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Thermal bowing on steel columns embedded on walls under fire conditions

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ABSTRACT

The contact of steel columns with building walls is responsible for huge thermal gradients within its cross-section during fire. Current regulatory codes for fire design of steel members provide a formulation to assess the load-bearing capacity of these members assuming uniform temperature through the cross-section; however, this is not what happens in the major part of the cases in real structures where the columns are embedded on walls. The walls on one hand will provide a temperature reduction on the columns, which is somehow favourable in terms of its fire resistance, on the other hand the differential heating on the columns cross-section may lead to unfavourable stresses (bending moments) responsible for instability (thermal bowing). Considering that the structural behaviour of columns is strongly dependent of the second order effects this is an important phenomenon which may lead to a significant reduction on its fire resistance. This paper presents the results of a numerical study to assess the influence of the differential heating on the fire design of steel columns. New interaction axial force–bending moment diagrams for non-uniformly heated H steel columns are proposed.

1. Introduction

The contact of steel columns with the building walls is responsible for huge thermal gradients within its cross-section developed during fire [1–3]. Current regulatory codes for fire design of steel members provide a formulation to assess the load-bearing capacity of these members assuming uniform temperature through the cross-section however this is not what happens in the major part of the cases in real structures where the columns are embedded on walls. The thermal gradients in case of fire will provoke a different behaviour from the one observed in isolated steel columns. Different temperatures in the flanges of the steel profile will lead to different thermal strains in the heated and unheated sides of the column that originates bending moments and a bow deflected shape towards the heated side. The mechanical properties of the steel reduce quickly when the temperature rises above 400 °C. The heated part of the steel cross-section behaves as a non-uniform or hybrid section, and from a certain moment during the fire, the effective centroid of the section moves towards the cold side, leading to arise of a bending moment which is opposite to the bending moment originated by the thermal stresses. The restraint to rotation may also play an important role in this inversion of bending moments in the column subjected to fire. The buckling of steel columns subjected to thermal gradients in fire is studied for around thirty years however the major part of the studies were developed only in the last decade.

Culver was maybe the first one to study the behaviour of steel columns under thermal gradients. In 1972, he presented a numerical study about the influence of the boundary conditions and distribution of temperatures along the length column on its behaviour in fire [4]. The combination of two types of boundary conditions, pinned and fixed ends, was studied. The studies were undertaken for wide flange I-sections of steel profiles. The longitudinal elongation of the column due to heating was considered free and temperature distribution over the cross-section assumed constant. Various distributions of temperature along the length of the column were considered. The numerical simulations held the column to be perfectly straight until the critical load was reached. The results of this work showed that the form of the temperature variation along the length of the member had an effect on the buckling strength. The pin-ended columns with the maximum temperature at mid-height showed the largest drop in buckling strength. There was greater reduction in the strength for slender columns. For the other boundary conditions studied, pinned in one of the ends and fixed in the other, the location of the maximum temperature had an influence on buckling strength. The maximum temperature near the strongest boundary resulted in the largest reduction in strength.

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Nomenclature

A	area of the steel cross-section
T	temperature
L	length of a column
L_0	buckling length of a column
I	moment of inertia
M	bending moment
N	axial force
P	load
P_0	initial applied load
b	width of the steel cross-section
e	distance
t	time
h	height of a column
d	displacement
λ	slenderness
f_y	yield strength of steel
h_w	height of the web
$k_{y,\theta}$, K_3	reduction factors of the effective yield strength for different temperatures
M_{Pe}	moment about the geometric centroid
M_T	moment of thermal origin
M_{pl}	plastic bending moment
$M_{N,Rd}$	design value of the plastic moment
$M_{pl,Rd}$	design value of the plastic bending moment
N_{Ed}	design value of the axial force
$N_{pl,Rd}$	design value of the plastic resistance
N_{pl}	plastic load
P_R	resultant of the axial stresses
t_f	thickness of the flange
th_w	thermocouple of the walls
ε_{nom}	nominal strains

In 1973, Ossenbruggen et al. [5] presented an analytical study on the behaviour of axially loaded steel columns subjected to thermal gradients across the cross-section of the member. The studies were carried out for two cases of loading and heating. In the first case, the column was loaded first and heated afterwards. The temperature distribution that would initiate failure was determined. In the second case, the previously loaded column was subjected to a temperature distribution less than that required to produce failure. The axial load was then increased until failure of the column occurred, thus determining the reserve strength of the heated column. The study was conducted on rolled steel I-sections. The influence on the cross-section of residual stress, thermal stress, material properties at high temperatures and thermal gradients were analysed. The results showed that the buckling strength of a column with a linear temperature distribution in the cross-section is lower than it is in the case where temperature distribution is uniform, even though the mean temperature throughout the length is the same. It was also concluded that the higher the thermal gradients in the cross-section the lower the column strength. This was explained by the higher thermal gradients that produce additional deflections and second order moments in the column.

In 1988, Cooke and Cooke and Morgan [6,7] published papers on the thermal bowing of steel elements in fire and how it affects building design. They presented both experimental and theoretical data, and suggests how the data can be used in the design of buildings to reduce the detrimental effect of thermal bowing. Concerning the thermal bowing of steel structures, it was stated that pin ended I-section steel columns first bow towards the heat source, straighten out and fail by bowing in the reverse direction. The influence of different parameters such as the length/thickness ratio of walls, the load level, the concrete type and the fire curve, was studied. The main recommendations drawn from the work carried out were that the following design factors that could reduce the thermal bowing effects: (a) choosing a material with a low coefficient of thermal expansion, (b) reducing the temperature difference and increasing the distance between exposed and unexposed surfaces, (c) transforming a member from a cantilever to a simply supported member wherever possible as the mid-span deflection is a quarter of the deflection of a member with a free end, and (d) providing edge support.

In 2000, Rotter and Usmani [8] and in 2001, Usmani et al. [9] presented studies on the structural behaviour of steel members under thermal effects. It was pointed out by the authors that framed structures of the ones tested at Cardington posse enormous reserves of strength through adopting large displacement configurations, and that thermally induced forces and displacements, not material degradation, governs the response in fire. These studies were based upon the analysis of the response of single structural elements under a combination of thermal actions and end restraints representing the surrounding structure. The papers describe the most fundamental relationship that governs the behaviour of structures when subjected to thermal effects. The most important factor that determines a real structure response to heating is the manner in which it responds to the unavoidable thermal strains induced on its members through heating. If the structure has insufficient end translational restraint to thermal elongation, the considerable strains are taken up in expansive displacements, producing a displacement-dominated response. Thermal gradients induce curvature, leads to bowing of a member whose ends are free to rotate, again producing large displacements (deflections). Curvature strains induced by the thermal gradient in members whose ends are rotationally restrained can lead to large hogging bending moments throughout the length of the member without deflection. A detailed analysis of a beam axially and rotationally restrained with end restraints perfectly rigid as well as with finite restraints as the ones offered by real structures to the structural elements, has been made. Thermal bowing was described to occur on structural elements exposed to fire when one side (heated side) expands more than other side (cool side). The key conclusion to be drawn from the discussion is that thermal strains are manifested as displacements if they are unrestrained or as stresses if they are restrained through counteracting mechanical strains generated by the restraining forces. The fundamental principles presented in these studies provided means of estimating forces and displacements in real structures under thermal effects.

In 2006, Garlock and Quiel [10] presented a study on the combined axial load and moment capacity (N–M capacity) of fire-exposed beam-columns with thermal gradients in which they have compared the load-bearing capacity of members with temperature gradients to those with uniform temperature. It was considered for wide-flange steel beam-columns the effects of the plate thickness, section depth, and direction of bending (i.e. strong *vs.* weak axis) on the N–M capacity envelope. The results showed that members that experience uneven heating, such as the perimeter columns of a steel framed building or beams carrying a floor slab, will develop a thermal gradient through their depth that may have a significant effect on its load-bearing capacity. A temperature distribution considered uniform through the section may lead to overestimation of the load-bearing capacity of the element. If the temperatures are high enough to reduce the yield stress, the