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Fire-resistance study of restrained steel columns with partial damage to fire protection

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ABSTRACT

In order to analyze the behavior of steel columns in fire with partial damage of fire protection, an analytical model is presented based on the differential equation of equilibrium, which may be used to predict the ultimate load bearing capacity of steel columns fixed at two ends and to predict the critical temperature of axially restrained steel columns. The imperfection of initial flexure of steel columns is taken into account in the model. The yielding of the edge fiber at the mid-span of a column subjected to elevated temperature is taken as the failure criteria for the fire resistance of the column. A numerical application is carried out to demonstrate the effect of the damage of fire protection on the ultimate load bearing capacity and axial force increase of axially restrained steel column in fire. Comparing with FEM, the model proposed in the paper has been validated and good agreement has been found.

1. Introduction

Unprotected steel structures do not have desirable fire resistance because the temperature of unprotected steel elements increase rapidly in fire due to the high thermal conductivity of steel. Thermal insulation materials are widely used to protect steel structures against fire by slowing down heat transfer from the fire to the steel elements, and hence reducing the rate of temperature increase in the steel. However, spray-on insulation materials are often rather fragile, and they may be easily damaged by mechanical actions, such as impact, resulting in a possible fire resistance reduction for the steel elements originally protected. So it is important to investigate the fire resistance of steel members with partial fire protection damage.

To the best of our knowledge, there are some published works related to the steel columns or beams with partial damage to fire protection. Ryder et al. [1] carried out a three-dimensional finite element analyses to investigate the effect of fire protection loss on the fire resistance of steel columns. Yu et al [2] carried out a numerical study to investigate the fire resistance reduction of protected steel beams caused by partial loss of spray-on fire protection. The results of a heat transfer analysis of steel columns with partial loss of fire protection using the finite element method were also presented by Milke et al [3]. Fontana and Knobloch [4][5] studied the behavior of steel columns subjected to fire using a three-dimensional finite element heat transfer and structural model, taking into account geometrical nonlinearities, local temperature distributions, thermal strains, and temperature dependent material properties. Pessiki [6] performed an analysis to examine the behavior of steel H columns in fire with damaged spray-applied fire resistive material subjected to concentric axial compression. A simple model to predict the ultimate load bearing capacity of hinged steel columns with partial fire protection damage is presented in our previous work [7].

A column in a structure is often axially restrained by the adjacent members like beams, slabs, and supports in the steel structures. At ambient temperature, the axial restraint can improve the ultimate load bearing capacity of the column [8], but in fire environment, the additional axial force of the column will be increased, which will cause an earlier yield or buckling of the column. In real structures, the loading conditions of steel columns subjected to the action of a localized fire will change with time, if their axial elongation is restrained. There are also some papers which deal with the restraint of the column in fire. A study by Rodrigues et al [9] showed that neglecting the effect of thermal axial restraint may result in overestimation of the fire resistance of columns. Valente and Neves [10] used a computer program based on the Finite Element Method to analyze the influence of elastic axial and rotational restraints on the critical temperature of columns. Huang and Tan [11] proposed a Rankine approach, which incorporates both the axial restraint and creep strain for the critical temperature prediction of an axially restrained steel column. Wang and Davies [12] carried out some tests to evaluate how bending moments in restrained columns would change and how these changes might affect the column failure temperatures.

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It can be seen from the above literature review that most of the works have been carried out using FEM, and fire protection damage has an obvious effect on the fire resistance of steel members. For a restrained steel column, the axial or rotational restraint has an influence on the critical temperature.

In this paper, an analytical model to predict the ultimate load bearing capacity of rigidly supported steel columns with partial damage in fire protection is presented. The difference between this paper and the previous FEM modeling is that a simple model is presented and the model can be employed to study the influence of fire protection missing either at the ends or at the central portion of the column. In addition, a numerical application to investigate the ultimate carrying capacity of the steel column and the variety of the axial forces that occur in the column when temperature is raised at two different degrees of axial restraint stiffness is performed.

2. Ultimate load bearing capacity of steel columns fixed at two ends

The fire protection sprayed on steel columns may be damaged, either at the ends or at the center portion of the steel column. If the damage at the two ends, it is assumed that the damage length of fire protection at the two ends of the column is the same. In this paper, it is further assumed that the temperature over both the portions of the column with fire protection and without fire protection due to damage is uniform.

Fig. 1 (a) shows the mechanical model of a steel column with fixed boundary conditions and damaged fire protection at its two ends. As we know, every column in the real building has some initial imperfection. The ultimate load bearing capacity for columns with initial imperfection is less than that of perfect columns. The initial flexure of the column may be expressed by

$$y_0 = \frac{1}{2} a_0 \left(1 - \cos \frac{2\pi}{l} x\right) \tag{1}$$

where l is the length of the column and a_0 is the initial flexure at the mid-span of the column.

If the lateral displacement of the column at the location without fire protection and with fire protection is represented by y_1 and y_2, respectively, according to the differential equation for equilibrium, the following equation can be obtained

$$\begin{cases} E_1 I (y_1 - y_0)'' + P y_1 - M = 0 & (0 \le x \le l_d) \\ E_2 I (y_2 - y_0)'' + P y_2 - M = 0 & (l_d \le x \le l/2) \end{cases} \tag{2}$$

where E_1 is the elastic modulus of steel at temperature T_1; E_2 is the elastic modulus of steel at temperature T_2; T_1 is the temperature in the portion of the column with damaged fire protection; T_2 is the temperature in the portion of the column with integrated fire protection; I is inertia moment of column; and l_d is the length of the damaged fire protection at one end of the column.

As the displacement and rotation at the two ends of the column are fixed and the rotation of the cross-section of the column is continuous through the entire length, the following boundary conditions can be adopted as

$$\begin{cases} y_1(0) = 0, y_1'(0) = 0 \\ y_1(l_d) = y_2(l_d), y_1'(l_d) = y_2'(l_d) \\ y_2'(l/2) = 0 \end{cases} \tag{3}$$

For convenience, the following parameters are used:

$$\mu = l_d/l, \varepsilon = a_0/l, P_{cr1} = \pi^2 E_{T1} I/l^2, P_{cr2} = \pi^2 E_{T2} I/l^2,$$

$$\alpha = \sqrt{P/P_{cr1}}, \beta = \sqrt{P/P_{cr2}} \tag{4}$$

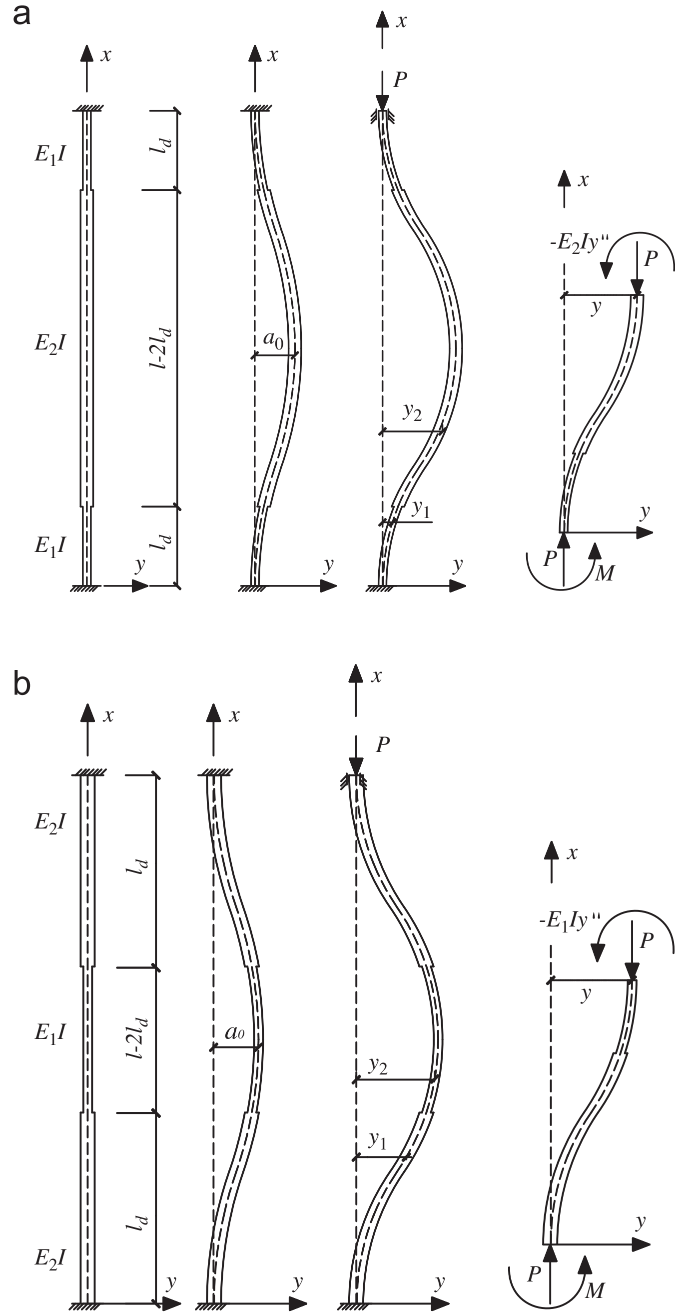

Fig. 1. Mechanical model of the steel column with fixed ends. (a) Fire protection to damage at the ends; (b) Fire protection to damage at the center.

where μ is the damage length ratio of fire protection of column; ε is the initial flexure ratio of column; P_{cr1}, P_{cr2}, α and β are intermediate variables and P is the axial force of column.

The general solution to Eq. (2) is given by

$$\begin{cases} y_1 = C_1 \sin\left(\sqrt{\frac{P}{E_1 I}} x\right) + C_2 \cos\left(\sqrt{\frac{P}{E_1 I}} x\right) + \frac{2 a_0 E_1 I \pi^2}{P l^2 - 4 E_1 I \pi^2} \cos \frac{2\pi}{l} x + \frac{M}{P} \\ y_2 = C_3 \sin\left(\sqrt{\frac{P}{E_2 I}} x\right) + C_4 \cos\left(\sqrt{\frac{P}{E_2 I}} x\right) + \frac{2 a_0 E_2 I \pi^2}{P l^2 - 4 E_2 I \pi^2} \cos \frac{2\pi}{l} x + \frac{M}{P} \end{cases} \tag{5}$$

where the parameters C_1, C_2, C_3, C_4, and M are determined by employing the boundary condition Eq. (3), and are given by

$$C_1 = 0 \tag{6}$$