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Thermal-induced restraint forces in reinforced concrete columns subjected to eccentric loads

Truong-Thang Nguyen*, Kang Hai Tan

School of Civil and Environmental Engineering, Nanyang Technological University 50, Nanyang Avenue, N1.1-B3-01, 639798, Singapore

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ABSTRACT

Analytical and numerical analyses are conducted in this paper to investigate the additional axial forces induced in eccentrically-loaded columns that are restrained from thermal elongation in concrete framed structures when a fire occurs. A simplified analytical model to directly determine these so-called thermal-induced restraint forces is proposed based on the concepts of equivalent distributed temperature as well as eccentricity- and temperature-dependent reduction factor of axial stiffness. The model is validated by fire tests conducted at Nanyang Technological University on twelve restrained concrete column specimens subjected to uniaxial and biaxial bending. Relatively good agreement between the analytical and the experimental results of restraint force development is obtained. Hence, the proposed model can be used to explain the effects of axial restraint ratio, eccentricity, initial load level, concrete strength, as well as uniaxial and biaxial bending on the development of restraint forces. It is also shown that the analyses using material models which implicitly consider concrete transient strain overpredict the restraint forces induced in restrained RC columns under fire conditions.

1. Introduction

When a framed building is exposed to fire, additional axial force may be generated within a heated column if its free thermal elongation is constrained by surrounding structural members with differential thermal responses. This so-called thermal-induced restraint force may result in a significant increase in the total axial force [1–18], as well as the additional bending moments acting on the column and thus, associated with deteriorations of material strength and stiffness at elevated temperatures, may lead to a premature failure of the column. Therefore, a proper prediction of the development of restraint force is critical in the fire resistance analysis of compression members in framed buildings.

There have been a considerable number of published studies on axially-loaded and restrained steel and composite columns ([1–8]), and on restrained reinforced concrete (RC) columns [9–18] subjected to fire. Based on early fire tests conducted on two axially-loaded and fully-restrained RC columns [9], a simplified equation to evaluate the magnitudes of restraint forces was proposed [10]. However, the equation was only applicable for columns under pure compression. In the subsequent fire tests conducted on a fair number of small-scale RC columns [11,12], no eccentric load was used. A number of experimental studies on full-scale specimens [13,14] were conducted on axially-restrained RC columns under concentric loads and axial loads with either unixial or equal biaxial eccentricities, but no analytical model has been introduced. The differences between the case of a heated column acting as a single element or being part of a frame is discussed numerically [15]. Kodur et al. [16] indicated in the state-of-the-art review and research-need assessment of the fire performance of RC columns that there has been little published information on the behaviour of RC columns under realistic loading, restraint, and fire conditions. As a result, there is no prescriptive provision in current structural fire-resistant design codes [17,18] for restrained RC columns subjected to eccentric loads, even though most columns in framed buildings are subjected to combinations of an axial force and bending about one and two principal axes, so-called uniaxial and biaxial bending, respectively. Recently, the problem of columns subjected to the combination of thermal restraint and eccentric loads have been studied more detailed in both numerical and simplified approaches [19,20]. Recent fire tests conducted at Nanyang Technological University (NTU) by the authors [21,22] showed that axially-restrained RC columns subjected to eccentric loads had lower restraint forces compared to those predicted by numerical analyses that neglect concrete spalling and implicitly account for concrete transient strain. To the authors' best knowledge, there is a pressing need to investigate and to enhance the understanding of the combined effects of axial restraint and eccentric loads on the development of restraint forces within heated RC columns.

* Corresponding author. Tel.: +65 6790 4577; fax: +65 6791 0676.
E-mail address: NTThang@ntu.edu.sg (T.-T. Nguyen).

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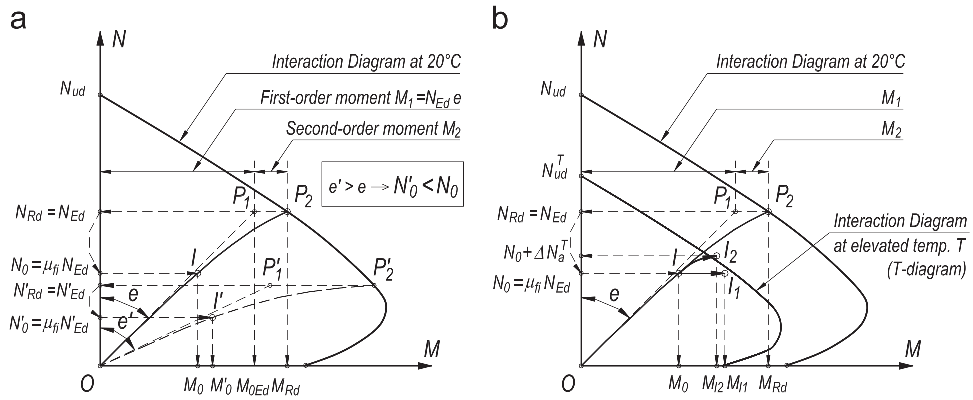

Fig. 1. Axial forces considered in fire resistance analysis of columns. (a) e-dependent initial applied load and (b) effect of restraint forces on failure.

This paper proposes a simplified analytical model to determine restraint forces taking into account the effects of restraint ratio, initial load level, eccentricity, uniaxial and biaxial bending, concrete spalling, and transient strain. The model is validated using twelve fire tests on axially-restrained and eccentrically-loaded RC columns conducted at NTU [21,22]. Reasonably good agreement between the experimental and the analytical results is obtained. The proposed analytical model is capable of predicting the trend observed from experiment, that is, the development of restraint force increases with an increase in restraint ratio and eccentricities but decreases when initial load level increases. On the other hand, it can also be analytically shown that the analyses implicitly considering transient strain over-predict the restraint force development.

2. Axial forces considered in analysis

Fig. 1(a) illustrates the cross-sectional M–N interaction diagram of an RC column designed at room temperature to sustain an axial load N_{Ed} at a first-order uniaxial eccentricity e that is represented by point P_1. Due to second-order effect the non-linear load path $N_{Ed}-M_{Ed}$ coincide with the M–N interaction diagram at point P_2 ($N_{Rd}=N_{Ed}$, $M_{Rd}=N_{Ed}e+M_2$). At the fire limit state, the column is only subjected to service condition with a lower load level, $N_0=\mu_{fi}N_{Ed}$, which is represented by an initial point I (N_0, M_0). The term μ_{fi} is referred to as a load reduction factor or initial load level. The figure also shows that if this column is designed for a higher first-order eccentricity, such that $e' > e$, its ambient axial resistance N'_{Rd} (point P_2'), as well as the corresponding initial applied load N'_0 (point I′) are respectively lower than N_{Rd} and N_0 associated with the smaller eccentricity e.

At a fire temperature T, due to the strength deteriorations of both concrete and reinforcing steel, the column M–N interaction diagram regresses to a smaller shape, so-called T-diagram (Fig. 1(b)). If there is no axial restraint, point I would move horizontally to point I_1 at the constant axial force N_0 and a bending moment M_{I1} greater than M_0. This movement is due to second-order effects arising from stiffness and strength degradations of materials as temperature elevates. The column is safe since point I_1 is still inside the T-diagram. However, when axial restraint exists, point I may move to point I_2 with an additional restraint force ΔN_a^T and an increased bending moment M_{I2}. If the column is defined to be failed in material mode when the M-N load path coincides with the M–N interaction diagram and if point I_2 is located on the T-diagram, the column would have failed although M_{I2} is smaller than M_{I1} (Fig. 1(b)). Hence, the thermal-induced restraint force ΔN_a^T may result in premature column failure. For biaxially-loaded columns with temperature-dependent interaction surfaces, the above-discussed movements take place in three-dimensional space and are too complicated to be presented in a figure and will be in clarified in Section 6.5.

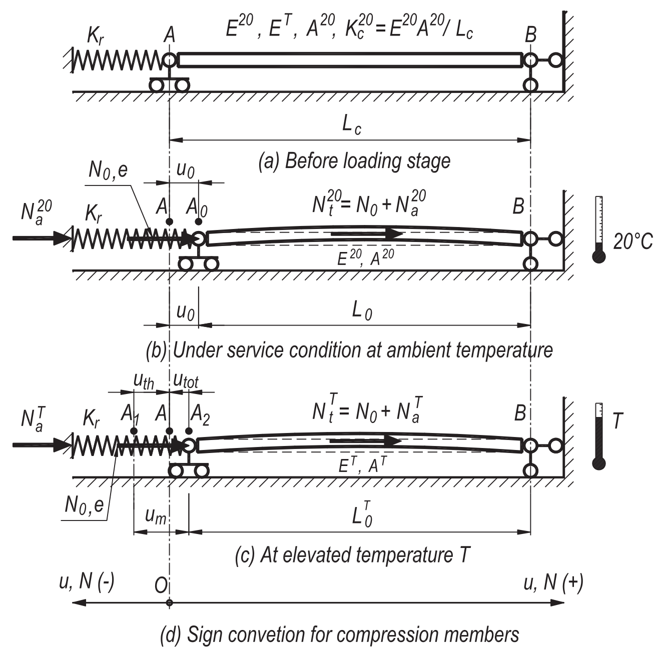

Fig. 2. Simplified model for analytical derivations.

3. Proposed analytical model

In order to directly determine the restraint forces induced in restrained columns subjected to eccentric loads, a simplified model is proposed on a pin-roller-and-pinned compression element of an idealised elastic material (Fig. 2(a)). As shown in Fig. 2(d), the positive sign convention for compression forces, compression axial deformation and displacement is employed in the analysis. At room temperature (T=20 °C), the element has an initial length L_c and an elastic axial stiffness $K_c^{20}=E^{20}A^{20}/L_c$, where E^{20} and A^{20} are the ambient material elastic modulus and gross cross-sectional area, respectively. Axial restraint is simulated by an idealised elastic spring stiffness K_r which represents the congregate axial restraints of surrounding members. As shown in Fig. 2(b), under an axial load N_0, which is at a first-order eccentricity e and determined based on μ_{fi} for fire limit state ($N_0=\mu_{fi}N_{Ed}$), the element contracts axially at the roller end by an amount of u_0 which corresponds to the spring expansion. As a