failure, direct shear failure and shear-bend combine failure, as shown in Fig.1. Parametric analysis was performed for each damage mode, respectively, to investigate the influencing parameters, including axial compression ratio R, the degree of the initial damages D, and restraint form.

![Figure 1. Three typical initial blast damages](image1)

![Figure 2. Three constraint forms](image2)

The axial compression ratio R can be defined by Eq. (1)

\[ R = \frac{N}{N_{cr}} \]

where N is applied load; Ncr is the buckling capacity of the column under room temperature. The value of axial compression ratio is usually not more than 0.5 in practical engineering, so it was taken from 0.1 to 0.5 in calculation.

The damaged level D can be defined by Eq. (2)

\[ D = \frac{\delta_h}{L} \]

Where \( \delta_h \) represents the maximum deflection of the column at middle height, or the displacement of shear slips; L is the height of the column. The shear-bend combine failure is expressed by the shear slip and the maximum deflection, for example, the shear slip at the column ends is supposed to 2% of the height L, the maximum deflection is 3% of the height L.

Three typical constraint forms were adopted during the simulation, the column bases were all fixed constraints, and the upper ends were the fixed constraints, hinge and free ends, respectively, shown in Fig.2.

Basic assumptions were adopted in calculation:

1. The heating process for the light-weight steel columns under fire was adopted from ISO834 standard time-temperature curve;
(2) The residual stress and strain after the blast were not taken into account;
(3) The geometric and material nonlinearities were considered in the analysis of refractory;
(4) The flange and web of the column were both thin, and the impact of thickness of stress and strain were not taken into account;
(5) The column was exposed to air, surrounded by fire;
(6) Bending damages were continuously distributed along the column, and the deflection curve was expressed by
\[ \gamma_0 = \frac{\delta_0 \sin (\pi x/L)}{15h} \]
(7) Shear damage occurred at 0.25m away from the column base and column head;
(8) When shear-bend combine failure happened, the shear slip occurred at 0.25m away from the column base and column head, meanwhile the bending damage was distributed along the rest.

3. Stability analysis

3.1. Evaluation of critical temperature
As the temperature increasing, the modulus of elasticity and yield strength will decrease (European Committee for Standardization, 1994; ISO834., 1975). When the temperature reached a certain value, the light-weight steel column will generate a great lateral displacement and loss of capacity. If the deformation rates of components became infinite, the fire-resistance of steel components may achieve the limit capacity state. The characteristics deformation rate of steel components actually exceed the value expressed by Eq. (3), the component will quickly destroy.

\[ \frac{d\delta}{dT} \geq \frac{l^2}{15h} \]  
(3)
where \( \delta \) is the maximum deflection of component; \( l \) is component length; \( h \) is the section height; \( t \) is the time in minutes. According to ISO834 recommended standard heating curve (BSI., 1990) \[ T = 20 + 345 \lg(8t + 1) \] and taking component parameters into Eq.(3), the critical temperature equation can be derived by Eq.(4).

\[ \frac{d\delta}{dT} \geq 0.002 \times 10^{\frac{T-20}{345}} \]  
(4)

3.2. Parameter description
As shown in Fig.3, the component with bending damage was bent when fire happened. Here, \( y_0 \) is the initial deformation at any point. When the component was under axial pressure, the deflection will increase to \( y + y_0 \). Meanwhile, there is an additional moment and the presence of additional moment will further increase the deflection (ECCS., 1983).

![Fig. 3 Calculation model with initial bending damage](image)

In order to facilitate the analysis and calculation, it is assumed that the initial deformation was a half-wave sine curve, then

\[ y_0 = \frac{\delta_0 \sin \frac{\pi x}{l}}{l} \]  
(5)
where $\delta_0$ is the bending maximum deflection.

At any point, the external force $N$ caused deflection $y$, and the combined deflection is $y+y_0$. Taking the initial damage state as a baseline to calculate curvature, then the internal moment $M = -EI \frac{d^2y}{dx^2}$. The equilibrium differential equation can be derived from the equal of the internal and external moments.

$$EI \frac{d^2y}{dx^2} = -N(y_0 + y) \tag{6}$$

Supposing, $\frac{N}{EI} = k^2$, substitute Eq.(3) into Eq.(6)

$$\frac{d^2y}{dx^2} + k^2y = -k^2 \delta_0 \sin \frac{\pi x}{l} \tag{7}$$

The differential equation solution is

$$y = A \sin kx + B \cos kx + \frac{k^2}{\pi^2 - k^2}\delta_0 \sin \frac{\pi x}{l} \tag{8}$$

According to boundary conditions, $x = 0$ and $x = l$, $y = 0$, getting $A = 0$ and $B = 0$. Then,

$$y = \frac{N}{N_E - N} \frac{\delta_0}{\pi} \sin \frac{\pi x}{l} \tag{9}$$

Where $N_E = \frac{\pi^2 EI}{l^2}$ is Euler critical load. When $x = \frac{l}{2}$, the total deflection is the maximum,

$$Y_m = \frac{\delta_0}{1 - N/N_E} \tag{10}$$

The member’s Euler critical stress under elevated temperature can be calculated by the Eq.(11)

$$\sigma_{ET} = \frac{N_{ET}}{A} \tag{11}$$

$$\sigma_{ET} = \frac{\pi^2 E_T}{A} \tag{12}$$

Where $A$, $l$ and $E_T$ are member’s sectional area, slenderness ratio, and modulus of elasticity under elevated temperature, respectively. Therefore, the maximum deflection under elevated temperature is

$$Y_{mT} = \frac{\delta_0}{1 - N/N_{ET}} \tag{13}$$

The mean section’s largest compression stress at the edge of member is

$$\sigma_{max} = \frac{N}{A} \frac{Y_m}{W} \tag{14}$$

Where $W$ is the sectional flexural resistance moment of member. Substitute Eq. (10) and Eq.(13) into Eq.(14)

$$\sigma = \frac{N}{A} \left[1 + \frac{\delta_0}{W} \frac{1}{A} \frac{1}{1 - N/N_{ET}}\right] \tag{15}$$

When the stress at the edge of member mean section reached yield strength, the plastic deformation increased rapidly, and then the component could lose stability. When $\sigma$ in Eq.(15) reached yield strength under elevated temperature $f_{yT}$, it can be rewritten in Eq.(16)

$$\sigma_{crT} \left[1 + \frac{\delta_0}{W} \frac{1}{A} \frac{1}{1 - \sigma_{crT}/\sigma_{ET}}\right] = f_{yT} \tag{16}$$

where $\sigma_{crT}$ is critical stress with bending damage under elevated temperature. From Eq.(16) can get
\[
\sigma_{cT} = \frac{1}{2} \left[ \left( 1 + \frac{\sigma_y}{f_y} \right) \sigma_{cT} + f_y - \left( 1 + \frac{\sigma_y}{f_y} \right) \sigma_{cT} + f_y \right] - 4f_y \sigma_{cT}
\]

(17)

Stability coefficient. To simplify the calculation process, the stability coefficient can be defined as Eq.(18) and Eq.(19), respectively,

\[
\sigma_{cT} = \phi_T f_y
\]

(18)

\[
\sigma_{cT} = \phi f_y
\]

(19)

Where \( \phi_T \) and \( \phi \) are the stability coefficients of columns with bending damage at high temperature and room temperature, respectively. \( \phi \) can be got according to the steel structure design code of China, it’s 0.949 in this paper.

Making a definition of \( a = \phi_T / \phi \) as stability coefficient ratio between bending damage in high temperature and room temperature, then

\[
a = \frac{\phi_T}{\phi} = \frac{\sigma_{cT}}{f_y} = \frac{\sigma_{cT}}{\sigma_{cT, \eta_T}}
\]

(20)

According to Eq.(17) and Eq.(19) as well as the reduction coefficient of yield strength under elevated temperature from Code, we can obtain coefficient stability ratio in different bending damage levels.

The EC3 which is widely applied to make comparative analysis was chosen in this paper. The stability coefficient ratio from CE3 was shown in Table 1.

**Table 1. Stability coefficient ratio (EC3)**

| Level | Temperature/°C | 100 | 200 | 300 | 400 | 500 | 600 |
|-------|----------------|-----|-----|-----|-----|-----|-----|
| 1%    |                | 0.8824 | 0.8816 | 0.8805 | 0.8791 | 0.8801 | 0.8778 |
| 3%    |                | 0.5895 | 0.5888 | 0.5878 | 0.5866 | 0.5874 | 0.5857 |
| 5%    |                | 0.4436 | 0.4431 | 0.4424 | 0.4415 | 0.4421 | 0.4408 |
| 7%    |                | 0.3558 | 0.3554 | 0.3549 | 0.3543 | 0.3547 | 0.3538 |
| 10%   |                | 0.2748 | 0.2746 | 0.2743 | 0.2738 | 0.2741 | 0.2736 |

3.3. Critical temperature

\[
\frac{N}{\phi_T A} = f_y
\]

(21)

where \( \phi_T = a \phi \), \( f_y = \eta_T f_y \), \( f_y = \gamma_f f \); \( \gamma_f \) is resistance coefficient of steel, \( \gamma_f = 1.1 \); \( f \) is the design strength of the light-weight steel column. Then, Eq.(18) can be rewritten as follow

\[
\frac{N}{\phi_A f} = a \eta \gamma_f
\]

(22)

The left item in Eq.(22) is just axial compression ratio \( R \) for finite element analysis, therefore

\[
R = a \eta \gamma_f
\]

(23)

**Table 2. Critical temperature (EC3)**

| Level | Axial compression ratio |
|-------|-------------------------|
|       | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
| 1%    | 820 | 716 | 667 | 625 | 583 |
| 3%    | 766 | 666 | 604 | 551 | 503 |
| 5%    | 716 | 625 | 552 | 477 | 400 |
| 7%    | 687 | 584 | 503 | 400 | 300 |
| 10%   | 654 | 535 | 395 | 330 | 270 |
If the damage level of a bending column is known, the different temperature stability coefficient ratio can be figured out. If the axial compression ratio R is known, the critical temperature of the bending damaged column can be easily calculated. As a transcendental equation of Eq. (23) is not convenient to solve and apply in engineering, the critical temperature can be computed by using numerical method in different damage levels and axial compression ratio, shown in Table 2.

As shown in Table 2, with the increment of damage level and axial compression ratio, the fire-resistance temperature of the light-weight steel column decreases and the bearing capacity reduces also. When the axial compression ratio and the level of damage are too large, the light-weight steel columns with initial damages cannot carry any load during a fire. When the axial compression ratio is 0.3 and damage degree is 5%, for example, the limit temperature for EC3 is 552°C.

4. Conclusions
(1) The critical temperature of the damaged column is highest at the upper bound hinged condition, followed by one end of the free case, both ends of the consolidation is the lowest. (2) Initial bending damage level of light-weight steel column is a major factor for the elevated temperature stability. The more serious damage for the column, the worse the stability. With the temperature increasing, the stability factor for a damaged light-weight steel column changed little. (3) In this paper, the formula deduced from the proposed method is quite consistent with finite element analysis results and can be used as a reference for fire design of bending light-weight steel column with initial damages.

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