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Behaviour of composite columns made of totally encased steel sections in fire

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ABSTRACT

Composite structures are nowadays used, principally in high-rise buildings, due to its high load-bearing capacity and seismic and fire resistance. There are already several research works on the fire behaviour of composite steel and concrete columns with restrained thermal elongation, mainly of numerical nature, but a few were carried out on composite columns made of totally encased steel sections. This paper presents the results of an experimental research carried out in this last type of columns subjected to fire. Several parameters that might have influence on its behaviour were tested, such as the initial applied load level, the stiffness of the surrounding structure (*i.e.* axial and rotational restraining to thermal elongation) and the dimensions of the cross-section that resulted in different slenderness values of the columns tested. The tabulated data of EN 1994-1-2 (2005), for these type of columns, showed to be very conservative and on the safe side, when compared with those resulted from the experimental tests of the present investigation, because the ones of this code may have an empiric base and resulted from columns tested without thermal restraining. The load level and concrete cover showed to have a big influence on the critical time of the columns. Increasing the first reduced while increasing the second increased the critical time of the tested columns.

1. Introduction

Composite steel and concrete construction is increasingly used due to the enormous benefits that it brings in terms of load-bearing capacity and seismic and fire resistance of its elements. Some researchers have already studied the behaviour of composite steel and concrete columns in fire with an experimental [1] or numerical [2] approach; however the number of studies that took into account the restraining to thermal elongation of the columns is too small.

The behaviour of a column when inserted in a building structure is different than when isolated. Restraints on the thermal elongation of the column, provoked by the building surrounding structure, plays a key role on its stability, since it induces an increase on its internal stresses, axial forces and bending moments, and a change on its deformed shape. The increasing of the stiffness of the surrounding structure to the column subjected to fire increases not only the axial but also the rotational restraining, where while the former reduces the latter increases the critical time (also the critical temperature) of the columns [3–6].

There are already some results of fire resistance tests on partially encased steel columns [7] and on concrete filled hollow columns [8] but very few on composite columns made of totally encased steel sections [9,10].

The composite columns made of totally encased steel sections have a complex behaviour in case of fire that is not yet fully understood. These columns despite being made of a composite steel and concrete section, have a steel profile totally encased by a large mass of concrete, which arises in case of fire or phenomena of spalling and cracking, similar to concrete columns. These columns could have a similar fire behaviour to concrete ones but how the internal steel profile behave and if this had a beneficial or harmful effect on the fire resistance of the column were not yet understood. The overview of the state of the art showed that not all of these aspects were considered on research works already carried out and the behaviour of these columns in fire needed further investigation. Another aspect was to understand the influence of the thermal restraining (rotational and axial) on the behaviour of these columns in case of fire. The necessity of more experimental and numerical studies on the behaviour of composite columns made of totally encased steel sections subjected to fire is evident.

In this way, this paper presents a series of fire resistance tests on this type of composite columns carried out at the Laboratory of Testing Materials and Structures of the University of Coimbra, Portugal. The parameters studied were: the initial applied load level, the stiffness of the surrounding structure (*i.e.* axial and rotational restraint to thermal elongation), and the type of cross-section (dimensions of the inner steel profile and concrete cover around). As a consequence different cross-sectional dimensions led to different slenderness values of the tested columns.

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Nomenclature

$\overline{\lambda}_z$	relative slenderness of the column related to the weak axis
μ	loading level of the column
P	force, load
P_0	initial applied load or serviceability load of the column
α	non-dimensional axial restraint ratio of the column
β	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 profile
A_c	cross-sectional area of the concrete
A_s	cross-sectional area of the steel reinforcing bars
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 at ambient temperature
$N_{pl,Rk}$	characteristic value of the plastic resistance of the composite section to compressive force
$N_{cr,z}$	critical load for the relevant buckling mode
$(EI)_{eff}$	effective flexural stiffness of the column
$(EA)_{eff}$	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 reinforcing bar section for the relevant bending axis
E_a	modulus of elasticity of the structural steel at ambient temperature
E_c	tangent modulus of elasticity of the concrete at ambient temperature
E_{cm}	secant modulus of elasticity of the concrete at ambient temperature
E_s	modulus of elasticity of the reinforcing steel at ambient temperature
f_{ck}	characteristic value of the compressive strength of the concrete at ambient temperature
f_{c28}	mean value of the compressive strength of the concrete at 28 days at ambient temperature
f_c	mean value of the compressive strength of the concrete at ambient temperature
f_{syk}	characteristic value of the yield strength of the reinforcing steel at ambient temperature
f_{sy}	mean value of the yield strength of the reinforcing steel at ambient temperature
f_{su}	mean value of the ultimate strength of the reinforcing steel at ambient temperature
f_{ayk}	characteristic value of the yield strength of the structural steel at ambient temperature
f_{ay}	mean value of the yield strength of the structural steel at ambient temperature
f_{au}	mean value of the ultimate strength of the structural steel at ambient temperature
c	minimum concrete cover of steel section
u_s	minimum axis distance of rebars

2. Experimental programme

2.1. Test set-up

Fig. 1a shows the test set-up, which was specially conceived and constructed, for fire resistance tests on building columns with restrained thermal elongation.

Fig. 1b shows the other view of the test set-up, during mounting of a fire test, but in this case with a test column inside the furnace.

The test set-up comprised a steel restraining frame of variable stiffness [3] that had the function of simulating the stiffness of the surrounding structure to the column subjected to fire. The use of a three-dimensional (3D) restraining frame allowed taking into account not only the axial but also the rotational stiffness to which a column is subjected in a real structure in case of fire.

The 3D restraining frame was composed by two upper and two lower beams, crossed orthogonally to each other, and four columns. The beams on this frame were of steel profile HEB300, grade S355. The connections between the beams and the columns were performed by four M24 bolts, grade 8.8, except the ones between the columns and upper beams where threaded M27 rods [4], grade 8.8, were used. Different hole positions in the flanges of the beams of this restraining frame, allowed assembling the columns in different positions and with this the surrounding structure has different stiffness values to the column in test.

The columns were subjected to a constant compressive load that tried to simulate the serviceability load of the column when inserted in a real building structure. This compression load was maintained constant all over the test and was applied by a hydraulic jack of 3 MN controlled by a load cell of 1 MN placed between the upper beam of the restraining frame and the hydraulic jack [2]. The hydraulic jack was placed in a reaction frame [1] in which a safety structure was also placed [5] to prevent damage in the test set-up resulting from the sudden collapse of the specimen.

The thermal action was applied by a modular electric furnace [6] following approximately the standard ISO 834 fire curve [11]. The furnace was composed by two modules of 1 m and one module of 0.5 m, in height, placed on top of each other forming a chamber around the column of about 1.5 m × 1.5 m × 2.5 m.

A special device [7] was built for measuring the restraining forces generated in the test column during the heating process due to the restraining of the surrounding structure. This device consisted of a hollow stiff steel cylinder that was rigidly connected to the intersection of the upper beams of the 3D restraining frame. On the head of the test column a massive steel cylinder was rigidly connected, that entered in the hollow steel cylinder and compressed a load cell of 3 MN inside it, due to the thermal elongation of the specimen during the fire test. This massive steel cylinder was Teflon (PTFE) lined in order to prevent any friction with the hollow steel cylinder.

The axial displacements of the columns were carried out by Linear Variable Displacement Transducers (LVDT). The axial displacements and rotations on the top were measured using three displacement transducers and on the bottom of the specimen by four displacement traducers, placed orthogonally forming a deformation plane [8]. The lateral displacements were not measured, because as it was a column made of concrete in its entire outline, the spalling during the test would disrupt these measurements. An additional displacement transducer was placed in the centre of the 3D restraining frame near the load application point [2].

Strain gauges were also used to measure the strains on the columns and beams of the 3D restraining frame to the columns in test. These strain gauges were used to confirm indirectly the restraining forces on the test columns.

As these tests had a long time duration the conduction phenomena could be a problem for some parts of the test set-up. It was necessary to develop a cooling system for the load cell inside the hollow stiff