On the buckling of axially restrained steel columns in fire

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A B S T R A C T

This paper describes the behaviour of restrained steel columns in fire. It follows the introduction of extra load into the column through the axial restraint of the surrounding cooler structure and the consequential buckling. Key to this understanding is the post-failure behaviour and re-stabilisation of the column, which is discussed with reference to a finite element model and an analytical model. Through bi-directional control of the temperature, the finite element model allows the snap-back behaviour to be modelled in detail and the effects of varying slenderness and load ratio are investigated. The analytical model employs structural mechanics to describe the behaviour of a heated strut, and is capable of explaining both elastic and fully plastic post-buckling behaviour.

Through this detailed explanation of what happens when a heated column buckles, the consequences for steel-framed building design are discussed. In particular, the need to provide robustness is highlighted, in order to ensure that alternative load paths are available once a column has buckled and re-stabilised. Without this robustness, the dynamic shedding of load onto surrounding structures may well spread failure from a fire’s origin and lead to progressive collapse.

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1. Introduction

1.1. Context

As the full-scale fire tests at Cardington have shown [1], whilst the majority of beams in a steel-framed building can be designed to function without the need for fire protection, columns are so critical to the load carrying capacity of a building that they must remain protected. A failure of a column on one floor can have a great effect on the floors above, meaning fire compartments can be breached and there is a danger of disproportionate collapse.

It is also the case that all columns in building frames are subject to axial restraint, since their purpose is to support structure above and this structure will have a vertical stiffness. It is therefore hugely important that the behaviour of columns in fire is understood, and in particular, the role that axial restraint plays in this behaviour.

A number of researchers have looked at this role, from both an experimental and analytical point of view. For example, Ali et al. [2], Rodrigues et al. [3] and Tan et al. [4] have all performed physical experiments on axially restrained columns at elevated temperatures. Shepherd et al. [5], Franssen [6] and Huang and Tan [7] have simulated such tests using finite element analysis techniques and extended these simulations to further investigate the role of axial restraint.

In this paper, the theoretical explanation behind the behaviour of steel columns in fire is presented, alongside the results of finite element analyses in order to illustrate particular characteristics of this explanation. Specifically, the differences in behaviour of columns’ pre- and post-buckling are contrasted and the details of snap-back buckling are examined.

1.2. Modelling

The behaviour of columns outlined in this paper is demonstrated through finite element analysis using a simplified model of an axially restrained column (see Fig. 1). All test cases model a $203 \times 203 \times 52UC$ pin-ended column of Grade 43 steel and length 5.16 m to give a minor-axis slenderness of 100. The column was divided into eight finite elements along its length and given an initial geometric imperfection and load ratio of 0.6 according to EC3 design rules. The finite element analysis was performed using the Vulcan program (http://www.vulcan-solutions.com/, accessed Feb 2010), which incorporates geometric nonlinearities and uses EC3 Part 1–2 material property variation to define how the elastic modulus and yield strength deteriorate with temperature.

Axial restraint was provided by an axial spring element at the same end of the column as the applied load. This elastic restraint was quantified by the use of the Relative Restraint Ratio, which