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Research of Resistance Capability and Equivalent Floor Live-load of Steel Frame under Fire

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Abstract. The increasing of equivalent floor live-loads is used to describe the weakening of ultimate carrying capacity of the structure by analyzing variety of the beam's ultimate moment and ultimate shearing force and the carrying capacity and stability of the column of steel-frame in fire, the formulas of the beam's ultimate shearing capacity, the carrying capacity and stability of column and the equivalent floor live-loads have been derived based on these. The variety rules of the carrying capacity of beam and column of the steel-frame with different thickness of the protection layers and the equivalent floor live-load have been analyzed in the example, the results showed that different equivalent floor live-load may be used to analyze the infection of fire temperature to the carrying capacity of structure in the computations of steel-frame in fire according to different time and fire temperatures of structure members, the mechanics computations of structure would be predigested and the variety of ultimate carrying capacity of steel-frame also could be estimated.

Introduction

Since steel frame structure is one of the most important load-bearing form of buildings, it is particularly significant that the method to calculate frame structure in fire hazard and in what ways the accurate evaluation to the impact of fire temperature to structural are studied. The different analysis theories, methods and material property in the fire resistance design of steel frame structure and steel members are introduced in [1–7]; The performance of one-story, one-bay steel frame in fire is studied in [8]. In the reference above, the performance of overall structure is estimated by the analyzing the ultimate bearing capacity of structural members based the variation of material property in fire hazard. On this basis, it is presented that the weakening of structural ultimate bearing capability due to fire temperature can be equivalent to the impact of the accretion of equivalent floor live-loads to structural stress state. The expressions of ultimate shearing force of steel frame beam in fire hazard, bearing capability of frame column, the stability inside and outside the plane and equivalent floor live-loads of structure are established. According to a example, the variation law with time of and ultimate bearing capability of steel frame with different protection layer is analyzed, which shows that the weakening of structural ultimate bearing capability due to fire temperature can be described directly by equivalent floor live-loads.

Fire Resistance of Frame Beam

Ultimate Bending Capability of Frame Beam. The ultimate bearing moment of frame beam applied by temperature axis force and bending moment is shown in [1] (Fig. 1)

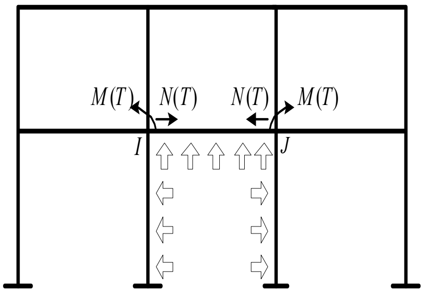

Fig. 1 The steel-frame in the local fire field

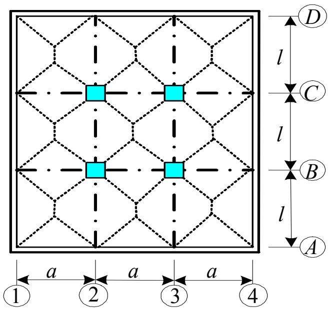

Fig. 2 The both directions floor-boards

$$M(T)=\begin{cases}\left[1-\dfrac{(2+\alpha_{\mathrm{w}})^2}{(4+\alpha_{\mathrm{w}})\alpha_{\mathrm{w}}}\left(\dfrac{N(T)}{Af_T}\right)^2\right]W_{\mathrm{p}x}f_T & \dfrac{N(T)}{Af_T}\le\dfrac{\alpha_{\mathrm{w}}}{2+\alpha_{\mathrm{w}}}\\ \dfrac{2\times(2+\alpha_{\mathrm{w}})}{4+\alpha_{\mathrm{w}}}\left(1-\dfrac{N(T)}{Af_T}\right)W_{\mathrm{p}x}f_T & \dfrac{N(T)}{Af_T}\ge\dfrac{\alpha_{\mathrm{w}}}{2+\alpha_{\mathrm{w}}}\end{cases} \tag{1}$$

where $\alpha_{\mathrm{w}}=A_{\mathrm{w}}/A_{\mathrm{f}}$; $A=A_{\mathrm{w}}+A_{\mathrm{f}}$; f_T is the yield strength at the fire temperature of T; A_{w} and A_{f} are respectively the sectional area of beam web and flange; $W_{\mathrm{p}x}$ is the plastic bending moment at room temperature; $N(T)$ is the temperature axis force of beam, it is expressed as:

$$N(T)=\frac{2K_{\mathrm{I}}K_{\mathrm{J}}l}{2E_TA(K_{\mathrm{I}}+K_{\mathrm{J}})+3K_{\mathrm{I}}K_{\mathrm{J}}l}(E_TA)\cdot\alpha(T-T_0) \tag{2}$$

where K_{I} is the axial constraint of frame beam at end I; K_{J} is the axial constraint at end J; α is the thermal expansion coefficient of steel under fire temperature; E_T is the elastic modulus of steel.

Ultimate Shearing Force of Frame Beam. The ultimate shearing force $V(T)$ of frame beam is as follows:

$$V(T)=\frac{f_{\mathrm{v}T}\cdot I_x\cdot t_{\mathrm{w}}}{H} \tag{3}$$

where $f_{\mathrm{v}T}$ is shearing strength of steel; I_x is the inertia moment of beam section; H is the area moment of the section to the neutral axis; t_{w} is the thickness of web

Fire Resistance of Frame Column

Calculation of frame column strength

$$\frac{N}{A_{\mathrm{n}}}\pm\frac{M_{xT}}{\gamma_xW_{\mathrm{n}x}}\le f_T \tag{4}$$

where N is the axis force of frame column; M_{xT} is the maximum of bending moment; γ_x is the corresponding plastic development coefficient of section to section modulus; A_{n} is the net cross-sectional area of frame column; $W_{\mathrm{n}x}$ is the gross cross-sectional modulus to the larger compression fiber inside the plane with bending moments.

Stability calculation inside frame column plane

$$\frac{N}{\varphi_{xT}A}+\frac{\beta_{\mathrm{m}x}M_{xT}}{\gamma_xW_{\mathrm{n}x}(1-0.8N/N_{\mathrm{E}xT})}\le f_T \tag{5}$$

$$N_{\mathrm{E}xT}=\pi^2E_TA/1.1\lambda_x^2 \tag{6}$$

where A is the gross sectional area of frame column; λ_x is the slenderness ratio of column; φ_{xT} is the stability factor of axial compression members inside the plane with bending moments; $\beta_{\mathrm{m}x}$ is equivalent coefficient of bending moments.

Stability calculation outside frame column plane

$$\frac{N}{\varphi_{yT}A}+\eta\frac{\beta_{tx}M_{xT}}{\varphi_{bT}W_{nx}}\le f_{yT} \tag{7}$$

where φ_{yT} is the stability factor of axial compression members outside the plane with bending moments; φ_{bT} is the integral stability factor of bending members with uniform bend.

Analysis of Equivalent Floor Live-Load of Steel Frame

The increase of fire temperature with time will consequentially lead to the decrease of bearing capability of structures that can be equivalent to the augment of floor live-loads. Thus the weakening of ultimate bearing force of structural members can be described as the augment of equivalent floor live-loads, for the frame structures, the basic compounding of loads should be the worst-case value of the compounding as follows:

$$\begin{cases} S_{GQ}=\gamma_G S_{Gk}+\sum_{i=1}^{n}\gamma_{Qi}\psi_{ci}S_{Qik} \\ S_{GQ}=\gamma_G S_{Gk}+\gamma_{Q1}S_{Q1k} \\ S_{GQ}=\gamma_G S_{Gk}+0.9\sum_{i=1}^{n}\gamma_{Qi}S_{Qik} \end{cases} \tag{8}$$

The amplitude of floor load standard value is denote as Δq, the partial factor of variable loads is γ_Q, namely

$$\gamma_Q=\max\left\{\sum_{i=1}^{n}\gamma_{Qi}\psi_{ci},\gamma_{Q1},0.9\sum_{i=1}^{n}\gamma_{Qi}\right\} \tag{9}$$

For floor framing of two-way slab (Fig. 2), the amplitude $\Delta q(t)\cdot a$ of trapezoidal linear loads on the beam has to be transformed into the amplitude $\Delta p(t)\cdot a$ of uniform linear loads when the amplitude of linear loads on the frame beam of ② is calculated.

Calculation of Amplitude of Equivalent Floor Live-Load Standard Values based on Decrease Values of Ultimate Bearing Moment of Frame Beam

According to the decrease values of ultimate bearing moment, the amplitude of equivalent floor live-load standard values is denoted as $\Delta q_1(t)$. The decrease values $\Delta M(T)$ of ultimate bearing moment of the steel frame beam in fire hazard shown in Fig. 3 is as follows:

$$\Delta M(T)=M_0-M(T)=\frac{\gamma_Q\cdot\Delta p(t)\cdot al^2}{8} \tag{10}$$

where $$\Delta p(t)=(1-2\alpha^2+\alpha^3)\cdot\Delta q_1(t) \tag{11}$$

According to Eq. (10) and Eq. (11), it can be obtained that the amplitude $\Delta q_1(t)$ of equivalent floor live-load standard values is:

$$\Delta q_1(t)=\frac{8[M_0-M(T)]}{\gamma_Q\cdot al^2\cdot(1-2\alpha^2+\alpha^3)} \tag{12}$$

where M_0 is the ultimate bearing moment of beam at normal temperature.

Calculation of Amplitude of Equivalent Floor Live-Load Standard Values based on Decrease Values of Ultimate Shearing Strength of Frame Beam

According to the decrease values of ultimate shearing strength, the amplitude of equivalent floor live-load standard values is denoted as $\Delta q_2(t)$. The decrease value $\Delta V(T)$ of ultimate shearing capability of the steel frame beam in fire hazard is as follows:

$$\Delta V(T) = V_0 - V(T) = \frac{I_x t_{\mathrm{w}}}{H}(f_{\mathrm{v}} - f_{\mathrm{v}T}) = \frac{\gamma_{\mathrm{Q}} \cdot \Delta p(t) \cdot a \cdot l}{2} \tag{13}$$

According to Eq. (11) and Eq. (13), it can be obtained that the amplitude $\Delta q_2(t)$ of equivalent floor live-load standard values is:

$$\Delta q_2(t) = \frac{2 I_x t_{\mathrm{w}} (f_{\mathrm{v}} - f_{\mathrm{v}T})}{\gamma_{\mathrm{Q}} \cdot H \cdot a \cdot l \cdot (1 - 2\alpha^2 + \alpha^3)} \tag{14}$$

Where V_0 and f_{v} are respectively ultimate shearing capability of beam and shearing strength of steel.

Calculation of Amplitude of Equivalent Floor Live-Load Standard Values based on Decrease Values of Ultimate Shearing Strength of Frame

According to the decrease values of ultimate shearing strength, the amplitude of equivalent floor live-load standard values is denoted as $\Delta q_3(t)$. The axis force varying value ΔN of frame column in fire hazard and the varying moment value ΔM_{cx} inside the plane are respectively:

$$\Delta N = \Delta q_3(t) \cdot a \cdot l \quad ; \quad \Delta M_{\mathrm{c}x} = k_{\mathrm{c}} \frac{\Delta q_3(t) \cdot a \cdot l^2}{12} \tag{15}$$

The decrease values of ultimate shearing strength of frame column:

$$\frac{\Delta N}{\varphi_x A} + \frac{\Delta M_{\mathrm{c}x}}{\gamma_x W_{\mathrm{n}x}} = f - f_T \tag{16}$$

According to Eq. (15) and Eq. (16), it can be obtained that the amplitude $\Delta q_3(t)$ of equivalent floor live-load standard values is:

$$\Delta q_3(t) = \frac{f - f_T}{\dfrac{al}{\varphi_x A} + \dfrac{k_{\mathrm{c}} a l^2}{12 \gamma_x W_{\mathrm{n}x}}} \tag{17}$$

Where $k_{\mathrm{c}} = \dfrac{i_{\mathrm{c}1}}{\Sigma i_{\mathrm{b}} + \Sigma i_{\mathrm{c}}}$ is the influence coefficient of beam and column constraint stiffness to the bending moments of frame column; $i_{\mathrm{c}1}$ is the linear stiffness of frame column; Σi_{b} is the linear stiffness summation of frame beam connecting to frame column; Σi_{c} is the linear stiffness summation of other frame columns connecting to the calculated frame column.

Calculation of Amplitude of Equivalent Floor Live-Load Standard Values based on Stability Variation inside the Plane of Frame Column

According to the calculation of the stability variation inside the plane of frame column, the amplitude of equivalent floor live-load standard values is denoted as $\Delta q_4(t)$. The axis force varying value ΔN of frame column in fire hazard and the varying moment value ΔM_{cx} inside the plane are respectively:

$$\Delta N = \Delta q_4(t)\cdot a\cdot l \quad ; \quad \Delta M_{cx} = k_c \frac{\Delta q_4(t)\cdot a\cdot l^2}{12} \tag{18}$$

The stability variation inside the plane of frame column is:

$$\frac{\Delta N}{\varphi_x A} + \frac{\beta_{mx}\Delta M_{cx}}{\gamma_x W_{nx}(1-0.8\,N/N_{Ex})} = f - f_T \tag{19}$$

According to Eq. (18) and Eq. (19), it can be obtained that the amplitude $\Delta q_4(t)$ of equivalent floor live-load standard values is:

$$\Delta q_4(t) = \frac{f - f_T}{\dfrac{al}{\varphi_x A} + \dfrac{k_c a l^2}{12\gamma_x W_{nx}(1-0.8\,N/N_{Ex})}} \tag{20}$$

Amplitude of Equivalent Floor Live-Load Standard Value of Structures

The Eq. (12), Eq. (14), Eq. (17) and Eq. (20) should be considered together in calculation, thus the amplitude of equivalent floor live-load standard values is:

$$\Delta q(t) = \max\{\Delta q_1(t), \Delta q_2(t), \Delta q_3(t), \Delta q_4(t)\} \tag{21}$$

Determination of Equivalent Floor Live-Load

The expression of equivalent floor live-load in fire hazard is as follows:

$$q(t) = q_0 + \Delta q(t) \tag{22}$$

where q_0 is the equivalent floor live-load standard value at normal temperature.

Examples

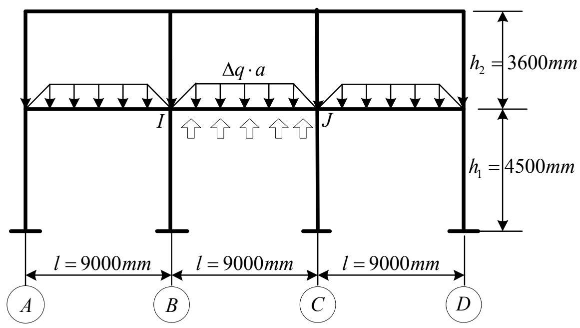

Fig.3 The calculation diagram of the steel frame

The structural calculation figure of axis ② of steel frame in Fig. 2 is shown in Fig. 3. The thick protection layer is adopted to frame beam and column. The sectional size of frame beam and column are respectively $b\times h = 250\times 640\times 20\times 12(\mathrm{mm})$ and $b\times h = 300\times 740\times 20\times 12(\mathrm{mm})$ .The steel mark of frame is Q235 and axis $B \sim C$ of frame is under fire locally. At normal temperature, the constant-load standard value of floor is $g_0 = 4.75\,\mathrm{k}N/\mathrm{m}^2$ and the live- load standard value of floor is $q_0 = 2.5\,\mathrm{k}N/\mathrm{m}^2$. The effective width of loads is a=6m . The thermal expansion coefficient α , yield strength f_T and elastic modulus of steel at high temperature are as follows [1]:

$$\alpha = 0.4\times 10^{-8}\Delta T + 1.2\times 10^{-5} - 3\times 10^{-4}/\Delta T \tag{23}$$

$$\frac{f_T}{f} = 1 + \frac{T}{767\ln(T/1750)} \qquad 0 \le T \le 600°\text{C} \tag{24}$$

$$E_T = (-17.2\times10 - 12T^4 + 11.8\times10^{-9}T^3 - 34.5\times10^{-7}T^2)E \quad (N/\text{mm}^2) \tag{25}$$

where $\Delta T = T - 20°\text{C}$ is the variation value of steel temperature; Δl is the variation value due to high temperature; l is the initial length of members; f and E are respectively yield strength and elastic modulus of steel at normal temperature.

To study the influence of local fire field to frames, according to reference [10] the ultimate bearing moment $M_b(T)$ of beam, the ultimate shearing force $V(T)$, the ultimate bearing moment $M_c(T)$ of column, the ultimate bearing axis force $N(T)$, the amplitude of equivalent floor live-load standard value $\Delta q(t)$ and equivalent floor live-load standard value $q(t)$ are computed with different thickness d_i of protection layer 1.5cm. The results are respectively shown in table 1 to Table5.

Table1 Variation of the ultimate and equivalent floor living load of the steel frame (d_i=1.5cm)

T(min)	*Mb(T)* (kN·m)	*V(T)* (kN)	*Mc(T)* (kN·m)	*N(T)* (kN)	q(t) (kN/m²)	△q(t) (kN/m²)
0	566.62	839.81	56.38	2104.3	2.50	
20	541.34	789.48	53.81	2049.6	3.019	0.519
40	495.24	696.31	50.01	1963.9	4.013	1.513
60	418.91	575.54	44.99	1817.2	5.719	3.219

Conclusions

- According to the analysis of ultimate bearing capability of steel frame in fire hazard, it is presented that the weakening of structural ultimate bearing capability due to fire temperature can be described by equivalent floor live-loads. Also the expressions of the ultimate shearing capability of frame beam, the ultimate bearing moment and axis force of frame column and the standard value of equivalent floor live-loads are established.
- By a concrete example, the varying law of steel frame beam, ultimate bearing capability and equivalent floor live-loads with different thickness of protection layer in fire hazard is analyzed.
- For the steel frames with different thickness of protection layer, the mechanical behavior of structure can be analyzed by different compounding of equivalent floor live-loads and permanent loads. The bearing capability can be determined and the structural analysis of steel structure in fire hazard is simplified.

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