Steel and Composite Structures, Vol. 5, No. 5 (2005) 395-405 395
DOI: http://dx.doi.org/10.12989/scs.2005.5.5.395

On the Chinese Code on fire safety design of steel building structures

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Abstract. This work introduces to the international scientific community the Chinese Code on fire safety design of steel building structures. The aim of the Code is to prevent the structure of a steel building subjected to fire from collapsing, ensure safe evacuation of building occupants, and reduce the cost for repairing the damages of the structure caused by fire. The main contents of the Code is presented in this paper, including the fire duration requirements of structural components, fundamental requirements on fire safety design of steel components, temperature increasing of atmosphere and components in fire, loading effect and capacity of various components in fire, and procedure for fire-resistant design of steel components. The analytical approach is employed in the Code and the effectiveness of the Code is validated through experiments.

Key words: fire-resistance; steel structures; design code.

1. Introduction

Fire is a disastrous effect on steel structure since the strength of steel will be greatly reduced with temperature increasing. For the design of steel structures for buildings where fire is likely to happen, fire-resistance has to be considered. The requirements of fire-resistance for steel structures are usually expressed as the fire-resistant duration for various structural components. To satisfy the requirements, the experiments on fire-resistance of steel components with or without fire protection can be conducted. However, there are a number of disadvantages to use experimental approach for fire safety design of steel components. Firstly, it is hard to consider the effects of the various load ratios over the component capacity in reality on the fire-resistance of the component through one or a few experiments. Secondly, it is difficult to simulate the restraint of adjacent structure relative to the considered component in the experiment, which has usually important effects on the fire-resistance of the component. Thirdly, the thermal effect is hard to be considered in the experiment. And finally, the cost of experiments is high. Hence, the advanced approach for fire-resistant design of steel components is based on fire safety check through analysis, which has been employed by BSI (1990), EC3 (2002), AS4100 (1990), etc.

The research on behaviour of steel structures subject to fire started from 1990 in China (Li *et al.* 1999). Since then lots of achievements have been made through theoretical and experimental research.

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Based on the achievements (Li *et al*. 1996, Li and Jiang 1999), the first code in China on fire safety of steel structures was initiated to compile in 1998 and formally issued in 2000 (Shanghai Technical Code on Fire Safety of Steel Structures 2000). The analytical approach is adopted in this code, which is validated through experiments. The key points of the code are presented in this paper.

2. Fire duration requirements of structural components

The aim of the code is to prevent the structure of a building subject to fire from collapsing, ensure safe evacuation of building occupants, and reduce the indirect economical loss due to the failure of the building and the cost for repairing the damages of the structure caused by fire. For this purpose, the requirements on the fire duration of structural components in various buildings are stipulated in this code, as shown in Table 1.

The fire-resistance duration requirement of a structural component is related to the function of the component in the structure and the grade of the building that the structure serves for. The more important is the structural component, the more serious the fire-resistance. The grade of a building is related to the purpose of the building (for domestic use or for industrial use), the height of the building (single-storey building, multi-storey building lower than 10 storeys, or high-rise building), and the possibility of fire hazard to be happed in the building. Table 2 gives the grades for domestic buildings (Chinese Code for Fire Protection Design of Building 1992, Chinese Code for Fire Protection Design of Tall Buildings 1997).

Table 1 Fire-resistance duration requirements of structural components (*h*)

Feature of structural components	Grade of buildings			
	Grade I	Grade II	Grade III	Grade IV
Column supporting multi-storey	3.00	2.50	2.50	0.50
Column supporting single-storey	2.50	2.00	2.00	-
Girder	2.00	1.50	1.00	0.50
Floor slab	1.50	1.00	0.50	0.25
Roof component	1.50	0.50	-	-
Exit stair component	1.50	1.00	1.00	-

Table 2 Grades of domestic buildings

Grade I buildings	Grade II buildings	Grade III buildings	Grade IV buildings
High-standard residential building; or ≥ 19 storey residential buildings;	10~18 storey residential buildings;	5~9 storey residential buildings;	1~2 storey residential buildings;
≥ 50 m in height commercial buildings;	<50m in height commercial buildings;	1~2 storey commercial buildings;	
≥ 50 m in height school buildings;	<50m in height school buildings;		1 storey school buildings;
≥ 10 storey hospital building	4~9 storey hospital buildings	2~3 storey hospital buildings	1 storey hospital buildings

3. Fundamental requirements on the fire safety design of steel components

For the fire safety of steel components, it is required that

$$t_d \geq t_m \tag{1}$$

or

$$R_d \geq S_m \tag{2}$$

where: t_d - the actual fire-resistant duration of structural components;
t_m - the required fire-resistant duration of structural components;
R_d - the actual load-bearing capacity of structural components in required fire duration;
S_m - the combined loading effect of structural components in required fire duration.

4. Temperature increasing of atmosphere and components in fire

4.1. Temperature increasing of atmosphere in fire

The standard temperature-time curve recommended by ISO834 is adopted for the temperature increasing of atmosphere during fire, which is expressed as:

$$T_g(t) - T_g(0) = 345\log_{10}(8t + 1) \tag{3}$$

where $T_g(t)$ - ambient gas temperature at time t, °C;
$T_g(0)$ - ambient gas temperature at time $t = 0$, °C;
t - time in minutes.

In addition, in order to get the more realistic ambient gas temperature increasing with time for the fire safety design of steel components, the following expression is recommended if related parameters can be determined beforehand:

$$\frac{T_g(t) - T_g(0)}{T_{gm} - T_g(0)} = \left[\frac{t}{t_m} \cdot \exp\left(1 - \frac{t}{t_m}\right)\right]^b \tag{4}$$

where T_{gm} - the maximum ambient gas temperature during the fire, °C;
t_m - the time when the ambient gas temperature reaches the maximum, min;
b - a parameter related to t_m, when $t \leq t_m$, $b = 0.8$; when $t > t_m$, $b = 1.6$;

4.2. Temperature development in steel components

(1) Under the assumption of uniform temperature distribution in a steel component subjected to fire, the temperature increasing in the steel component in a interval Δt can be determined with:

$$T_s(t + \Delta t) - T_s(t) = \frac{B}{\rho_s \cdot c_s} \cdot [T_g(t) - T_s(t)] \cdot \Delta t \tag{5}$$

where: $T_s(t)$ - the temperature in steel components at time t, °C;
$T_g(t)$ - the ambient gas temperature at time t, °C;

ρ_s - density of steel, kg/m^3;
c_s - specific heat of steel, J/(kg · K);
B - comprehensive heat transfer coefficient, determined by

$$B = (\alpha_c + \alpha_r)\frac{F}{V} \quad \text{for components without fire insulation} \tag{6a}$$

$$B = \frac{1}{1 + \dfrac{c_i\rho_i d_i F_i}{2c_s\rho_s V}} \frac{\lambda_i F_i}{d_i V} \quad \text{for components with fire insulation} \tag{6b}$$

where α_c - convective heat transfer coefficient between gas and component, $\alpha_c = 25$(W/(m^2·K));
α_r - radiant heat transfer coefficient between gas and component, which can be determined by

$$\alpha_r = \frac{2.885}{T_g - T_s}\left[\left(\frac{T_g + 273}{100}\right)^4 - \left(\frac{T_s + 273}{100}\right)^4\right](\text{W}/(\text{m}^2 \cdot \text{K}))$$

λ_i - thermal conductivity of fire protection material, W/(m·K);
d_i - thickness of the insulation, m;
c_i - specific heat of the fire protection material, J/(kg·K);
F - surface area of the component per unit length exposed to fire, m^2/m;
F_i - interior face area of the fire insulation per unit length, m^2/m;
V - volume of the component per unit length, m^3/m;

When the ISO 834 fire atmosphere temperature increase is employed for structural fire-resistant design, a simplified formula for predicting the temperature increasing in the steel component is proposed in the code. It is expressed as

$$T_s(t) = (\sqrt{0.044 + 5.0 \times 10^{-5}B} - 0.2)t + T_{s0} \tag{7}$$

where T_{s0} - the initial temperature of the component before a fire happening, generally let T_{s0}=20°C.

5. Loading effect

During a fire, structural components should be strong enough to carry various loading effects to keep the structural stability. Since fire is a accidental event, only the most possible values of various loading effects and their combinations are needed to consider for fire-resistant design of structural components. The following loading effect combination rule is recommended in the code as

$$S_m = \gamma_G C_G G_k + \sum \gamma_{Qi} C_{Qi} Q_{ik} + \gamma_W C_W W_k + \gamma_F C_F(\Delta T) \tag{8}$$

where: G_k - characteristic value of dead load;
Q_{ik} - characteristic value of live load;
W_k - characteristic value of wind action;

ΔT - structural temperature elevation of steel due to fire;
C_G, C_{Qi}, C_W, C_f - factors of various loading effects;
γ_G - partial factor for dead load effect, $\gamma_G = 1.05$;
γ_{Qi} - partial factor for live load effect, $\gamma_{Qi} = 0.7$;
γ_W - partial factor for wind action, $\gamma_w = 0$ or 0.3;
γ_F - partial factor for structural thermal effect, $\gamma_F = 1.0$

6. Capacity of various components in fire

With temperature elevation caused by fire, the strength and elastic modulus of steel components will be reduced. The formulas recommended by ECCS (1983) governing the reduction of elastic modulus and yield strength of steel are employed in the code. With the reduced elastic modulus and yield strength of steel under high temperature due to fire, the load bearing capacity of various steel components can be formulated with the same approach as for the situation of normal temperature.

6.1. Axial tension

The capacity of an axial tension steel component under fire condition is governed by

$$\frac{N}{A} \leq f_{yT} \tag{9}$$

where N - the combined axial force effect in the component under fire condition;
A - the area of cross section of the component;
f_{yT} - the characteristic value of yield strength of steel at elevated temperature.

6.2. Axial compression

The capacity of an axial compression steel component under fire condition is determined by

$$\frac{N}{\varphi_T A} \leq f_{yT} \tag{10}$$

where

$$\varphi_T = \alpha\varphi \tag{11}$$

φ - factor of stability for the axially compressed steel component at normal temperature;
α - coefficient, as listed in Table 3.

Table 3 Coefficient α

Slenderness ratio of components	Temperature of structural components (°C)							
	200	300	400	500	550	570	580	600
≤ 50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96
100	1.04	1.08	1.12	1.12	1.05	1.00	0.97	0.85
150	1.08	1.14	1.21	1.21	1.11	1.00	0.94	0.74
≥ 200	1.10	1.17	1.25	1.25	1.13	1.00	0.93	0.68

6.3. Bending component

The capacity of a bending steel component is governed by

$$\frac{M_x}{\varphi_{bT} W_x} \le f_{yT} \tag{12}$$

in which $\varphi_{bT} = \alpha_b \varphi_b$

where M_x - the maximum moment in the component under fire condition;
W_x - the modulus of the component cross-section;
φ_b - the factor of stability for the bending component at normal temperature;
φ_{bT} - the factor of stability for the bending component at elevated temperature;
α_b - a coefficient determined by

$$\alpha_b = 1.150 + 0.154 \sin\left(\frac{T_s}{460}\pi - 0.46\pi\right) \qquad 0° < T_s \le 500°C \tag{13a}$$

$$\alpha_b = 1.292 - 0.6565 \times 10^{-4}(T_s - 500)^2 \qquad 500°C < T_s \le 600°C \tag{13b}$$

6.4. Compression and bending component

The capacity of compression and bending steel components under fire condition can be governed by

$$\frac{N}{\varphi_{xT} A} + \frac{\beta_m M_x}{\gamma_x W_x (1 - 0.8/N_{EXT})} \le f_{yT} \quad \text{in the bending plane} \tag{14a}$$

$$\frac{N}{\varphi_{xT} A} + \frac{\beta_t M_x}{\varphi_{bT} W_x} \le f_{yT} \quad \text{out of the bending plane} \tag{14b}$$

where β_m, β_t - equivalent moment factors;
N_{EXT} - Euler critical load of the component in the bending plane at elevated temperature, determined by $N_{EXT} = \frac{\pi^2 E_T A}{\lambda^2}$, in which λ is the slenderness of the component and E_T is the elastic modulus where of steel at elevated temperature;
γ_x - factor representing the plasticity development, $\gamma_x = 1.05$ for I and box sectional component;
φ_{xT}, φ_{yT} - factor of stability for the axially-compressed steel component in the bending plane and out of the bending plane respectively at elevated temperature.

7. Procedure for fire-resistant design of steel components

The following procedure can be adopted in practice for the fire-resistant design of steel components:
(1) Determine the fire-resistant duration requirement of the component considered according to Table 1;

(2) Assume a thickness of fire insulation selected for fire-protection of the component;
(3) Calculate the temperature of the component exposed to a fire in the time of required fire resistant duration with Eq. (5) or Eq. (7);
(4) Determine the combined loading effect on the component under fire condition with Eq. (8);
(5) Check the load-bearing capacity of the component under fire condition with Eqs. (9), (10), (12) or (14), and
(6) If the load-bearing capacity of the component under fire condition is too small or too large, adjust the thickness of fire insulation and repeat the above step (1) through step (5).

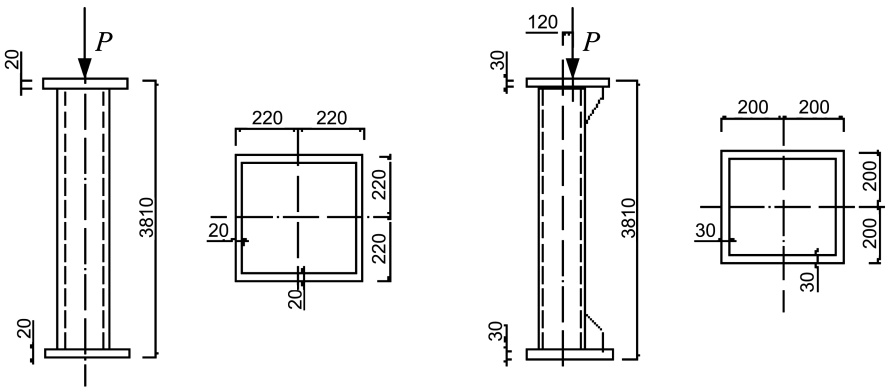
8. Experimental validation

In order to validate the effectiveness of the approach for the fire safety design of steel components presented hereinabove, a series of experiments have been carried out in Tongji University (Li *et al.* 2000a, 2000b) on steel columns and steel beams subject to fire.

8.1. Experiments on the axially compressed column and eccentrically compressed column

The purpose of the experiments is to validate the fire safety design method employed by the Code for axially and eccentrically compressed steel columns. The axially compressed specimen is a box column welded by steel plate with a thickness of 20 mm, and the eccentrically compressed specimen is also a box column welded by steel plate with a thickness of 30 mm, as shown in Fig. 1. The height of the columns is 3810 mm, but only a segment of 3000 mm of the columns were enclosed in the stove, as shown in Fig. 2. The slenderness ratio of the axially compressed one is 22.2 and that of the eccentric column is 25.2. The offsetting of the load for the eccentrically compressed column is 120 mm. The column specimens were made of Q235 steel, the yielding strength and Young's modulus of which are 255 MPa and 1.85×10^5 MPa, respectively. The specimens were protected by fireproof paint with a thickness of 10 mm, and the thermal conductivity λ to be 0.12 W/(m · K).

The load on the specimens was kept constant while the temperature in the stove increased according to ISO834 standard. The load for axially compressed column specimen was 4116 kN and that for



(a) Axially compressed column (b) Eccentrically compressed column

Fig. 1 Sketches of specimens of columns

(a) Axially compressed column (b) Eccentrically compressed column

Fig. 2 Specimens of columns in the stove

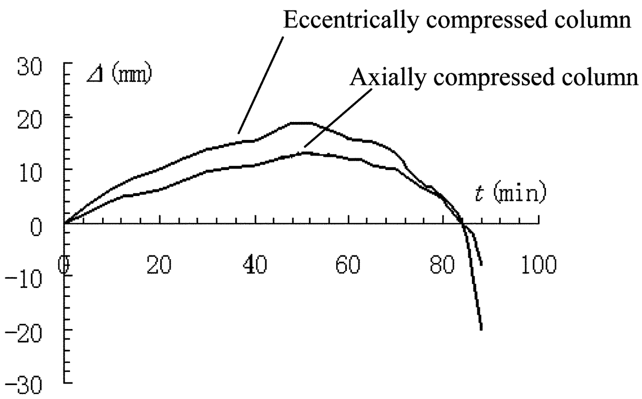


Fig. 3 The variation of axial deformation with time

eccentrically compressed column specimen was 3528 kN. Fig. 3 shows the variation of the axial deformation of the specimens with the lasting time of fire exposures. The fire-resistant duration of the axially compressed column and the eccentrically compressed column were measured 88 minutes and 85.2 minutes, respectively.

8.2. Experiments on the axially restrained beam

The purpose of the experiments is to validate the fire safety design method employed by the code for bending beams with thermal effects due to restraints.

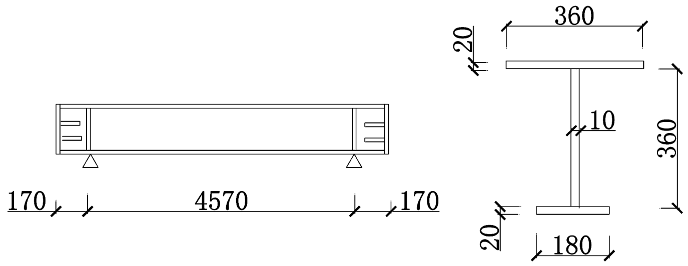


Fig. 4 Configuration of the beam

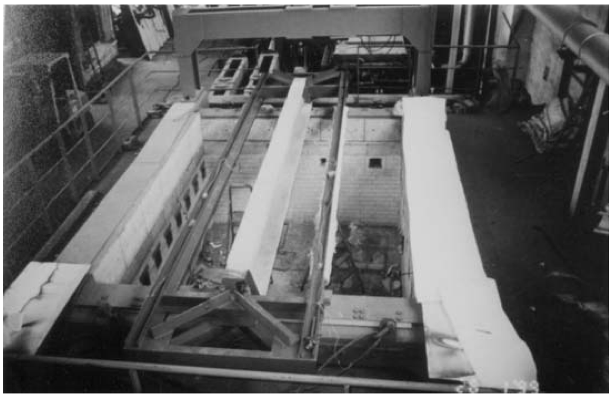


Fig. 5 The configuration of furnace for the experiment on beam

A beam specimen welded by three plates is shown in Fig. 4. The steel for the specimen is Q235, the yielding strength of which is 225 MPa and the Young's modulus is 1.85 MPa. The specimen was protected by fireproof paint with a thickness of 15 mm and the thermal conductivity λ to be 0.102 W/(m·K).

Fig. 5 shows the furnace for the fire-resistant experiment on the beam. The ends of the beam were restrained by a truss, as shown in Fig. 6. The truss is heavily insulated by ceramic materials with a thickness of 40 mm. So the axial expansion of the beam is restrained when heated and the thermal effects on the beam was simulated. Four point loads were applied on the beam, as shown in Fig. 7.

The ISO834 standard fire was also adopted for the beam specimen. The axial force in the beam due to the restraint of the truss was measured to be 1140 kN when the beam failed. The measured fire-resistance duration of the beam was 54 minutes.

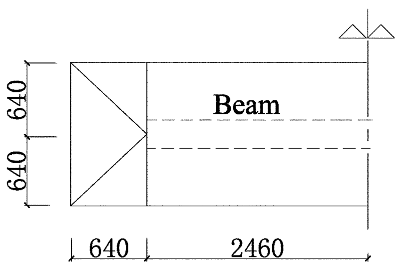
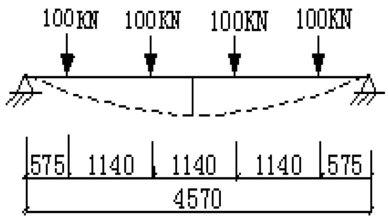


Fig. 6 Sketch of the truss



(a) Location of the loads on beam

(b) A view of the loads on beam

Fig. 7 Loads on the beam specimen

Table 4 The comparison between measurement and prediction for fire-resistance duration of specimens

Members	Predicted result(min)	Experimental measurement(min)	Relative error
Axially compressed column	94	88	6.82%
Eccentrically compressed column	90	85.2	5.63%
Axially restrained beam	53.8	54	0.4%

8.3. Comparison between prediction and measurement

The fire-resistance duration of the axially compressed column, the eccentrically compressed column and the restrained beams can be predicted through the approach proposed in the *Chinese code on Fire Safety Design of Steel Structures*.

The comparison between the results obtained by the experimental measurement and the Code prediction is shown in Table 4. It can be seen that the fire-resistance of steel components can be satisfactorily predicted with the Code.

9. Conclusions

The main content of *Chinese code on Fire Safety Design of Steel Structures* is presented in this paper. The principle of the code is to meet the requirements of fire-resistance on the basis of limit state of steel structures under fire condition. The analytical approach is employed in the code for the fire safety of various steel components through checking the load-bearing capacity of the components exposed to a fire in the time of required fire resistant duration. The effects of the load level, thermal action and structural restraint on the fire-resistance of steel components can be considered. The effectiveness of the approach adopted by the Code is validated through experiments.

Acknowledgments

The work reported in this paper was financially supported by the Natural Science Foundation of China through project No. 59478038.

References

British Standard BS5950: Part8: 1990, *Structural Use of Steel Work in Building*. BSI.

CEN, DAFT ENV 1993: Eutocode3: *Design of Steel Structures*, July 2002.

Standards Association of Australia: *AS4100 (1990) - Steel Structures*, SAA, Sydney, 1990.

Li, G.Q., Jiang, S.C. and He, J.L. (1999), "The First Code on Fire Safety of Steel Structures in China", *The Second Int. Conf. on Advances in Steel Structure*. HongKong. 1031-1038.

Li, G.Q., Jiang, S.C. and Shen, Z.Y. (1996), "Research into analysis and design for fire-resistance of tall steel buildings", Technical Report, Tongji University.

Li, G.Q. and Jiang, S.C. (1999), "Prediction to nolinear behaviour of steel frames subjected to fire", *Fire Safety Journal*, **32**(4), 347-368.

Shanghai Technical Code on Fire Safety of Steel Structures, 2000.

Chinese Code for Fire Protection Design of Building, 1992.

Chinese Code for Fire Protection Design of Tall Buildings, 1997.

ECCS, European Recommendations for the Fire Safety of Steel Structure, 1983.

Li, G.Q., He, J.L. and Jiang, S.C. (2000a), "Fire-resistant experiment and theoretical calculation of steel columns", *Building Structure,* **30**(9), 12-15.

Li, G.Q., He, J.L. and Jiang, S.C. (2000b), "Fire-resistant experiment and theoretical calculation of a steel beam", *China Civil Engineering Journal*, **32**(4), 23-26.

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