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Letter

The mechanics and deformation of high temperature steel frame rapidly cooled by spray water in fire fighting

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HIGHLIGHTS

- A steel frame at high temperature is introduced by integrating a new nonstationary mechanics and deformation based on the cooling location and cooling rate.
- The mechanics is mainly affected by the cooling location and cooling rate.
- The results are very useful for providing a new evaluation method for the structure's damage and failure in a practical fire fighting.

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ABSTRACT

A finite element is established for analyzing the dynamical mechanics and deformation of steel frame at high temperature when it is rapidly cooled down by spray water in fire fighting. The simulation result shows that remarkable mechanical coupling effects are produced in the process, and the sectional stress in rapid cooling down is found considerably larger than that in heating-up. Meanwhile, the stress and deformation of a beam mainly related to cooling rate and location are much larger than those of a column in rapid cooling. In fire fighting, the structure on the first or second floor was more dangerous than those on other floors in rapid cooling. These results could provide a theoretical reference for the design of steel structure and fire fighting.

In recent years, steel frame is widely used for high-rise buildings. Because of its defects in fire resistance, those steel structures are mainly cooled down by spray water to protect them from damage in fire. However, some structures at high temperature often suddenly are destroyed in fire fighting, and the failure is no foreboding [1–12].

In fire, steel structure is at high temperature when fire fighting system starts [10–15]. In rapid cooling by spray water, the deformation cannot recover in a very short period, but large stress is produced inside the structure because the temperature is different, and the stress is even much larger than its yield stress, so the large stress can cause the structure destroyed instantly [4–11]. The simulation results can provide a reference for steel structure and fire fighting designs along with a new method of the damage evaluation for steel structure in fire fighting.

In fire, fire just happens at parts of building, the effect of heating on steel structure is very different. According to the effect of local fire on steel structure, the simulation modeling can be simplified as a three-floor and three-span steel structure (see Fig. 1), its finite element calculation modeling is shown in Fig. 2.

In Fig. 1, all of the steel frames are made of H-type structural steel (steel Q235), the sectional dimension of beam is H250 × 250 × 9 × 14 mm, and the sectional dimension of all the secondary beams is H150 × 150 × 7 × 10 mm, the sectional dimension of column is H300 × 300 × 10 × 15 mm. All the joints of beam-to-column are welded. The loading acting on all beams is just the slab weight. Each column is acted by a vertical load at 300 kN on its top end. Water nozzle is fixed at the ceiling center, its outlet is 10 cm far from the ceiling and the spray angle is 90°.

In cooling, the temperature drop rate of structural steel can be calculated according to the following equation [1]:

$$T = \begin{cases} T_h - 10.417\,(t - t_h)\,, & (t_h \leqslant 5\ \text{min}), \\ T_h - 4.167\left(3 - \dfrac{t_h}{60}\right), & (5\ \text{min} < t_h \leqslant 10\ \text{min}), \\ T_h - 4.167\,(t - t_h)\,, & (t_h > 10\ \text{min}), \end{cases} \quad (1)$$

where t was time (minute), T_h was the max temperature (°C), t_h was the time at T_h (minute).

For the structure, the floor slab is made of concrete C25, thickness 14 cm, its density and Poisson's rate change little in heating

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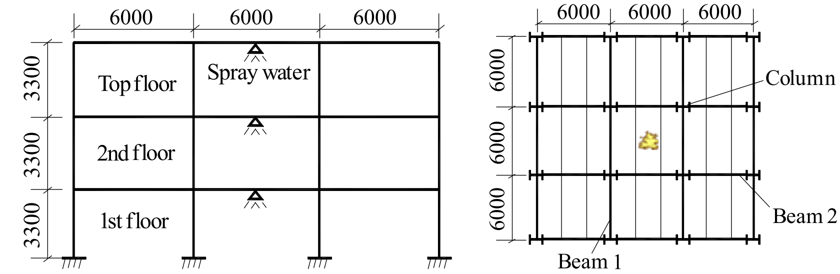
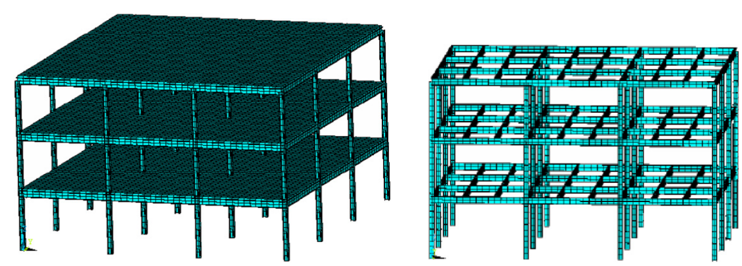


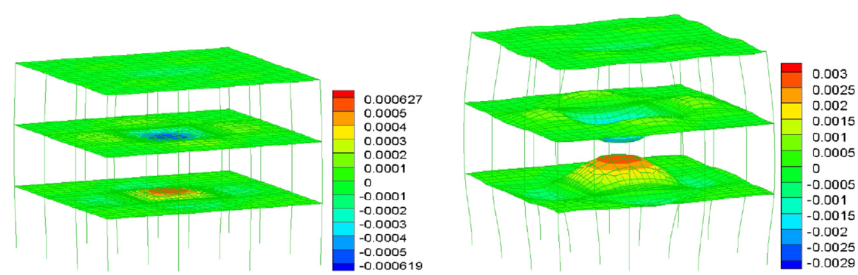
(a) Front view. (b) Top view.

Fig. 1. Sketch of the simulation modeling for a steel frame structure (in mm).



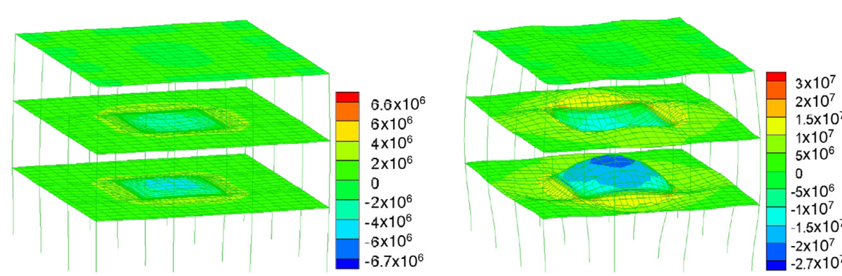
(a) The whole calculation model. (b) The calculation model for beams and columns.

Fig. 2. Finite element modeling.



(a) 100 s. (b) 200 s.

Fig. 3. The deformation distribution (m) at Z direction.



(a) 100 s. (b) 200 s.

Fig. 4. Tensile stress distribution (Pa) of floor slab after cooled.

and cooling, so its density is taken as the constant 2600 kg/m^3, and its coefficient of thermal expansion is 1.8×10^{-3} mm/(m·°C), its Poisson's rate is about 0.24. The thermal conductivity of concrete at temperature T can be calculated as follows [6,7]:

$$\lambda_T = 0.012\left(\frac{T}{120}\right)^2 - 0.24\left(\frac{T}{120}\right) + 2. \tag{2}$$

For concrete C25, its specific heat capacity can be calculated as follows [6,7]:

$$C_p = -4\left(\frac{T}{120}\right)^2 + 80\left(\frac{T}{120}\right) + 900. \tag{3}$$

For structural steel, its density changes little to 7800 kg/m^3. The Poisson's ratio is 0.3, coefficient of thermal expansion is