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Fire design of steel columns: Effects of thermal gradients

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ABSTRACT

The behavior and design of steel columns subjected to thermal gradients due to fire loading were evaluated numerically and experimentally. The numerical (FEM) modeling approach was verified using experimental data from large-scale tests. The FEM modeling approach was used to conduct parametric studies to evaluate the effects of different heating configurations on steel column strength, and failure behavior at elevated temperatures. The analyses were conducted by coupling transient heat transfer analysis with implicit dynamic stress analysis. Columns subjected to four sided heating configuration had uniform temperature distributions through the cross-section. The columns were subjected to non-uniform (partial) heating to produce thermal gradients through the cross-section. The analysis results indicated that the column strength and failure behavior depended on the column slenderness, axial loading, and heating configuration. Failure modes included flexural buckling about the weak axis, flexural buckling about the strong axis, and flexural-torsional buckling. The analysis results also indicated that columns subjected to uniform heating had significantly higher heat influx. In most cases, columns subjected to non-uniform heating failed at lower average temperatures than columns subjected to uniform heating. However, the columns subjected to uniform heating reached their failure temperatures faster than the columns subjected to non-uniform heating due to the higher heat influx. The exceptions were very slender columns subjected to axial loads greater than 50% of their ambient load capacity. The results from the parametric studies were used to develop design equations for wide flange steel columns subjected to non-uniform heating resulting in thermal gradients through the cross-section.

1. Introduction

Current design guidelines for steel columns in fire conditions are based on assumptions that may not be true for columns in a real building fire. Uniform temperature distribution is one of the most significant assumptions that can potentially lead to overestimation of column load capacity.

The American Institute of Steel Construction [AISC] guidelines [1] for designing steel columns at elevated temperatures were originally proposed by Takagi and Deierlein [2]. The AISC equation (A-4-2) calculates the strength limit state of steel columns at elevated temperatures and accounts for the inelastic flexural buckling mode of failure of wide-flange steel columns. The AISC equation is based on the steel yield stress (F_y^T) and elastic modulus (E^T) values at elevated temperatures similar to those in Eurocode-3 [3]. Agarwal and Varma [4] have proposed another set of design guidelines, wherein they recommended the use of the AISC [1] column design curves at ambient temperature along with a set of calibrated steel yield stress (F_y^T) and elastic modulus (E^T) values. Current column design equations in Eurocode-3 [3] were proposed by Talamona et al. [5]. All these design equations assume that the columns are heated uniformly. This assumption may not necessarily be true for real compartment fires such as perimeter columns, which are more likely to be heated from one side, producing thermal gradients in the column cross-section.

Columns can have non-uniform temperature distributions through their cross-sections and along their length. Temperature variations along the length are ignored in the design process for the following reasons:

(i) Post-flashover fires are assumed to cause sufficient turbulence and mixing of hot gases to maintain uniform temperature through the height of the compartment. A number of popular post-flashover fire models (e.g., Swedish [6], COMPF2 [7], OZONE [8], and Lie [9]) for predicting the compartment fire temperatures are based on the assumption of a single-zone model, wherein the gas temperature inside the compartment is assumed to be uniform. The parametric air Temperature–time (T–t) curve prescribed by the Eurocode-1 [10] is also based on a single-zone model.

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(ii) The geometric properties of both columns and fire protection are uniform along the length. This helps with uniform temperature distribution along the column length.
(iii) Assigning the temperatures of the hottest cross-section to the entire column length is considered a conservative assumption.

It may not always be safe to assume uniform temperature distribution across the column cross-section. Olawale [11], Garlock and Quiel [12], and Antonio et al. [13] have shown that a column designed using uniform temperature distribution across the cross-section may not be safe when only one side of the column is exposed to fire. They used numerical schemes to demonstrate that columns with thermal gradient across the column cross-section may fail when the average temperature of the column is lower than the failure temperature of columns heated uniformly.

Thermal gradient across a column cross-section has the following consequences: (1) the hotter side of the column expands more than the cooler side, making the column bow towards the hotter side. This is referred to as the bowing effect. When coupled with the axial compressive load acting on the column, it produces a secondary moment that may cause an increase in compression on the cooler side, and a reduction in compression on the hotter side of the column. (2) The column cross-section becomes structurally asymmetric because the mechanical properties of steel (e.g., yield stress and elastic modulus) are temperature dependent. Garlock and Quiel [14] have presented a detailed discussion on the structural asymmetry produced by the uneven heating of the column cross-section. They have shown that the effective centroid (location of the instantaneous neutral axis) shifts towards the cooler side of the cross-section and that this shift of the neutral axis coupled with the compressive axial load produces a bending moment causing an increase in compression on the hotter side and a reduction in compression on the cooler side of the cross-section, making the column bend towards the cooler side. The shift of the effective centroid does not depend on the length of the column. However, as the axial load applied on the column increases, the bending moment increases too. Garlock and Quiel [14] have also pointed out that the bowing effect causes an increase in compression on the cooler side, and the shift in the neutral axis causes an increase in compression on the hotter side, and the two effects are not additive.

Most of the research work (experimental and analytical) conducted on steel columns at elevated temperatures focuses on uniformly heated columns, e.g., Olesen [15], Vandamme and Janss [16], Aasen [17], Janss and Minne [18], and Franssen et al. [19]. A few efforts to develop design guidelines for a steel column with a thermal gradient are discussed here.

Garlock and Quiel [12] used a fiber-based approach to develop an axial force–moment (P–M) interaction curve for a wide-flange column cross-section exposed to uneven heating and compared the results with the case of uniform heating. The study concluded that: (1) the thermal gradient in a column can alter the plastic P–M interaction curve significantly and that (2) the assumption of uniform temperature distribution can give an unconservative estimate of the section capacity. Using the methodology and findings of this research, Quiel and Garlock [20] have also developed a numerical scheme for predicting the thermal and structural response of a perimeter column (potentially having thermal gradient) subjected to fire.

Dwaikat et al. [21] conducted fire tests on four steel columns subjected to thermal gradient. The tests were conducted in a furnace and uniform heating was applied from all sides. In order to induce thermal gradient in the column cross-section, fire protection was partially removed from surfaces of the specimens. The columns were fixed against rotation and translation at one end and partially restrained against rotation and translation at the other end. The setup was designed to imitate loading conditions similar to that of a column in a Moment Resisting Frame (MRF). It was observed that, due to the thermal gradient, the columns behaved like a beam-column. Load level, fire scenario, and the direction of the thermal gradient were found to have a significant influence on the fire response of such columns. Dwaikat and Kodur [22] used a combination of fiber-based analysis of the column cross-section and detailed FE analysis to develop an equation for calculating the capacity of beam-columns with thermal gradient effects. The equation proposed by Dwaikat and Kodur [22] is a modified version of the current AISC design equations for beam-columns at ambient temperature. Further, the capacity of a W14 × 176 column with a thermal gradient along the web calculated by detailed FE analysis was compared with the capacity calculated using the proposed equation. It was found that the proposed equation offers a better estimate of the capacity than the beam-column design equations meant for uniformly heated columns. This study focused on the inelastic flexural buckling mode of failure. It was based on the analysis of columns with ends restrained against rotation. These equations need to be calibrated and potentially modified for simply supported members and for the possibility of flexural torsional buckling mode. A more detailed validation study should be conducted to ensure that the proposed equation works for columns with various sizes, load levels, levels of heating, and magnitudes and both directions of the thermal gradient.

Choe [23] has conducted full scale column tests at elevated temperatures with thermal gradient along the flange width. The column flanges were heated using a number of ceramic fiber radiation heaters. Individual heaters were controlled independently and were assigned different target temperature–time (T–t) histories to induce the desired level of heat flux at different locations on the column surface. In comparison to a furnace test, this setup allows better control over temperature distribution in a column cross-section. Table 1 summarizes the test matrix for the three column specimens SP1, SP2 and SP3. In the table, L/r_y is slenderness ratio in the weak axis, P^T_u is an imposed axial load, P_u^{20} is an axial load capacity of a column at ambient temperature, and $T_{eq,\ uniform}$ is the failure temperature of an equivalent column heated uniformly. The values of $T_{eq,\ uniform}$ were obtained from another set of tests conducted on similar columns heated uniformly and reported by Choe et al. [24]. The findings of these tests are used as benchmarks to validate the numerical analysis scheme developed and the column design equation proposed in this paper.

The objective of this paper is to explore the possible modes of failure of a steel column exposed to uneven heating and to identify and quantify various factors that control the load capacity, behavior, and failure mode of such columns. A design equation similar to the one proposed by Dwaikat and Kodur [22] has been proposed for a pin-ended column that accounts for pure flexural as well as flexural-torsional buckling modes of column failure. This equation is validated for columns of different sizes and slenderness values with the two different directions of thermal gradient and various levels of heating and loading.

Table 1
Test matrix of the column tests with thermal gradient (Choe [23]).

Specimen	L/r_y	Direction of thermal gradient	SFRM	P^T_u (kN)	P^T_u/P^{20}_u	Failure temperature (°C)			
						T_{max}	T_{min}	T_{avg}	$T_{eq,\ uniform}$
SP1-W8 × 35	69	Along flanges	Full	800	0.4	570	480	550	600
SP2-W14 × 53	71	Along flanges	Full	1450	0.67	470	390	430	500
SP3-W14 × 53	71	Along flanges	Partial	1450	0.67	430	270	340	500