Fire Safety Journal 67 (2014) 82–95

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Mechanical response of a partially restrained column exposed to localised fires

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ARTICLE INFO

Article history:
Received 25 November 2013
Received in revised form
22 April 2014
Accepted 11 May 2014
Available online 4 June 2014

Keywords:
Analytical method
Partially restrained column
Localised fires
Non-uniform heating of column

ABSTRACT

Recent trends in structural fire engineering research have focussed on the response of buildings with large open plan spaces to so-called travelling fires. These fires travel horizontally across the floor plate of a building and result in time and spatially varying thermal exposure and response of the structure to the fire. What has received little attention, however, is the effect that non-uniform thermal exposure has on columns. Recent tests conducted at SP demonstrated the effect of a small non-uniformity of thermal exposure, resulting in a thermal gradient of around 1 °C/mm, on a column exposed to a pool fire. The curvature resulting from a non-uniform thermal exposure where the column is pinned, or in cases where the column is partially restrained, will result in an eccentricity in the column's loading and large second order effects.

This paper describes the effect of thermal exposure varying in both the horizontal and vertical axes to columns by means of including this thermal boundary in a solution of classical Euler beam theory. The resulting solution allows for a variation in the stiffness of the rotational restraint at both ends of the column and a non-uniform temperature exposure through the column's section and along its height. The resulting equations help to understand better the impact of the assumptions of 'lumped capacitance' on steel columns, suggesting a challenge to this assumption in some instances, as well as to enhance understanding of the impact of non-uniform fires on steel columns.

1. Introduction

Loss of strength and stiffness in steel as a result of high temperatures means that exposure of steel columns to fires may reduce their load bearing capacity in fire. This may lead to potential instability in a structure where appropriate alternate load paths or mechanisms are not available. Design procedures for columns in fire, such as those described in Eurocode 3 [1], are typically based on the assumption that the temperature distribution in columns is uniform. The objective of design is therefore to prevent or limit the effects of increased temperature such that the column is able to maintain its strength and stiffness for a specified period of time to ensure the safe evacuation of all building occupants as well as stability of the structure for a period following evacuation. Alternative methods for structural fire engineering now focus on the optimisation or removal of passive protection, allowing components to heat up so long as the structure can be shown through calculation or otherwise to remain stable for a given period of time.

Past research into the behaviour of steel columns in fire has focused on evaluating the response of columns heated while considering the interaction with the surrounding structure. For example, some authors have studied the response of steel columns with different restraint conditions experimentally. In Ref. [2], the authors report on a series of tests which were carried out to evaluate the response of steel columns with axial restraint. They state that an increase in axial restraint stiffness is normally coincident with an increase in rotational restraint stiffness. The authors conclude that the negative effects of increasing axial restraint stiffness are offset by the positive effects of increasing the rotational restraint stiffness. Other research has been carried out to evaluate the effect of rotational restraint on steel columns in fire [3], where a number of medium scale tests were performed on partially restrained steel columns subject to fire. Using varying levels of restraint it was found that increasing the restraint increased the failure temperature without having a considerable effect on the restraint forces.

Other research has focussed on developing analytical solutions to describe the mechanical response of heated columns in fire considering the thermal and mechanical boundary conditions. In Ref. [4], the authors study the effect of axial restraint on '+' shaped steel columns in fire. Using a specially formulated finite element code, the authors apply uniform temperatures. They

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http://dx.doi.org/10.1016/j.firesaf.2014.05.013
0379-7112/

Nomenclature

A	area
c_p	heat capacity
E	modulus of elasticity
E_{ref}	reference modulus of elasticity
$\overline{F}$, F_i	force in section and slice, respectively
f	slope of the thermal gradient with height
f_r	slope of the variation (with height) in residual curvature under partial restraint
f_P	slope of the variation (with height) in residual curvature, under partial restraint after application of axial load
I_{tot}	total second moment of area of the sections
I_{zz}	second moment of area about the z axis
k	$\sqrt{P/EI}$
k_{RA}, k_{RB}	rotational spring stiffness at connection a and b, respectively
L	length of column
$\overline{M}$	resultant moment in column section
$M^r_{P(a)}$, $M^r_{P(b)}$	restraining moment from the partial restraint to the applied load P at a and b, respectively
$M^r_{th(a)}$, $M^r_{th(b)}$	restraining moment from the partial restraint to thermal expansion at a and b, respectively
$M^{tot}_{P(a)}$	total moment at a after application of axial load, P
m_i	the modular ratio of slice i
P	axial load on column
r	radial distance to the extreme fibre
T	temperature (varying along the column and through the section)
ΔT	equivalent temperature increase of a section
T'_x	equivalent thermal gradient across a section
T'_{xa}, T'_{xb}	$T'_x(y=0)$ and $T'_x(L)$, equivalent thermal gradient at lower and upper end of the column
v_{th}	thermal deflection
v_p	deflection as a result of applied load
v^r_{th}	deflection of a partially restrained column under thermal effects only
$\overline{z}$	arbitrary reference position
z_i	distance in section to neutral axis at slice i from the arbitrary reference position
α	coefficient of thermal expansion
ε_T	thermal strain
$\varepsilon_{\varnothing}$	curvature strain
λ	thermal conductivity
ρ	density
σ_{max}	stress in the extreme fibre
σ_Y	yield stress

conclude in their study that axial restraint to the column can significantly increase the compressive load in a heated column and that rotational restraint appears to generally increase the fire resistance time of a column. This is in line with the findings described above and in Ref. [2].

Quiel and Garlock have presented a closed form solution for determining the demand on both a beam and a column in an assembly as part of a perimeter framing system of a structure [4]. Dwaikat and Kodur have also presented a simplified version of this methodology [5]. The method accounts for a thermal gradient through the beam section, resulting in a displacement to the *P–M* interaction diagram. The solution includes consideration of both temperature dependent material properties as well as the interaction between the two members, including push-out forces acting on a column caused by expansion of the beam. In Ref. [5], the authors also demonstrate that a thermal gradient through the weak axis has little effect on the *P–M* diagram, suggesting that a thermal gradient in this axis may be neglected.

All of this work assumes uniform temperature along a columns height throughout the analysis. However, as has been discussed elsewhere [6,7], fires are rarely uniform and are known to travel around a compartment. Alternatively, localised fires may lead to non-uniform temperature distributions within a compartment and throughout an element of structure. Non-uniform heating along a column's height as well as the impact of localised fires on steel beams has been considered elsewhere [8].

Tan and Yuan have studied the response of pin-ended steel columns exposed to a two zone fire, with the upper portion of the column heated to a higher extent than the lower part of the column, [9]. However they assume lumped capacitance (or uniform heating) in the two areas of the column. Elsewhere, researchers have considered non-uniform thermal exposure as a result of removal of passive fire protection [10] and derive an expression for the behaviour of a steel column when exposed to fire and with portions of a protected covering removed. The model accounts for partial axial restraint and is shown to have good performance when compared with a finite element model.

Usmani et al. [11] describes fundamental behaviour of members subject to various restraints by providing analytical solutions to e.g. deflections and stresses of beams subject to different thermal loading, including a thermal gradient across a beam. Tsalikis et al. studied the effect of a thermal gradient on the response of a pinned steel column [12]. Using a thermal gradient which varies through the section, the authors included thermal bowing in a simple application of beam theory to an unrestrained column.

This paper presents an overview of an experiment which is published elsewhere but which indicates the presence and magnitude of the likely thermal gradients through a steel section exposed to fire. We then review the means of calculating the thermal gradient and average temperature increase based on a reference value of the stiffness. This allows us to account for a temperature gradient through the column's cross section which also varies along the column's length. This type of thermal exposure is demonstrated to occur as a result of a localised fire around a column's base, and it is expected that the temperature gradients would be worse in the event of a fire located adjacent to the column as opposed to directly underneath the column as in the experiment which is discussed.

This is achieved through analysis of the response of a column of length L under a load, P, with a thermal gradient which varies along the height of the column. Two separate cases are studied, one where the column is simply supported, Fig. 1a, and one where the column is partially restrained, Fig. 1b, with ends restrained by springs of rotational stiffness k_{RA} and k_{RB}.

An extension of Euler beam theory to evaluate the response of the steel column which is exposed to a localised fire is presented. The solution accounts for partial restraint of the column's ends, and allows for rotational restraints of different stiffness to be prescribed to the ends of the column.

2. Non-uniform temperature exposure

In order to facilitate the discussion of the temperature exposure of unprotected steel columns subjected to localised fires, reference