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Fire resistance of partially encased steel columns with restrained thermal elongation

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ABSTRACT

The behaviour of composite columns made of partially encased steel sections subjected to fire has been studied numerically by several researchers. Experimental studies are scarce and there are still many phenomena to study. The influence of the axial and rotational restraint on the behaviour of these types of columns subjected to fire is still under research. This paper presents the results of a series of fire resistance tests on these types of columns with restrained thermal elongation. A new experimental set-up, specially conceived for fire resistance tests on building columns, was used for the tests. The experimental set-up was conceived so that the axial and rotational restraint of the columns would be similar to the conditions in a real building. The parameters studied were the load level, the axial and rotational restraint ratios and the slenderness of the column. The main conclusion of this work is that for low load levels the stiffness of the surrounding structure has a major influence on the behaviour of the column subjected to fire. Increasing the stiffness of the surrounding structure led to reductions in the critical times. The same behaviour was not observed for the high load levels.

1. Introduction

Steel elements, when unprotected, they behave poorly under fire conditions. The deterioration of the mechanical properties of the steel, and its high thermal conductivity lead to very low critical temperatures, and poor fire resistance. Fire protection materials can be used to improve the fire resistance of steel elements, but they may entail problems such as longer construction times, higher costs, increasing the structural elements' cross-section and aesthetic issues. Combining steel with other materials, as in composite structures, can be a solution.

Composite steel and concrete structures are very popular nowadays because concrete can be used both as a fire protection and as a resistant material. Concrete can be used in partially or totally encased steel sections or to fill hollow steel sections. In the case of fire the concrete protects the steel part of the cross-section from excessive heating. The steel, on the other hand, reduces concrete spalling and cracking since the concrete is partially or totally encased in the element's cross-section.

The behaviour of composite columns made of partially encased steel sections subjected to fire has been numerically investigated by several authors, especially in this decade, but even so only a few experimental studies have been published on these types of columns with restrained thermal elongation. The major part of the experimental studies published until now is on hollow steel columns.

In 1964 Malhotra and Stevens presented the results of fourteen fire resistance tests on totally encased steel stanchions with free thermal elongation [1]. These tests were complemented with ten structural tests on stanchions at room temperature to determine their ultimate strength. The variables analyzed in the high temperature tests were the thickness of the encasement, the type of aggregate in the concrete, the effect of limited heating and the load eccentricity. Three types of concrete were used on the stanchions, one of ordinary concrete made with gravel and two types of lightweight concrete made with expanded clay and foamed slag. Several stanchions were heated for less time than their ultimate fire resistance and their residual strength determined. The results showed that the concrete cover has a significant effect on fire resistance, and the lightweight concrete leads to higher fire resistance of the elements than the ordinary gravel concrete. It was also found that the load level influences the fire resistance of the stanchions; those tested with higher load levels exhibited lower fire resistance. Also, stanchions tested with eccentric loading had higher fire resistance than those tested with centered loading, due to the fact that the working loads applied to the first ones, according to BS 449, were smaller. Finally, the stanchions tested for limited heating showed that the reduction of their residual strength is approximately linear with longer fire exposure.

In 1990 Lie and Chabot tested five concrete-filled circular hollow columns and proposed a mathematical model to predict

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Notation

$\bar{\lambda}_z$ Relative slenderness of the column related to the weak axis;
μ_o Load level of the column;
P Force;
P_0 Initial applied load or serviceability load of the column;
α_A Non-dimensional axial restraint ratio of the column;
β_R Non-dimensional rotational restraint ratio of the column;
$K_{A,S}$ Axial stiffness of the surrounding structure;
$K_{A,C}$ Axial stiffness of the column;
$K_{R,S}$ Rotational stiffness of the surrounding structure;
$K_{R,C}$ Rotational stiffness of the column;
A_a Cross-sectional area of the structural steel;
A_c Cross-sectional area of the concrete;
A_s Cross-sectional area of the steel reinforcement;
L_c Length of the column;
$l_{c,z}$ Buckling length of the column for the relevant bending axis;
N_{Rd} Design value of the buckling load of the columns at room temperature;
$N_{pl,Rk}$ Characteristic value of the plastic resistance of the composite section to compressive normal force
$N_{cr,z}$ Critical force for the relevant buckling mode;
$(EI)_{\text{eff}}$ Effective flexural stiffness of the column;
$(EA)_{\text{eff}}$ Effective axial stiffness of the column;
$I_{a,z}$ Moment of inertia of the structural steel section for the relevant bending axis;
$I_{c,z}$ Moment of inertia of the un-cracked concrete section for the relevant bending axis;
$I_{s,z}$ Moment of inertia of the steel reinforcement section for the relevant bending axis;
E_a Modulus of elasticity of the structural steel at room temperature;
E_c Effective modulus of elasticity of the concrete at room temperature;
E_{cm} Secant modulus of elasticity of the concrete at room temperature;
E_s Modulus of elasticity of the steel reinforcement at room temperature;
f_{ayk} Characteristic value of the yield strength of the structural steel at room temperature;
f_{ck} Characteristic value of the compressive strength of the concrete at room temperature;
f_{syk} Characteristic value of the yield strength of the steel reinforcement at room temperature.

the temperature distribution within the cross-section and the structural response to fire [2]. The heat transfer analysis was based on a division of the circular section into annular elements while the gas temperature around the section was considered uniform. The effect of moisture in the concrete was taken into account by assuming that when the temperature of an element within the cross-section reaches 100 °C or more, all the heating of that element drives out moisture until it is dry. This mathematical model was later adapted for concrete-filled rectangular hollow columns and fiber-reinforced concrete-filled circular hollow columns.

In 1996 Lie and Kodur published a numerical study on the behaviour of hollow columns filled with bar-reinforced concrete whose results were compared with those from experimental tests [3]. They investigated the influence of several parameters on the behaviour of the columns subjected to fire, such as the column section dimensions, the load level, the effective length of the column, the percentage of steel bar reinforcement, the concrete strength, the axis distance of the steel reinforcement bars to the inner wall of the steel profile and the type of aggregate used in the concrete. They concluded that the main parameters influencing the fire resistance are the diameter or width of the column, its effective length, the load level and the concrete strength. This study proposed expressions for the calculation of the fire resistance of circular and square hollow steel sections filled with bar- or fiber-reinforced concrete.

The same authors presented another study in 1996 on the behaviour of fiber-reinforced concrete-filled hollow columns. The benefits of this type of concrete on the fire resistance of the columns were compared with those of the plain and bar-reinforced concrete [4].

In 2002 Han et al. carried out six compressive strength tests on protected and unprotected concrete-filled rectangular hollow columns, after exposure to the ISO 834 fire curve [5]. The unprotected columns were heated in a fire resistance furnace for 90 min while the fire protected ones were heated for 180 min. After cooling down the columns were compressed with centered or eccentric loading in order to determine their residual buckling strength. The experimental results were compared with those calculated using various existing codes. The authors proposed a mechanical model for the determination of the residual strength of columns of this type after exposure to the ISO 834 fire curve. The model is based on the determination of a residual strength index that is the ratio between the residual strength corresponding to the fire duration time of the columns and the ultimate strength of the columns at room temperature. The model takes into account changes in the materials' mechanical properties with the temperature, the fire duration, the cross-sectional dimensions, the steel ratio, the depth-to-width ratio, the slenderness ratio and the load eccentricity ratio. It was found that the loss of strength of the columns without fire protection is greater than that of the fire protected ones. The slenderness ratio, cross-sectional dimensions and fire duration have a significant influence, while the steel ratio, the depth-to-width ratio, the load eccentricity ratio and the strength of the steel and the concrete have a moderate influence on the residual strength index.

In 2003 Wang and Davies published the results of an experimental study on the fire performance of non-sway loaded concrete-filled steel hollow column assemblies using extended end plate connections [6]. The objective of the study was to investigate the effects of the rotational restraint on the bending moments and effective lengths of the columns. Rectangular steel columns filled with concrete and connected to a pair of steel beams at one end by means of extended end plate connections were tested under fire conditions. The columns were subjected to different axial load levels with either equal or unequal loads in the connected beams. The columns with thinner steel walls suffered local buckling. The same was not observed in those with thicker walls, leading to the conclusion that their effective length can be determined according to the design recommendations of EN1994-1-2 [7]. In this case the effective length of the column can be taken as 0.7 times its height.

Following on from the previous study, Han et al., published another study in 2003 on the behaviour of a concrete-filled steel square hollow section (SHS) and rectangular hollow section (RHS) columns subjected to fire [8]. The columns were tested with and without fire protection and subjected to axial and eccentric loads. The influence of several parameters on the residual strength index was studied: fire duration, sectional dimensions, slenderness ratio, load eccentricity ratio and strength of the steel and concrete. The main conclusions were that the SHS and RHS columns behaved in a relatively ductile manner in fire due to the infill of concrete and