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Storey stability of unbraced steel frames subjected to non-uniform elevated temperature distribution

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ABSTRACT

Current studies on stability of steel frames are primarily based on the assumption that steel columns are subjected to uniform elevated temperature. However, the temperature distribution of real fire in a building may be non-uniform due to thermal buoyancy effect. In this study, the elastic stability of unbraced steel frames subjected to a non-uniform elevated temperature distribution along the longitudinal direction of the column is investigated based on the concept of storey based buckling and a two zone fire model. First, to simulate a steel column exposed to non-uniform elevated temperature, an analytical model is proposed to examine the effects of axial loading, non-uniform elevated temperature distribution, and thermal boundary restraints on the lateral stiffness of steel columns in unbraced frames. The lateral stiffness equation of the column model is derived based on Euler–Bernoulli beam theory. Then, the procedure to evaluate the stability capacity of unbraced steel frames subjected to non-uniform elevated temperature distribution is concluded. Numerical examples are presented to demonstrate the evaluation procedure of the proposed method and investigate the frame stability subjected to different scenarios of frame members exposed to the non-uniform elevated temperature distribution. The validity of the proposed method is verified by the numerical analysis with the use of finite element analysis.

1. Introduction

The stability of steel columns and frames subjected to elevated temperature has been extensively studied since the 1970s [1–3,8–11]. Among these studies, investigations based on the assumption that steel frames or members are subjected to uniform elevated temperature have prevailed. On the other hand, the foregoing researches and the current design standard CSA S16-09 [4] are primarily focused on the stability of isolated columns or braced frames at elevated temperature. The stability of unbraced steel frames in fire with considering stiffness interactions between columns in the same storey is rarely investigated. Xu and Zhuang [5] analyzed the stability of unbraced steel frames exposed to fire based on the storey-buckling concept. The analysis was also based on the assumption that steel frames experience uniform elevated temperature. However, steel columns may experience non-uniform temperatures in compartment fires. In current research, the one-zone fire model, which is primarily used to represent the assumption of a uniform temperature in compartment fires, is only suitable for modeling post-flashover fires [6]. In a real building fire, however, hot air and smoke accumulate at the upper layer and beneath the ceiling, while the cooler air stays at the lower layer of the compartment. Therefore, a more accurate two-zone fire model was developed [7]. In the two-zone fire model, the compartment fire is separated into two fire zones: a hot upper zone and a cool lower zone. Each zone maintains a uniform temperature, and the temperature distribution that deteriorates a whole structural column along the longitudinal direction in a compartment fire is thus non-uniform. Therefore, the conclusion for stability of unbraced steel frames drawn based on the storey-buckling concept by Xu and Zhuang [5] may not be accurate when considering that the frame is subjected to non-uniform elevated temperature distribution during the pre-flashover stage of a compartment fire.

Few studies have been conducted on the behavior of steel structures subjected to non-uniform elevated temperature distribution. Culver [8] investigated the buckling loads of wide-flange steel columns subjected to non-uniform temperature distribution along the length of the columns, but the influence of end restraints was not considered. Becker [9] studied the effects of longitudinally non-uniform temperature distribution on fire protected steel structures, but the study was accomplished by numerical method and the longitudinal non-uniform temperature distribution was induced by the heat declined at floor levels. Tan and Yuan [10,11] developed an analytical method to study the elastic and inelastic

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buckling strength of a pin-ended steel column subjected to longitudinal non-uniform elevated temperature distribution. Nevertheless, the beam-to-column rotational restraints were not considered, and the studies were focused on the stability of a single column, neglecting the interactions between the columns in a frame.

This study investigates unbraced steel frames subjected to a two-zone fire. The term "non-uniform temperature distribution" in the following denotes two different temperatures along the longitudinal direction in a compartment fire. The lateral stiffness of a steel column experiencing non-uniform temperatures is first derived, and the procedure to evaluate the frame buckling strength, based on the storey-buckling concept, is then summarized. Numerical examples are presented to demonstrate the difference between the frame buckling strength at uniform and non-uniform elevated temperatures. To simplify the analysis, the assumption of uniform temperature along the cross section of the member was adopted. The rotational stiffness of beam-to-column connection is assumed to remain constant at elevated temperature and, as well, the thermal expansion of beams at elevated temperature is neglected.

2. Storey-based stability of unbraced steel frames in two-zone fire

In the two-zone fire model, structural columns experience non-uniform elevated temperature which results in material deterioration. Taking the frame shown in Fig. 1 as an example, the temperature of the hotter upper zone is T_u, while the temperature of the cooler lower zone is T_l. Correspondingly, the height of the upper layer is L_u, and the height of the lower layer is L_l. Obviously, the expansion of Column *B* will be constrained by the unheated Beam *E*. To better investigate the behavior of such columns subjected to non-uniform fire and restricted by their adjoining members, an analytical model shown in Fig. 2 is proposed, where R_u and R_l are the stiffness of the rotational restraints at the upper end and lower end of the column, respectively; and k is the stiffness associated with the axial restraint related to the unheated adjoining beams as derived by Xu and Zhuang [5].

2.1. Column internal axial force at the non-uniform elevated temperature

As shown in Fig. 2, the internal axial force of the column subjected to the non-uniform elevated temperature distribution must take into account the additional force induced by thermal expansion of different column segments. For the column model shown in this figure, ΔL denotes the shortening of spring k due to the thermal expansion of both segments of the column. P is the external applied load, and P_c is the internal axial force of the column. R_u and R_l are the beam-to-column rotational stiffness at the upper and lower ends, respectively. E_u and E_l, the elastic Young's Modulus of the upper segment at temperature T_u and the lower segment at temperature T_l, respectively, can be defined as

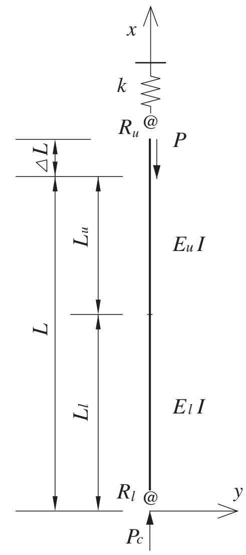

Fig. 2. Column with thermal restraints subjected to non-uniform elevated temperature distribution.

$$E_u = \lambda_u E_{20} \tag{1a}$$

$$E_l = \lambda_l E_{20} \tag{1b}$$

where λ_u and λ_l are the material degradation factors associated with temperature T_u and T_l, respectively; and E_{20} is the Young's Modulus at ambient temperature. In this study, the stress–strain relationship is adopted from ASTM [13], and the material degradation factor λ can thus be stated as

for $0\,^\circ\mathrm{C} < T \leqslant 600\,^\circ\mathrm{C}$.

$$\lambda = \frac{E_T}{E_{20}} = \left[1.0 + \frac{T}{2000\ln\left(\frac{T}{1100}\right)}\right] \tag{2a}$$

for $600\,^\circ\mathrm{C} < T < 1100\,^\circ\mathrm{C}$

$$\lambda = \frac{E_T}{E_{20}} = \frac{690 - 0.69T}{T - 53.5} \tag{2b}$$

where T is the elevated temperature. For the upper and lower segments, T is denoted as T_u and T_l, respectively. The strain and stress are defined as positive when the column expands and the column is in tension. The static equilibrium of the column can be stated as

$$P + k\Delta L = P_c \tag{3}$$

The spring shortening ΔL in Eq. (3) is equal to the whole column's elongation, which can be expressed in terms of the axial strain of the column as

$$\Delta L = (\varepsilon_{Tu} + \varepsilon_{eu})L_u + (\varepsilon_{Tl} + \varepsilon_{el})L_l \tag{4}$$

where ε is the total normal strain of the column. ε_{eu} and ε_{el} are the mechanical elastic strains for the upper and lower segments, while ε_{Tu} and ε_{Tl} are the thermal strain of the column for its upper and

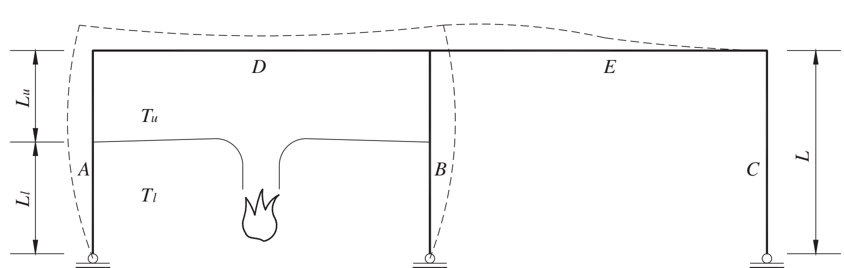

Fig. 1. Steel frame subject to compartment fire.