# STEEL STRUCTURAL FIRE-RESISTANCE DESIGN FOR PROTECTING THE WORLD CULTURAL HERITAGE

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**Abstract**

Minlou is the biggest unit among the world cultural heritage Mingxiao mausoleum erected in A.D. 1405 in Nanjing, China. In A.D. 1853, the timber roof of Minlou collapsed in the fire, and only brick wall survived. To prevent the survival brick wall from weather erosion, a steel truss with timber decorating would be built up in 2008. The finite element analysis was operated to examine the steel truss loading capacity exposed to the most severe fire scenario caused by the combustible timber member. Finally, the fire protection measures were proposed when the structural fire-resistance is satisfied with the objectives of performance-based. The outcome illustrates that steel structural fire-resistance can't depend on results from single element testing in the standard furnace, and provides a snapshot to demonstrate that critical temperature method is efficient for structural fire safety design.

**Keywords:** fire-resistance, fire safety design, steel truss, critical temperature

## INTRODUCTION

Mingxiao tomb buried the first emperor of Ming Dynasty erected in A.D. 1405, composed of a series of buildings. It lies to the east of suburban area in Nanjing, near the west side of Mao Mountain. Minlou is with 39.25m width and 18.4m span which is the biggest building among Mingxiao tomb. The timber roof of Minlou building has been destroyed in the war and brick wall survived in A.D.1853 shown in Fig.1. To prevent the survival brick wall from weather erosion, National Administration of Cultural Heritage approved the emergency measure of rebuilding a roof to cover the survival brick wall. A steel truss with timber decorating was employed shown in Fig.2. There are dozens of corbel arches and hundreds of stock rafters within the steel structural system. Timbers are the fire resource within the service period. To prevent the steel truss from fire, structural design for fire safety is important.

Fig. 1 Minlou building without roof

Fig. 2 Rebuilding roof with ancient shape

## 1 ADVANCED METHOD OF STRUCTURAL FIRE SAFETY DESIGN

The China code CECS200:2006 has been introduced for designing structures to resist fire by calculation. In principle, fire loading can be treated as any other form of loads. However, the structural behaviour in fire in all but the simplest case is much more complex than normal temperature for the material characteristics varied with temperature. Hand calculation methods aren't suitable to structural thermal analysis. Computer-based finite element methods are employed which include the non-linear material properties temperature dependent and the effects of thermal expansion. The critical temperature method carries out a structural analysis for the fire situation, and check critical temperature in fire limit stat. The basic fire-resistance steps for this project are:

1. Design fire scenario for calculation the maximum temperature of members in the duration.
2. Establish the global finite element model under design loading.
3. Calculate the thermal & mechanical response of global structure at each temperature step ($\Delta t = 5$ □) and check the loading capacity of each member. When structure collapsed, the critical temperature has been gotten.
4. If the maximum temperature of structures (or elements) subjected to design fire, $T_m$, is lower than the critical temperature of structures (or elements), $T_d$, given by structural fire analysis, the structural fire-resistance is satisfied without fire protection.
5. If the maximum temperature of members in duration is higher than the critical temperature, design fire protection for steel roof to reduce the temperature. Then go to step3 continued.

## 2 DESIGN FIRE

According to the function of building and the total amount of combustible material, the probable fire scenario can be designed. Fire Dynamics Simulation (FDS developed by NIST) software based on computational fluid dynamic model is employed to simulate the design fire scenario to result the non-uniform fire temperature distribution (Yong, 2005).

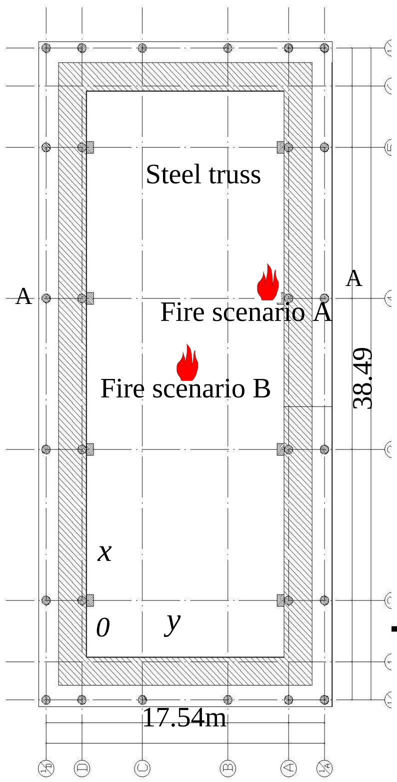



Fig.3 The plane at level 7.15m

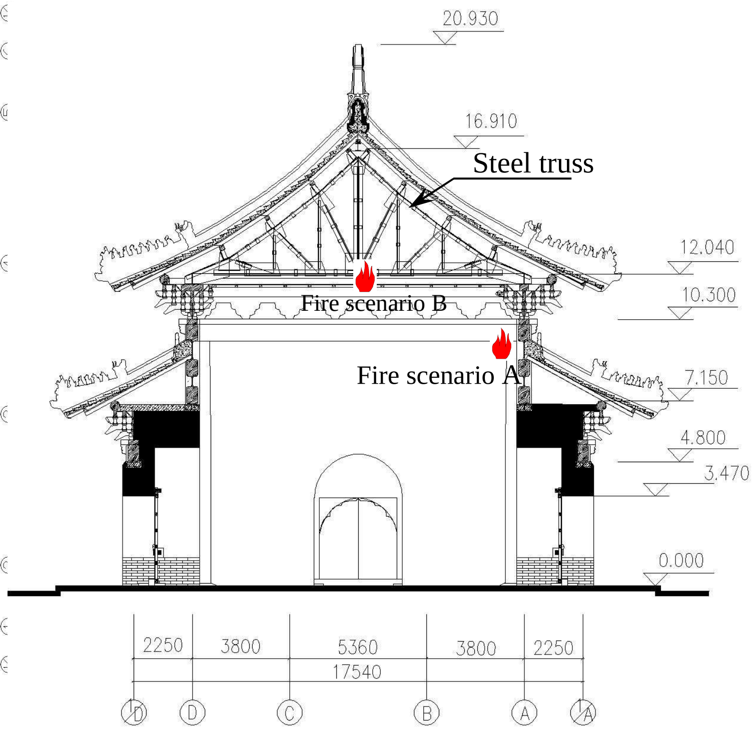



Fig.4 A-A profile

### 2.1 Fire scenarios

Basic premises for design fire are below:

1. There is no heat energy exchange between outside and compartment. The ambient temperature is 20°C.
2. Doors are open as ventilators and the fire is fuel controlled.

3. The fire grows as t-squared type and fire growth coefficient is 0.04689 $kW/s^2$.

Shown in Fig.3 and Fig.4, there is no combustion on the ground, but there are a number of timber elements at the level 7.15m and 10.3m.
Scenario A– dozens of corbel arches are taken for the fire source at the level 7.15m;
Scenario B – a stock beam and wooden ceiling is taken for the fire source at the level 10.3m

## 2.2 Fire heat release rate & smoke temperature

The test on the ratio of heat release (HRR) for wooden piles has been run by Babrauskas and his colleagues since 1980s at NIST. The database is employed to estimate the HRR in Scenario A and B, which is available on NIST web shown in Figure 5 ~ Figure 6. After ignition10min, the highest HRR is 1.8MW.

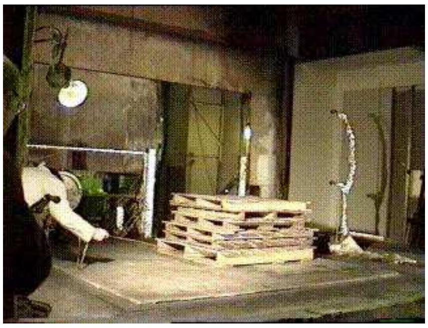


Fig.5 Wooden pile before test

Fig.6 Full development period

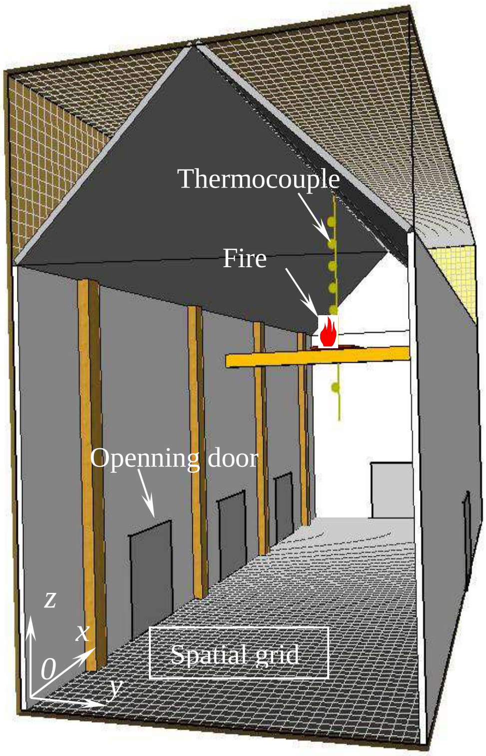



Fig.7 Numerical model for fire

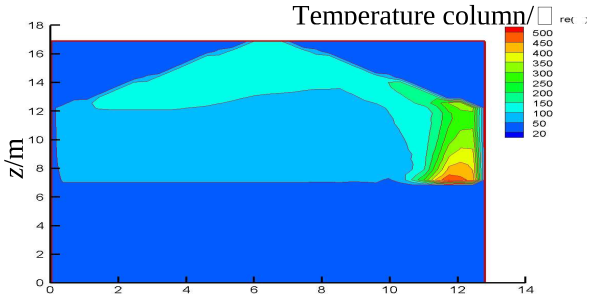



Fig.8 Temperature contours after ignition 30min for scenario A

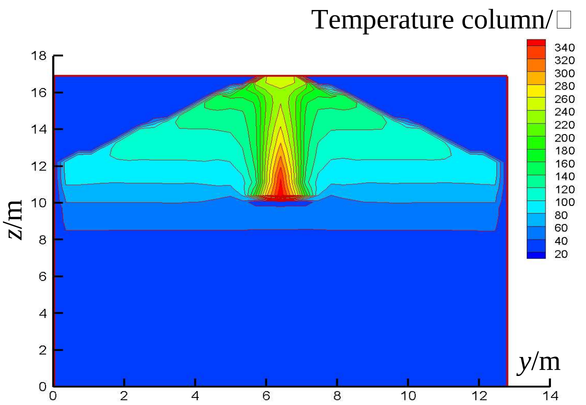



Fig.9 Temperature contours after ignition 30min for scenario B

Considered of fire moving and duration, a conservation fire scenario is designed with 1.8MW heat release for fast T-square growth type and last 1.5h. The fire simulation model shown in Fig. 7 is derived from FDS software to result the non-uniform temperature distribution graphically as Fig. 8 and Fig. 9.The maximum smoke temperatures are 490°C and 340°C for scenario A and B respectively.

## 3 MATERIAL PROPERTIES & GLOBAL FE MODEL

The material properties are given in Table 1, and the stress-strain curves with temperature was shown in Fig. 10. The section and axial forces for each member is shown in Fig. 11.

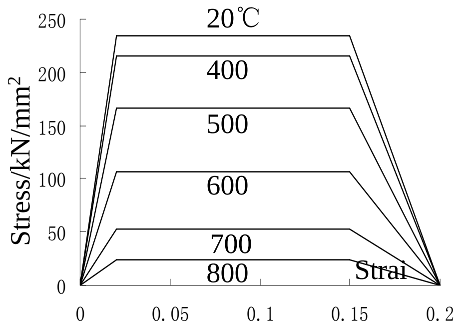
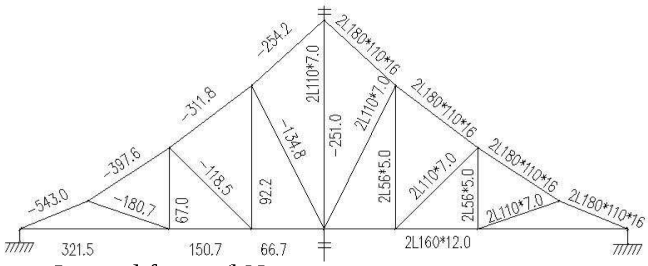



Fig.10 Stress-strain relations for steel




Internal forces /kN Pressure is dimension

Fig.11 Internal forces and

Tab. 1 Material properties at high temperature

| Parameter Name | symbol | value | unit |
|---|---|---|---|
| Thermal expansion coefficient | $\alpha_s$ | 1.4×10-5 | m/(m ·℃) |
| Thermal conductivity | $\lambda_s$ | 45 | W/(m·℃) |
| Specific heat | $c_s$ | 600 | J/(kg ·℃) |
| Density | $\rho_s$ | 7850 | kg/m3 |
| Poisson ' s ratio | $\upsilon_s$ | 0.3 | — |

Shown in Fig.12, the supports are restrained in the horizontal and vertical directions, but rotationally free for FE model. 3D elements were used to represent the steel tubes.

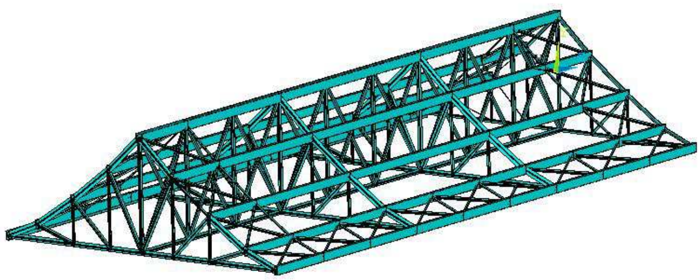


Fig.12 Global FE model of steel roof

## 4 CALCULATION TEMPERATURE IN STEEL MEMBERS

For Ref.3 propose, in the large space building fires if the distance from the flame to the surface of steel members is far enough, heat transfer between the flame and the steel member may be disregarded. Otherwise the radiant heat must be considered in the heat equilibrium equation based on the lumped differential formulation given by

$$\frac{\Delta T_{sf}}{\Delta t}=\frac{1}{V\rho_s c_s}\times$$
$$\left\{\varepsilon_r\varepsilon_s c_0 F\left[\left(T_g+273\right)^4-\left(T_{sf}(t)+273\right)^4\right]+\varepsilon_f\varepsilon_s\varphi_{sf}\xi F\left(1-\varepsilon_g\right)c_0\left[\left(T_f+273\right)^4-\left(T_{sf}(t)+273\right)^4\right]+F\varepsilon_c\left(T_g-T_{sf}(t)\right)\right\} \quad (1)$$

Where $c_s$ , $\rho_s$ specific heat of steel [J/ (kg ·℃) ] and the density of steel [7850kg/m$^3$] respectively

$\Delta t$ time interval (recommended Δt is not more than 5 seconds)

$\varepsilon_r$ resultant emissivity representing the radiation transmitted between the hot smoke and the steel member surface [ $\varepsilon_r = 0.5$ ]

$\varepsilon_s$ , $\varepsilon_f$ emissivity of steel members and flames respectively [ $\varepsilon_c$ =0.8 , $\varepsilon_f$ =0.7 ]

$\varepsilon_c$ convective heat transfer coefficient [25W/(m$^2$⊙℃) ]

$c_0$ stefan-Boltzmann constant [5.67×10$^{-8}$ W/m$^2$ ·K$^4$]

$F$ surface area of the unprotected steel member per unit length [m$^2$/m]

$V$ volume of the unprotected steel member per unit length [m$^3$/m]

$T_g$ smoke temperature [℃]

$T_{sf}$ temperature of the unprotected steel member, which is due to heat transfer by convection and radiant from hot smoke and by flame radiant

$T_f$ average temperature of flame [℃]

$\varphi_{sf}$ configuration factor in the particular case of two parallel surfaces

$\xi$ ratio of the flame radiated surface for the unprotected steel member

### 4.1 Configuration factor

The configuration factor is a measure of how much of heat from flames is received by steel member surfaces, between flame area and differential surface of steel members.
The height of flame “$Z_1$” is given by

$$Z_1 = 0.144 Q_s^{0.4} \tag{2}$$

where $Q_s$ is the heat release rate [kW].
Shown in Fig. 13(a), *Eq.3* is used, and shown in Fig.13(b) *Eq.4* is used.

$$\varphi_{sf}^{a} = \frac{1}{2\pi}\left(\frac{X}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\frac{X}{\sqrt{1+Y^2}}\right) \tag{3}$$

$$\varphi_{sf}^{b} = \frac{1}{2\pi}\left(\tan^{-1}Y - \frac{1}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}}\right) \tag{4}$$

where $X=A/C$，$Y=B/C$；$C=H-Z_1$, shown in Fig. 14.
Induce each geometric parameter into *Eq.3* and *Eq.4*. The configuration factors for each side of the bottom chord, which is made of two angles back to back, can be gotten.

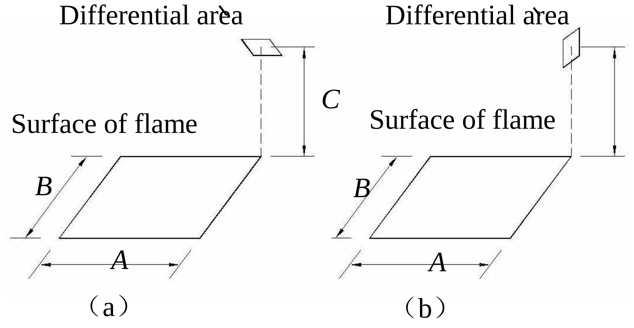



Fig.13 Location of differential area

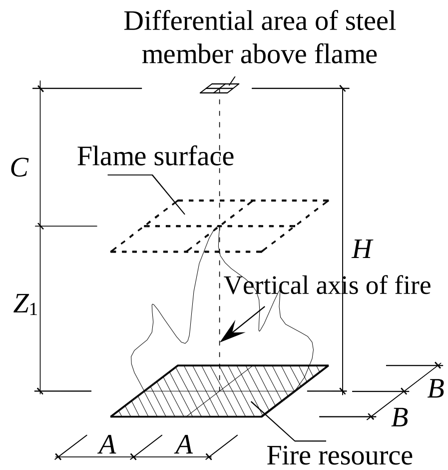



Fig.14 Geometrical data for the configuration factor

### 4.3 Ratio of the effective surface area exposed to flame radiation

$\xi$ is the ratio of the surface area of the unprotected steel member exposed to flame radiation, given by

$$\xi = \sum_{i=1}^{n} \varphi_{sf}^{i} F_{sr}^{i} / \varphi_{sf} F \tag{5}$$

Where $F_{sr}^{i}$ each surface area of unprotected steel members exposed to flame radiation,

$\varphi_{sf}^{i}$ configuration factor for each surface of unprotected steel members.

Induce each parameter into *Eq.5*, the ratio of the surface area of the unprotected chords exposed to flame radiation can be gotten.

Finally, induced parameters given above into the *Eq.1*, the history of temperature of steel members $T_{sf}$ can be gotten with step-by-step method. The maximum temperature of steel members in scenario A will reach 550℃ during 1.5h duration, and decay from the vertical axis of fires away.

## 5 FIRE PROTECTION

In scenario A the chords above the fire source buckled at the temperature 380℃ and regarded as the critical temperature of steel truss.

The fire protect material ensures that the maximum temperature in the steel truss is lower than the critical temperature which would cause structural failure during the fire duration. For given fire protection material properties and the fire duration, the temperature of steel members can be estimated by *Eq.6* (Yong, 2006).

$$\frac{T_g - T_s}{T_g - T_g(0)} = -a + (1+a) \cdot e^{\left(-b \times 10^{-4} t\right)} \tag{6}$$

Where $T_s$ the temperature in steel members, $T_g(0)$ the ambiance temperature (20°C),

*a* and *b* fitting coefficient from reference (Yong, 2006),which are dependent on fire protect material properties $d_i / \lambda_i$ .

Assuming the rate of the thick of fire protection material $d_i$ to equivalent thermal conductivity coefficient of fire protection material $\lambda_i$ is $d_i / \lambda_i = 0.1$, then $T_s = 353$ °C can be derived from *Eq.6* for given fire duration 1.5h. The thick of fire protection material $d_i$ should be determined by $\lambda_i$ for different fire protection materials.

## 6 CONCLUSIONS

This paper provides a snapshot of information and analysis to demonstrate the critical temperature method is sufficient for fire safety design. A detailed FEA of the space truss was carried out to obtain the critical temperature, and the fire protection measure of the steel roof was carried out. The performance-based structural fire safety design showed that the Minlou roof can maintain its structural loading capacity within 1.5h under fire protection.

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