International Journal of Smart Home
Vol. 9, No. 11, (2015), pp. 29-36
http://dx.doi.org/10.14257/ijsh.2015.9.11.04

The Analysis on Time-dependent Reliability of Steel Structural Components under Fire Conditions

Qiao Mu[1*], Gai Fangfang[1], Zhao Jitao[1] and Sheng Shan[2]

[1]*Heilongjiang University of Science and Technology, Harbin 150022, China*
[2]*Harbin Electric Machinery Company Limited, Harbin 150046, China*
252385246@qq.com

Abstract

The stability of steel beams with mechanical properties will be at a loss if they are under high temperature. This paper presents a straightforward and possible time-variant model of the steel beams to be resistant against fire, and also a reliability index analysis method. According to the ISO834 standard heating curve, the steel beam's reliability is evaluated.

Keywords*: fire; structural reliability analysis; steel structure*

1. Introduction

As an important engineering structural material, steel structure has many advantages over other structures, such as good reliability, high strength, great plasticity and toughness. However, as mentioned above, due to the fact that the mechanical property of the steel structure is remarkable reduced under the circumstance of high temperature, steel structure is vulnerable to the fire. The fire resistance of steel structures has been the focus in the fields of academic and engineering, especially after the collapse of World Trade Center towers during "9.11" terrorist attacks. The application of steel structures has become wider and wider domestically since the 21st century. As a result, the amount of fire accidents on steel structures increases. Besides, the breakages of steel structures or even collapses caused by fire accidents become more and more frequent. However, there is no national standard for the fire resistance of steel structures in China, so it is quite urgent to implement fire resistance design and to ensure the safety of steel structures.

This paper is going to deduce the limit state equation of steel structure components with time changes, from the variation of ultimate bearing capacity under the influence of standard temperature curve. Through practical examples, this paper analyzes how the reliability index of steel structures will be influenced with the decrease of heating time by the following three aspects: the thermal conductivity, the thickness and the loading rate of the steel structural protective layer. Through the basic math formula of reliability, this paper deduces steel structures' digital characteristics of internal force in fire accidents, and then puts forward the design of reliable steel structures [1].

ISSN: 1975-4094 IJSH

2. The Functionality of Steel Structures under the Influence of Indoor Fire Temperature Curve

2.1. The Temperature Rise of Steel Structure Components in Indoor Fire Temperature Curve

This chapter focuses on steel structure components with light protective layer and analyzes the internal temperature rise of steel structures under the influence of random temperature field. Due to the fact that the quality of light protective layer is light, the quantity of heat which is absorbed by the layer during the temperature-rise period compared with the steel structures can be neglected. The judgment of the light protective layer can be based on the following formula:

$$c_s \cdot \rho_s \cdot V \geq 2c_i \cdot \rho_i \cdot d_i \cdot F_i \tag{1}$$

c_s——specific heat capacity of steel
ρ_s——the steel density
V——the volume of a unit length of the component
c_i——specific heat capacity of protective layer
ρ_i——the density of the protective layer
d_i——the thickness of the protective layer
F_i——the internal surface area of a unit length of the protective layer

The quantity of heat which is transmitted from the air to the structure components can be divided into two sections: the heat by thermal radiation and the heat by thermal convection. According to Fourier Heat Conduction Theorem, the heat which is transmitted to the steel structure components by the above two sections via protective layer can be calculated:

$$q = K \cdot F_i \cdot (T_g - T_s) \tag{2}$$

T_g——the temperature of the room on fire
T_b——the temperature of the protective layer
K——synthesized heat-exchange coefficient

According to principle of thermal equilibrium, heat balance equation can be established by the lumped capacitance method. The heat which is absorbed by the light protective layer can be neglected. The following fitting formula can calculate the temperature rise of steel structures under the influence of standard temperature rise curve [2]:

$$T = (\sqrt{0.044 + 5 \times 10^{-5} B} - 0.2)t + 20 \tag{3}$$

$$B = \frac{\lambda_i}{d_i} \cdot \frac{F_i}{V} \tag{4}$$

t——the burning time of fire;
λ_i——the heat conductivity coefficient of protective layer;
d_i——the thickness of protective layer;
F_i——fire area of the components;
V——the volume of the components.

3. The Functionality of Steel Structural Components under the Influence of Indoor Fire Temperature Curve

To establish the functionality of steel structural components under the condition of high temperature, this paper presumes:

(1)Every cross-sectional area of the steel structural component is equal, and the fire retardant coating and the properties are well-distributed;

(2)At every moment, the internal temperature of the steel structural component under the condition of high temperature is well-distributed;

(3)With the change of temperature, the variation of the strength reduction factor and elasticity modulus reduction factor of the steel should be selected according to relevant principles in Chapter Two.

3.1. The Functionality of Steel Structural Beam under the Influence of Indoor Fire Temperature Curve

When the cross section of the flexural steel components is not impaired, the bearing capacity is controlled by overall stability. The critical bending moment of the flexural symmetric cross section of the component around strong axes can be represented as [2]:

$$M_{cr} = C_1 \frac{\pi^2 E I_y}{l^2}[C_2\alpha + C_3\beta + \sqrt{(C_2\alpha + C_3\beta)^2 + \frac{I_\omega}{I_y}(1 + \frac{G I_t l^2}{\pi^2 E I_\omega})}]\beta_b \tag{5}$$

C_1, C_2, C_3 ——coefficient related to load;

α ——the distance between the point of action of transverse load and the shear center of cross section;

β ——parameter related to the shape of the component;

I_y ——inertia moment of cross-section of the component around the weak axis;

I_ω ——sector inertia moment of cross-section of the components;

I_t ——torsion inertia moment of cross-section of the components;

l ——span of the component;

E ——elasticity modulus of steel;

G ——shear modulus of steel;

β_b ——equivalent moment factor of component overall stability.

If the influence of the rising temperature on loading conditions and physical dimension can be neglected, only the elasticity modulus and shear modulus are influenced by the high temperature among all the material parameters. The above formula can be converted into：

$$M_{crT} = C_1 \frac{\pi^2 E_T I_y}{l^2}[C_2\alpha + C_3\beta + \sqrt{(C_2\alpha + C_3\beta)^2 + \frac{I_\omega}{I_y}(1 + \frac{G_T I_t l^2}{\pi^2 E I_\omega})}]\beta_b \tag{6}$$

M_{crT} ——critical bending moment of the steel beam under high temperature;

E_T ——elasticity modulus when the temperature of steel is T;

G_T ——shear modulus when the temperature of steel is T.

The critical bending moment of the flexural members under normal and high temperatures can be represented as:

$$M_{cr} = \varphi_b W f_y \tag{7}$$

$$M_{crT} = \varphi_{bT} W f_{yT} \tag{8}$$

W ——gross section modulus of the component;

φ_b ——integral stability coefficient of the flexural member under normal temperature;

φ_{bT} ——integral stability coefficient of the flexural member under high temperature;

f_y ——yield strength of steel under normal temperature;

f_{yT} ——yield strength of steel under high temperature.

Out of overall consideration of formula(5) (6) (7) (8), Poisson ratio of the steel is the same under high temperature and normal temperature, stability checking parameter a_b in literature [2], it can be represented as below:

$$a_b = \frac{\varphi_{bT}}{\varphi_b} = \frac{M_{crT} f_y}{M cr f_{yT}} = \frac{E_T}{E} \cdot \frac{f_y}{f_{yT}} \tag{9}$$

To coordinate with the Design Code for Steel Structures [3] (GB50017-2003), in which φ_b should be replaced by correction factor $\varphi_b^{'}$ when the integral stability coefficient $\varphi_b > 0.6$, stability checking calculation of steel beam under high temperature should adopt the following formula $\varphi_{bT}^{'}$ when $\varphi_{bT} > 0.6$:

$$\varphi_{bT}^{'} = 1.07 - \frac{0.282}{a_b \varphi_b} \le 1.0 \tag{10}$$

That is：

$$\varphi_{bT}^{'} = \begin{cases} a_b \varphi_b & a_b \varphi_b \le 0.6 \\ 1.07 - \dfrac{0.282}{a_b \varphi_b} \le 1.0 & a_b \varphi_b > 0.6 \end{cases} \tag{11}$$

The resistance random process of steel beam under the influence of steel beam can be represented as:

$$\begin{aligned} R(t) &= K_p R_p(t) \\ &= K_p R_0 \cdot \varphi(t) \\ &= K_p \varphi_{bT} W f_y \varphi_y(t) \end{aligned} \tag{12}$$

In fundamental portfolio, the functionality of steel beam under the influence of high temperature can be represented as [4, 5]:

$$\begin{aligned} Z(t) &= R(t) - G - Q(t) \\ &= K_p \varphi_{bT}^{'} W f_y \varphi_y(t) - G - Q(t) \end{aligned} \tag{13}$$

If divide the fireproof limit into equal m parts, the stochastic process of load and resistance can be discrete into random variables. The failure probability of structure is:

$$\begin{aligned} P_f(Time) &= \{\min[R(t_i) - G - Q(t_i)] < 0, \quad t_i = (i-0.5)\tau, \quad i = 1,2,\ldots,m\} \\ &= P\{\bigcup_{i=1}^{m} R(t_i) - G - Q(t_i) < 0, \quad t_i = (i-0.5)\tau, \quad i = 1,2,\ldots,m\} \\ &= P\{\bigcup_{i=1}^{m} R_i - G - Q_i < 0\} \end{aligned} \tag{14}$$

Postulate Q_i are independent then:

$$P_f(Time) = 1 - P\{\bigcap_{i=1}^{m} R_i - G - Q_i \geq 0\}$$

$$= 1 - P\{\bigcap_{i=1}^{m} Q_i \leq R_i - G\} \quad (15)$$

$$= 1 - \int_0^{+\infty}\int_0^{+\infty}\cdots\int_0^{+\infty} \prod_{i=1}^{m} F_{Q_\tau}(r - g_i) f_{R_1,R_2,\ldots,R_m}(r_1, r_2, \ldots, r_m) f_G(g) dr_1 dr_2 \ldots dr_m dg$$

$f_{R_1,R_2,\ldots,R_m}(r_1, r_2, \ldots, r_m)$ —— The joint probability density function of $R_1, R_2, \ldots, R_m$

$f_G(g)$ ——The probability density function of constant load G

$F_{Q_T}(\cdot)$ ——The probability density function of live load Q_i

A random variable Q' was introducted in order to solve such a high dimensional integral. The distribution function is $F_{Q'}(q')$ and the probability density function is $f_{Q'}(q')$, (15) can be serialized into:

$$P_f(Time) = 1 - \int_0^{+\infty}\int_0^{+\infty}\cdots\int_0^{+\infty} f_{Q'}(q') f_{R_1,R_2,\ldots,R_m}(r_1, r_2, \ldots, r_m) f_G(g) dQ' dr_1 dr_2 \ldots dr_m dg$$

$$Q' < F_{Q'}^{-1}(\prod_{i=1}^{m} F_{Q_\tau}(R_i - G)) \quad (16)$$

$$= 1 - P\{Q' - F_{Q'}^{-1}(\prod_{i=1}^{m} F_{Q_\tau}(R_i - G)) < 0\}$$

$$= P\{F_{Q'}^{-1}[\prod_{i=1}^{m} F_{Q_\tau}(R_i - G)] - Q' < 0\}$$

$$= P\{g(R_1, R_2, \ldots, R_m, G, Q') < 0\}$$

$F_{Q'}^{-1}(\cdot)$ is the inverse function of $F_{Q'}(\cdot)$

$$g(R_1, R_2, \ldots, R_m, G, Q') = F_{Q'}^{-1}[\prod_{i=1}^{m} F_{Q_\tau}(R_i - G)] - Q' \quad (17)$$

We should pay attention to that the derivation process of function (17) Q' distribution is independent of the whole analysis process. So we can introduct the random variable without determining its distribution type. To give Q' engineering significance make $Q' = Q_T$

$$g(R_1, R_2, \ldots, R_m, G, Q_T) = F_{Q_T}^{-1}[\prod_{i=1}^{m} F_{Q_T}(R_i - G)^{\frac{1}{m}}] - Q_T \quad (18)$$

The biggest variable load effect Q_T obeys extreme value type I distribution. If

$$Q = F_{Q_T}^{-1}[\prod_{i=1}^{m} F_{Q_T}(R_i - G)^{\frac{1}{m}}] \quad (19)$$

According to the relationship between the function and its inverse function

$$F_{Q_T}(Q) = \prod_{i=1}^{m} F_{Q_T}(R_i - G)^{\frac{1}{m}} \quad (20)$$

Expansion (20) by the probability distribution function of the distribution of extreme value type I

$$F_{Q_T}(Q) = \exp\{-\exp[-a_T(Q-u_T)]\}$$
$$= \exp\{-\frac{1}{m}\sum_{i=1}^{m}\exp[-a_T(R_i-G-u_T)]\} \quad (21)$$

(21) can be obtained

$$Q = -\frac{1}{a_T}\ln[\frac{1}{m}\sum_{i=1}^{m}\exp(-a_T R_i)] - G \quad (22)$$

The function of reliability structural member under fire can be got [4]

$$g(R_1, R_2, ..., R_m, Q_T, G) = -\frac{1}{a_T}\ln[\frac{1}{m}\sum_{i=1}^{m}\exp(-a_T R_i)] - G - Q_T \quad (23)$$

4. Calculation Examples of Reliability Analysis on Beam under High Temperature

The steel beam of an office is shown in figure 1 (calculation diagram of steel beam is shown in Figure 2). The framed girder adopted thick fireproof coating protective layer, the thickness of which is 3.0cm. The basic information about the component: domestic rolling common I-steel beam, grade of steel is Q235, $f = 215MPa$; the span of the component is 4m with no lateral strut; Cross-section is $I36b$ with superficial area per unit length $1.289m^2/m$ and the volume per unit length $8.364\times10^{-3}\ m^3/m$. If the heating area of the beam in the fire is four fifths of the superficial area, it can be represented as $F_i = 0.8\times1.289 = 1.031m^2\ /m$. There is uniform distributed load q along the direction of the major axis on beam top flange. The section modulus of girder cross-section is $W = 920.8cm^3$. The integral stability coefficient of the beam under normal temperature is $\varphi'_b = 0.73$. The heat conduction coefficient of the fireproof coating material of the beam is $\lambda_i = 0.093W\ /(m\cdot{}^0C)$. The resistance of the component complies with lognormal distribution, and the statistical parameter is provided by literature [6]. $\mu_{K_P} = \mu_{X_P}\mu_{X_m}\mu_{X_A} = 1.2225$, $\delta_{K_P} = \sqrt{\delta_{X_P}^2+\delta_{X_m}^2+\delta_{X_A}^2} = 0.1908$. Permanent load effect complies with lognormal distribution. $\mu_G = 15kN\cdot m$, $\sigma_G = 0.9kN\cdot m$. Maximum variable load effect complies with extreme type I. $\mu_Q = 36.078kN\cdot m$ $\sigma_Q = 8.406kN\cdot m$. The fire endurance of the beam is 60min. The target reliability index is $\beta = 3.2$. Whether it can meet the needs of fire resistance design is to be judged.

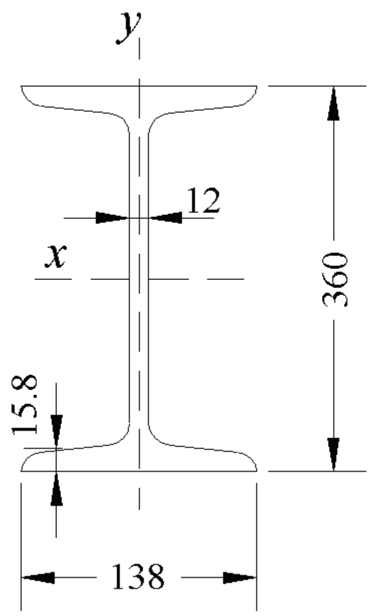

Figure 1. Schematic Diagram Beam Section

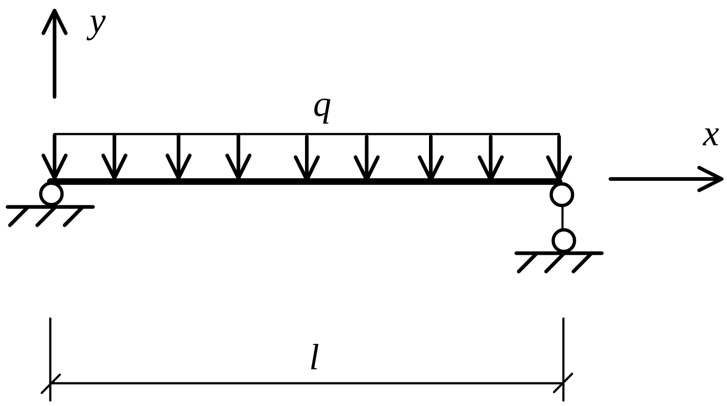

Figure 2. Calculation Diagram of Steel Beam

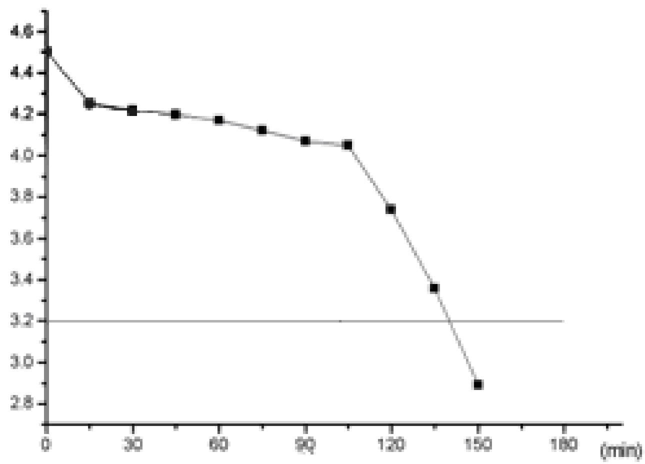

Figure 3. Curve of Reliability Index with Fire Duration

Table 1. Resistance of Beam at Different Time

Time（min）	15	45	75	105
Resistance（kN·m）	164.52	160.55	155.08	116.31

By substitution of the data in Table 1 obtained the reliability index of the beam with fire duration as Figure 1. Substitute it into equation (23), the reliability index of the beam in fireproof limit is 3.42.

5. Conclusions

(1) This paper presents that the steel members which are time-variant models are effected by ISO834, based on the steel-performance deterioration rule when the temperature is high.

(2) This paper also presents a reliability analysis method which is easy and viable. The new method is similar to the recommended norm under the circumstances of high temperature. Besides, this new method has some reference value of studies on steel members' reliability analysis.

References

[1] D. Ma, S. Liu, X. Fei, X. Wang, Z. Yang and Z. Zhou, "Design of Bayesian Network Assessment System on Underground Building Fire Risk", Journal of Harbin University of Science and Technology, vol. 18, no. 4, **(2013)**, pp. 103-107.

[2] G. Li, L. Han, G. Lou and S. Jiang, "Fire resistance design of steel structure and steel - concrete composite structure, China Building Industry Press", Beijing, **(2006)**.

[3] "Code for Design of Steel Structures (GB50017-2003)", The national standard of the people's Republic of China, **(2003)**.

[4] M. Qiao, Z. Wang, D. Zhu and Y. Han, "A Time-variant Reliability Analysis of Reinforced Concrete Beams under High Temperature", Journal of Harbin Engineering University, vol. 32, no. 8, **(2011)**, pp. 997-1000.

[5] M. Qiao, F. Gai, J. Zhao, "Design Method for Reliability for Reinforced-concrete members exposed to fire", Journal of Heilongjiang University of Science and Technology, vol. 24, no. 2, **(2014)**, pp. 211-215.

[6] Z. Wang, M. Qiao, Y. Han and D. Zhu, "A Time-variant Reliability Analysis of Steel Structures at High Temperature", The 14th International Symposium on Applied Electromagnetics and Mechanics, **(2009)**, pp. 607-608.

