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Behavior of thermally restrained RC beams in case of fire

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ABSTRACT

The thermal deformation of a reinforced concrete (RC) beam in case of fire, when prevented by the surrounding structure, induce axial forces and/or bending moments in the structural element changing its resistance. A few experimental studies on this subject address the analysis of simply supported beams, and, in some cases, when thermal restraint is imposed, the level of applied stiffness is not clearly quantified. Trying to fill this gap of knowledge, this paper reports a series of fire resistance tests on axially and/or rotationally restrained RC beams under flexural bending. The main objectives of this research were to verify the failure modes and fire resistance of the RC beams comparing the behavior of restrained with those unrestrained. Other important aspects analyzed were the evolution of temperatures in the cross section, the magnitude of the restraining forces and the vertical displacements developed. The results showed that the performance of RC beams can significantly be affected by the thermal restraint, since in some cases an increase of up to 100% in the fire resistance was registered.

1. Introduction

Reinforced concrete (RC) beams, when exposed to fire, present thermal deformations. If these beams are simply supported the increase of the temperature significantly reduces their load bearing capacity [1–3]. These deformations consist in the longitudinal elongation of the beams, which results in a displacement at the supports, if they are free to elongate, and in an accentuated bending of the beams, which occurs gradually downwards, generating rotation at the supports, if they are not fixed [4,5]. While elongation is due to thermal elongation of the beams, the deflection results from the non-linear thermal gradients developed across the beam's cross-section and from the reduction of the modulus of elasticity of the materials. When these deformations are restrained by the supports (continuity effect) or the boundary conditions (surrounding structure) additional efforts appear contributing to the rise of the load-bearing capacity of the beam [6]. Moreover, in response to fire exposure continuous flexural members are benefited by changes in the moment distribution and their higher level of redundancy against failure, as the moment is reduced at mid-span where the beam's flexural capacity is reduced faster due to higher temperatures in the steel bars [7].

Some authors have demonstrated that the introduction of axial and rotational restraints led to an increase on the fire resistance of the RC beams. Lin et al. [7,8] and Guo and Shi [9] pointed out with the results of experimental tests that the moment redistribution can be favourable to continuous beams resistance and the shear stresses are not a significant problem in the fire resistance. The redistribution of moments was also commented by Gustaferro and Lin [10] presenting additional information about some precautions that must be taken into account so that the beams are able to accommodate the increasing of negative applied bending moments. Issen et al. [11] and Gustaferro [12] showed by numerical studies that increments in the axial restraining promote an increasing on the beam's fire resistance. Dwaikat and Kodur [13] confirmed that axial restraining generally increases spalling in RC beams and suggested the study of these beams should be based on realistic heating rates, loads and boundary conditions. Some other researchers have also numerically verified that fire resistance of RC beams can be benefited by the restraint effects, as Biondini and Nero [14], Bernhart [4], Riva and Franssen [15], Cvetkovska; Todorov and Lazarov [16] and Wu and Lu [17].

Recently, some design methods proposed by the American Concrete Institute [18] and the European Committee for Standardization [19] are available to predict the fire resistance of RC beams. The ACI 216R-89 standard [18] allows to calculate the load bearing capacity of simply supported beams exposed to fire taking into account the reinforcement and concrete types, the intensity of the bending moment and the thickness of the concrete cover measured from the centre of the rebar to the element surface. For statically indeterminate and restrained to

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Notation

d	effective depth to the bottom longitudinal reinforcement
y	vertical displacement of the beam at mid-span
E	equivalent beam's modulus of elasticity
A	beam's cross-sectional area
J	beam's inertia moment
k_a	axial restraining to the beam's thermal elongation
k_r	rotational restraining to the beam's supports
l	beam's span
N_{rest}	axial restraining forces
T	furnace's temperature
t	time
T_{beam}	beam's temperature
$t_{cr,r}$	critical time of the beam in terms of resistance criterion
$t_{cr,d}$	critical time of the beam in terms of deformation criterion
$t_{N,\max}$	time when the maximum restraining forces in the beam are reached
μ	mean value
σ	standard deviation

thermal elongation beams this standard offers also an analytical fire design methodology. On the other hand, EN 1992-1-2 [19] proposes three fire design methodologies. The first is a tabular method, in which to meet a required fire resistance, the beam must comply with minimum dimensions for width and concrete cover, according to prescribed values in the tables. It is quite simple and can be applied to simply supported or continuous beams, with the disadvantage, however, of limiting the calculations to a limited number of cases. The seconds are the simplified calculation methods, the 500 °C Isotherm method and the Zone method. These methods calculate for a given fire exposure time the load bearing capacity of the beam. This value can be then confronted with the applied bending moment and the fire resistance is determined when these moments are equal. The resisting moment is determined similarly to ambient temperature design, but strength reduction factors in the material properties due to the fire exposure need to be applied. It is important to say that the EN 1992-1-2 simplified calculation methods are based on sectional analysis where the structural context (and thus the restraining effects) are ruled out a priori. On the other hand, using these methods to quantify the beneficial effect of the restraining forces (by evaluating the increase of the bending resistance as a function of the applied axial force) is always possible.

As this topic is far from closed this article intends to contribute to a better understanding on the behavior of axially and/or rotationally restrained RC beams subjected to fire. The study is based on results of an experimental programme carried out at the Materials and Structures Testing Laboratory of Coimbra University (LEME-UC), Portugal. The main objective of these tests was to relate different axial and rotational restraint levels with the beam's fire resistance. Another important goal of this research was to provide experimental data for numerical studies with the aim of conducting parametric studies with different restraint levels. Finally, this knowledge is maybe useful for the development of new simplified calculation methods for fire design of RC beams.

2. Experimental tests

2.1. Test set-up

The experimental program comprised firstly four-point-bending tests on simply supported beams at ambient temperature for determining their ultimate load bearing capacity (Fig. 1). These tests were carried out for having reference values to compare with the ones calculated according to EN 1992-1-1 [20] requirements and define the loads to be applied in the tests at high temperatures.

The test set-up was composed by the following elements, illustrated in Figs. 1 and 2: one specimen positioned over two supports (No. 1 in Fig. 1), a roller support (No. 2 in Figs. 1 and 2) allowing the rotation and displacement in the axial direction of the beam, and a pinned support (No. 3 in Figs. 1 and 2) allowing only the rotation; a hydraulic jack (No. 4 in Fig. 1), suspended by a reaction frame (No. 5 in Fig. 1) and positioned over a load distribution system that applied the load in two concentrated points (No. 6 in Fig. 1).

The test set-up for the fire resistance tests is similar to the one used for ambient temperature tests but with the furnace attached. The fire resistance furnace used to heat the specimens is of modular type (Fig. 3). Simply supported beams were tested in the following configurations: without thermal restraint, with only axial restraint, and, finally, with simultaneous axial and rotational restraint.

The supports were made of refractory stainless steel, typically used for elevated temperature applications. They prevented the vertical and lateral displacements as well as the lateral rotations of the beams. The furnace had 4500 × 1000 × 1000 mm of internal dimensions and was capable to heat up to 1200 °C following fire curves of different heating rates.

In these tests it is important to clarify that the two points of action of the forces divided the specimen in three equal lengths (1 m, equivalent to one third of the span) thus submitting the central part of the specimen to pure bending.

The load was applied by an ENERPAC hydraulic jack, model RR 3014 controlled by a servo hydraulic central unit W + B NSPA700/DIG2000 (No. 7 in Fig. 1). The loads applied to the specimens during the tests, both at ambient temperature and fire conditions, were measured using a F204 Novatech load cell with a maximum capacity of 250 kN (No. 8 in Fig. 1).

In the fire resistance tests the axial thermal restraint was materialised by two simply supported steel beams that were positioned perpendicular to the test specimen by means of a set of appended steel parts (No. 9 in Fig. 4). The threaded rods shown in Fig. 4 (No. 10), once tightened, had the main objective to eliminate the potential plugs between the test specimen and the restraining beam. The appended steel parts had the function of prolonging the length of the tested beam and connect it to the outside restraining system. Because the appended parts resulted in a set of very rigid steel elements, all of them (appended parts and specimen) behaved similarly. Thus, they simulated a part of the concrete beam, representing a longer specimen.

In the fire resistance tests the axial stiffness were materialised by a low flexural stiffness beam positioned in the extremity of the testing

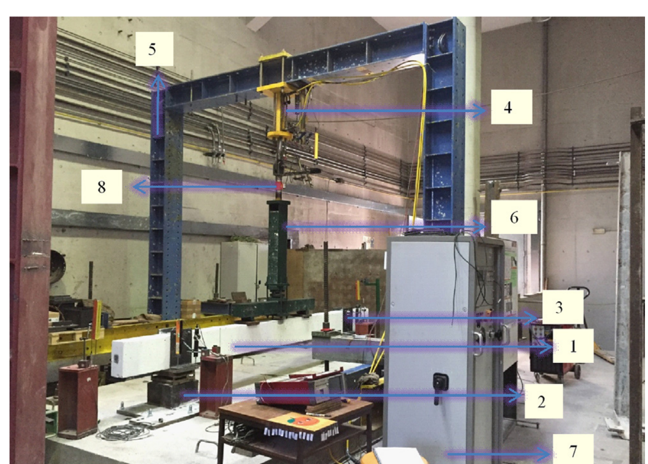

Fig. 1. Test set-up for ambient temperature tests.