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FIRE RESISTANCE TESTS ON CONCRETE COLUMNS

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ABSTRACT

The reinforced concrete elements are known to have enhanced fire behaviour however there are many things that can affect that performance. In the last years there have been carried out, in the University of Coimbra, Portugal, dozens of fire resistance tests on concrete columns where it was tested the influence of various parameters on the behaviour of these columns. Several parameters that might have influence on the behaviour of concrete columns in fire, were tested: cross section shape (round and square), longitudinal reinforcement ratio, slenderness of the column, stiffness of the surrounding structure (restraint level), load level and the load eccentricity.

The restraining level to the thermal elongation of the columns showed not being a relevant parameter in their fire resistance probably due the increase in rotational restrain associated with the increase in the axial restraint. The first increases the fire resistance while the second reduces. The increasing of the load level lead to a reduction, while the increasing of the longitudinal reinforcement ratio or the decreasing of the slenderness of the columns lead to an increasing of the fire resistance.

The spalling was also an aspect analysed in these tests. The higher load levels, the shape of the cross-section, the type of concrete with or without steel and / or polypropylene fibres, and the steel reinforcement ration was parameters that showed to have influence on concrete cracking and spalling.

Keywords: column, reinforced concrete, fire resistance, restraining, spalling

INTRODUCTION

The performance of a reinforced concrete (RC) building structure in fire depends particularly on the behaviour of the columns. These structural elements are of great importance on the structural integrity of the building because they contribute to its load carrying capacity and global stability. The collapse of one or more essential columns can lead to the progressive collapse of the entire building.

Common reinforced concrete structures under fire action have generally satisfactory behaviour. However, its performance could be much improved if it was well-known the effect of all parameters that influence the fire resistance of this type of structures.

In the seventies a lot of fully restrained RC columns were tested at Braunschweig University, in Germany (Klingsch et al, 1977). The columns had square cross-section and different distribution of reinforcement bars. They were tested columns with eccentricities equal to the half, the same and higher to the side length of the column. Different load levels were also tested. In these tests it was observed that columns of higher eccentricities and smaller load levels led to higher fire resistances. Higher cross-sections and number of steel reinforcement bars, distributed along the side of the column, increased the fire resistance.

Lie and Lin, in 1985 and 1989 (Lie and Lin, 1985; Lie, 1989), reports the results about their studies on the influence of the thermal restraint on the behaviour of RC columns subjected to fire. The experimental tests were carried out on fully restrained columns and the results compared with the ones of numerical simulations. The parameters tested were, beyond the grade of thermal restraining, the: cross-sectional shape, concrete cover, longitudinal reinforcement ratio, load level, eccentricity of loading, grade of fire exposure, height of column, type of aggregates, concrete strength, moisture content and differential heating of the columns. Columns of 3810mm height, of rectangular with 203mmx406mm, 305mmx457mm and 203mmx915mm and circular cross sections with 355mm diam., were tested.

The results obtained indicate that full restraint against the axial thermal elongation of the RC columns has little influence on their fire performance. The authors also indicate that restraint on thermal elongation can be beneficial for the columns fire performance if the surrounding structure is able to redistribute part of the loading.

The authors also found that the use of calcareous aggregates (instead of silicon aggregates) increases significantly the fire resistance of the columns. Columns of rectangular presented a better fire performance than columns of square cross-section. It was also discussed that increasing the reinforcement ratio increase in small extent the fire resistance of the columns. The application of loading with small eccentricity can cause a small reduction in the fire resistance of the columns. The influence of the concrete strength and humidity was also insignificant on the fire resistance of the columns.

Dotreppe et al, in 1997 (Dotreppe et al, 1997), published results of a research study on the behaviour of RC columns subjected to fire. The columns tested had 2100mm and 3950mm tall. The parameters tested were the: cross sectional dimensions, concrete cover, load level, slenderness of the columns, longitudinal reinforcement ratio and eccentricity of the loading. The main results of these tests were among others that the columns with higher rebar diameter presented smaller fire resistance then others with smaller rebar diameter. The authors suggested that when more steel reinforcement is necessary in the columns it is better to use rebars of smaller diameter in more quantity then less of higher diameter.

Spalling occurred in many of the test columns presenting them big cracks along the steel reinforcement. The concrete and steel have similar thermal expansion up to 400°C, however, for higher temperatures, steel has a thermal expansion higher than concrete which may cause cracking along the steel rebars. The steel reinforcement should be protected in order not to be exposed to temperatures above 300°C. The authors also suggested that the height of the columns and support conditions could be responsible for these results.

The columns with a higher loading level showed lower fire resistance. The increasing of the cross section led to an increasing of the fire resistance of the columns. The increasing of the height of the columns has a negative effect on load-bearing capacity at high temperatures due to an increase of geometrical nonlinear effects. Finally note that the increasing of the concrete cover has a positive effect on the fire behaviour of the columns, although quite insignificant.

Franssen and Dotreppe, in 2003 (Franssen and Dotreppe, 2003), presented another paper reporting the results of fire resistance tests on RC columns that were performed at the University of Liege. The tests were carried out to examine the influence of the circular shape on the behavior of RC columns under fire conditions and consequently on spalling. The columns were 2100mm tall and had a cross-sectional diameter of 300mmr. This paper describes the test procedure, the observations made, and the values obtained for the fire resistance. The authors stated that the diameter of the longitudinal reinforcement had no significant influence on spalling and despite this phenomenon the values obtained for fire resistance were relatively high. The circular shape of the cross-section does not prevent the occurrence of spalling. An increase of the load level leads to a significant decrease of the fire resistance. They have also applied the simplified calculation methods usually used for square columns on the circular columns. They concluded that these methods needed a reformulation for the case of circular columns.

Ali et al, in 2004 (Ali et al, 2004), presented the results of an extensive experimental programme (99 fire resistance tests) involving half-scale (1.8m) columns made of ordinary and high strength concrete. The experimental results were used in a parametric study to evaluate the influence of the axial restraint, loading level and heating rate on the performance of RC columns subjected to high temperatures. In the study it was shown that increasing the loading level decreased the restraining forces and column’s failure times. The increasing of the degree of axial restraint increased the generation of restraining forces and had a minor influence on the column’s failure times. The low heating rate led to higher failure times of the columns.

The authors noted that the explosive spalling occurred in the first 45 minutes of fire test. It was discussed in this work that increasing the loading level does not lead to an increasing of the degree of spalling however low heating rates reduce the risk of spalling. For normal strength concrete it was also observed that increasing the restraint degree increased the degree of spalling. The same was not observed for the high strength concrete contradicting the usual belief that this type of concrete is more susceptive to spalling.

The authors report also that the existence of voids inside the concrete can be responsible for explosive spalling of concrete. The size and distribution of voids in concrete can change the risk of explosive spalling in the concrete. The adding of polypropylene fibres reduced a lot the risk of spalling in the concrete.

Xu and Wu, in 2009 (Xu and Wu, 2009), presented the results of experimental tests on reinforced concrete (RC) columns with L-, T- and +-shaped and square cross-sections. The effects of axial load ratio, fire exposure conditions, axial deformation and fire resistance of the columns, were analysed. The experimental results showed that when the axial load ratio is 0.55, the fire resistances of the columns with L-, T-, and +-shaped cross-sections subjected to fire on all sides were 60–73% that of the column with the square cross-section. In case of columns subjected to fire on all sides, its fire resistance with differently-shaped cross-sections increased in the following order: L-shaped cross-section, T-shaped cross-section and +-shaped cross-section. Load ratio and fire exposure had significant effects on the fire resistance of the columns.

In order to know the behaviour of reinforced concrete columns in fire several fire resistance tests were carried out on square and circular cross-section concrete columns with restrained thermal elongation. The tests were carried out in the Laboratory of Testing Materials and Structures of the University of Coimbra, Portugal. Some of the results of these tests are presented and discussed in this paper (Martins and Rodrigues, 2010; Rodrigues et al, 2010).

MATERIAL AND METHODS

Test set-up

The experimental tests on reinforced concrete columns were conducted in the Laboratory of Testing Materials and Structures of the University of Coimbra, in Portugal. In Figure 1 the test set-up for fire resistance tests on columns with restrained thermal elongation, is illustrated.

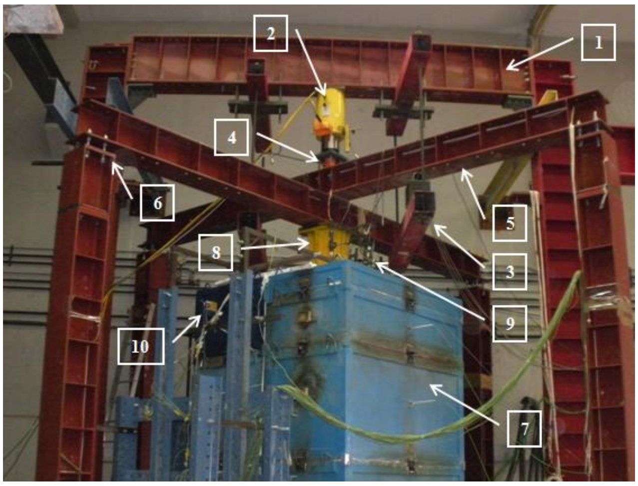


Fig.1 Test setup

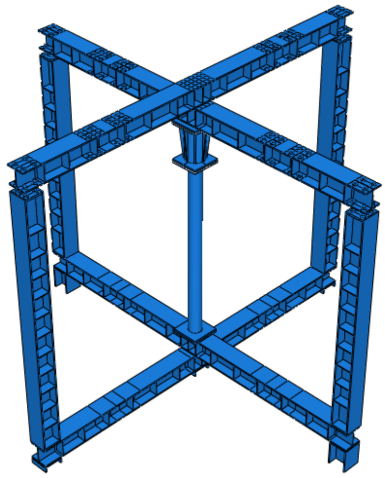


Fig.2 Scheme of the 3D restraining frame

A two-dimensional (2D) reaction frame (1) consisted of two HEB500 columns and an HEB600 beam of S355 steel class was used to support a hydraulic jack (2) which applied a compression load to the columns. This hydraulic jack had a maximum capacity of 3 MN and was controlled by a servo hydraulic central unit W+B NSPA700/DIG2000. The load that was being applied by the hydraulic jack was controlled by a load cell (4).

A safety structure (3) was mounted in the 2D reaction frame to prevent the destruction of the system in case of sudden collapse of the test column.

In addition, the stiffness of the surrounding structure of the columns under test was realized by a three-dimensional (3D) restraining frame (Fig. 2) with four HEB300 columns and four identical beams of S355 steel class, orthogonally arranged (5). The stiffness could be varied by changing the position of the columns or the height of the beams. During these experimental tests, only the position of the columns was changed.

The connection between the columns and top beams of the 3D restraining frame was done by threaded rods (6) that allowed in the beginning of the test by unscrewing the nuts to transfer the loading applied by the hydraulic jack to the test columns.

The specimens were heated with a vertical electric furnace (7). This furnace was 1500 mm x 1500 mm x 2500 mm in internal dimensions and capable to heat up to 1200ºC and to follow fire curves with different heating rates.

The restraining forces generated in the column due to the heating were measured by a load cell of 3 MN located inside a void steel cylinder of high stiffness (8). This cylinder was rigidly connected to the restraining frame by means of high-resistant bolts as well as all connections between the elements in the experimental set-up. A massive steel cylinder, rigidly connected to the testing column, entered in a void steel cylinder and due to the thermal elongation of the column compressed the load cell.

The axial displacements and rotations on the top and bottom of the column were measured by displacements transducers, LVDT (9), orthogonally arranged in three different points, forming a deformation plan. The lateral deflections of the columns could be measured by cable transducers located along the height of the column in two bending planes (10).

Test specimens

The tested columns were 3000 mm tall and square or circular cross-sections. The square cross-section columns had 160 mm x 160 mm and 250 mm x 250 mm and the circular cross-section ones had 250 mm and 300 mm in diameter (Fig. 3 and Table 1). The circular columns had six longitudinal ϕ12 or 20 mm and the square columns had four ϕ10, 16 or 25 mm rebars (Table 1). The transversal reinforcement was performed by ϕ 6 or 8 mm diameter stirrups with a spacing of 100 mm until 700 mm from the supports, and a spacing of 150 mm in the central part (Fig. 3). The ϕ6 mm diameter stirrups were used with the ϕ12 mm diameter rebars in the circular columns and with the ϕ10 or 16 mm diameter rebars in the square columns. The ϕ8 mm diameter stirrups were used with the ϕ20 mm diameter rebars in the circular columns and with the ϕ25 mm diameter rebars in the square columns (Fig. 3). The concrete covering related to the stirrups for all tested columns was 30 mm.

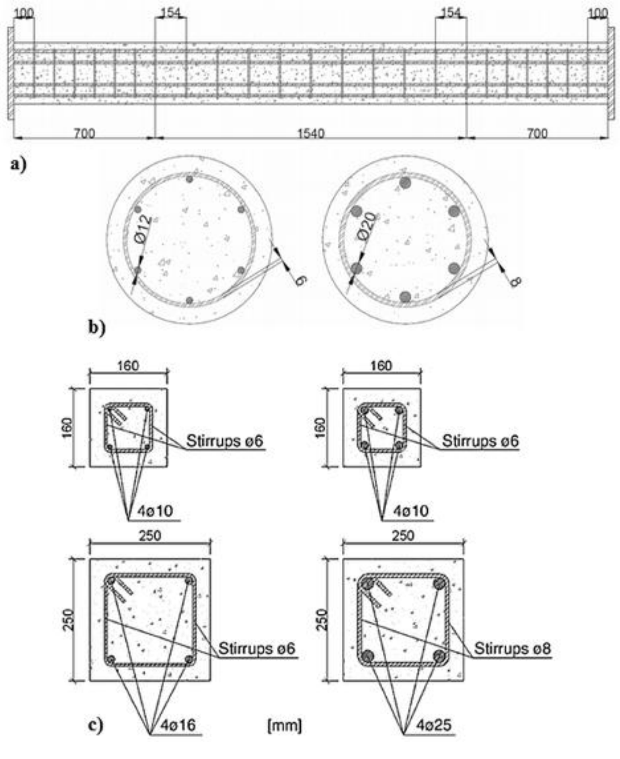


Fig.3 Test specimens

All specimens were fabricated with reinforcing bars of A500NR steel and calcareous aggregate concrete C20/25.

The temperatures were measured in five cross-sections on the circular columns and in three cross-sections on the square columns (Fig. 4). Type K thermocouples were used to measure the temperatures on the specimen while probe thermocouples were used to measure the furnace temperatures.

Test Plan

The experimental programme consisted of 20 (10 circular + 10 square) fire resistance tests on concrete columns with restrained thermal elongation. However, in this paper are selected for presentation sixteen tests whose results are compared. The characteristics of the specimens tested are summarised in Table 1.

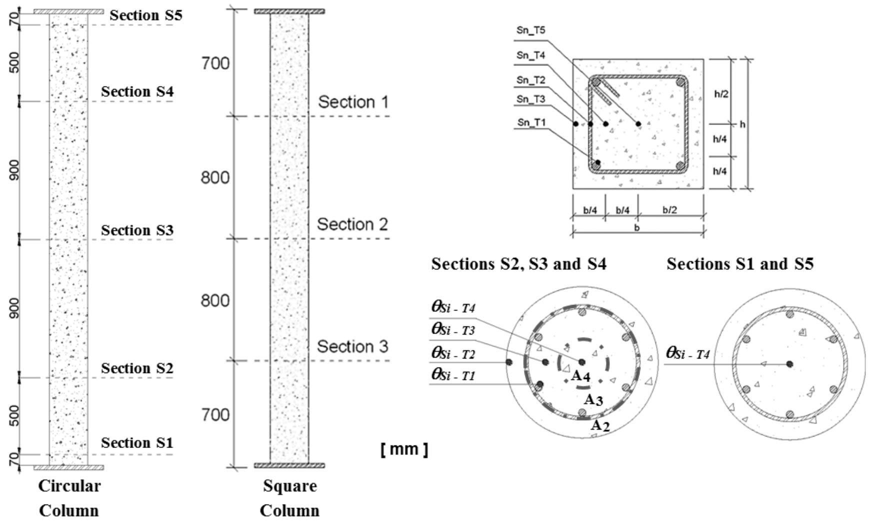


Fig.4 Test specimens and location of the thermocouples

Table 1 Characteristics of the tested columns

Column reference	Cross-section		Longitudinal reinforcement		Reinforcement ratio A_s/A_c (%)	Slenderness
	Diameter, d or h x b (mm)	Area, A_c (mm^2)	Number and diameter (mm)	Area, A_s (mm^2)		
C16-10-k1 C16-10-k2	160 x 160	25600	4ϕ10	314	1.23	77
C16-16-k1 C16-16-k2	160 x 160	25600	4ϕ16	804	3.14	77
C25-16-k1 C25-16-k2	250 x 250	62500	4ϕ16	804	1.27	49
C25-25-k1 C25-25-k2	250 x 250	62500	4ϕ25	1964	3.14	49
C25-12re-70LL-13K C25-12re-70LL-128K	250	49087	6ϕ12	679	1.38	58
C25-20re-70LL-13K C25-20re-70LL-128K	250	49087	6ϕ20	1885	3.84	58
C30-12re-70LL-13K C30-12re-70LL-128K	300	70686	6ϕ12	679	0.96	48
C30-20re-70LL-13K C30-20re-70LL-128K	300	70686	6ϕ20	1885	2.67	48

For the circular columns the reference C25-12re-70LL-13K corresponds to a 250 mm diameter circular column (C25) reinforced with 12 mm diameter longitudinal steel reinforcing bars (12re). The designation 13K indicates that the value of the axial stiffness of the surrounding structure was 13 kN/mm. The circular columns were tested for stiffness of the surrounding structure of 13 kN/mm and 128 kN/mm.

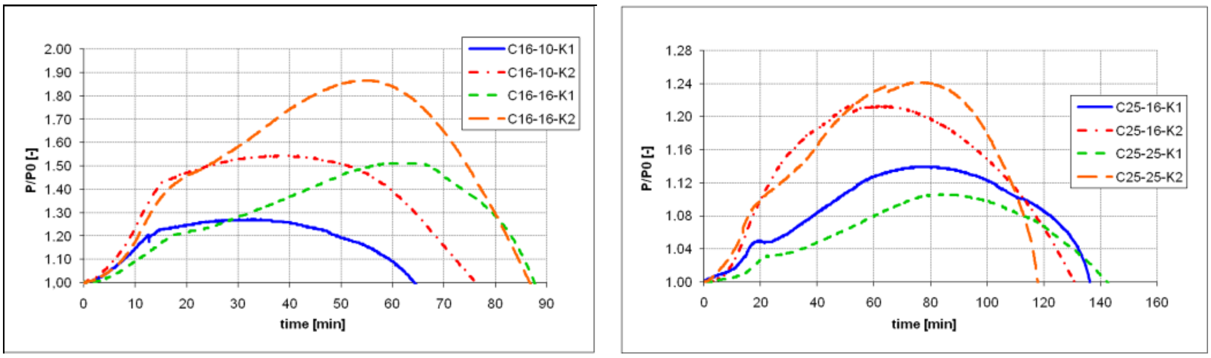
For the square columns the reference C16-10-k1 corresponds to a cross-section of 160 mm x 160 mm reinforced with 10 mm diameter longitudinal steel reinforcing bars. The designation k1 indicates 13 kN/mm and k2 indicates 45 kN/mm for the value of the axial stiffness of the surrounding structure. The square columns were tested for stiffness of the surrounding structure of 13 kN/mm and 45 kN/mm.

All the columns were axially loaded with 70% (referenced by 70LL in the circular columns) of the design value of buckling load at ambient temperature calculated according to EN 1992-1-1 (EN 1992-1-1, 2004). These loading levels intended to simulate different serviceability load conditions of the columns when they are inserted in a real building structure.

RESULTS

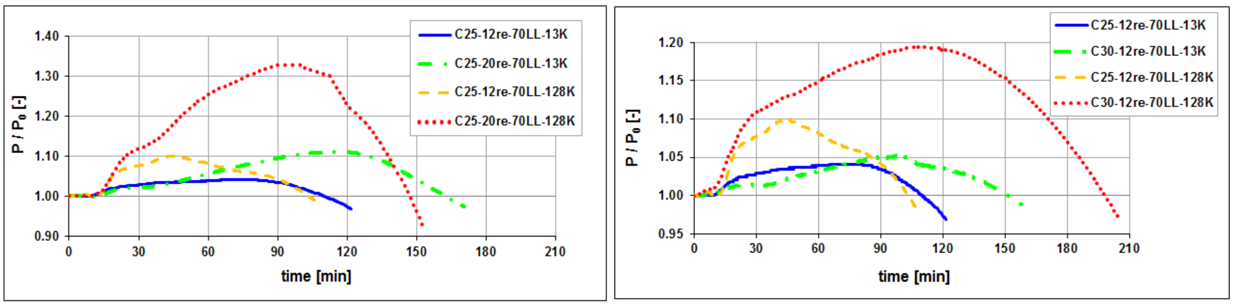
Restraining forces

Figures 5 and 6 present the development of the restraining forces on square and circular cross-section columns in function of the time, respectively. The restraining forces started to increase up to a maximum and then decreased due to the degradation of the mechanical properties of the materials.



(a) Square 160 mm x 160mm (b) Square 250 mm x 250mm

Fig.5 Restraining forces on square columns



(a) Circular d= 250mm (b) Circular d= 300mm

Fig.6 Restraining forces on circular columns

In Figures 5 and 6, it can be observed that higher stiffness of the surrounding structure higher the restraining forces. In Figure 5, for the square cross-section columns, increasing the cross-section dimensions increasing the critical time. The increasing of the longitudinal rebars diameter led also to an increasing of the critical times however this was more notorious for columns with cross-section 160 x 160 mm. For the columns 250 mm x 250 mm increasing the rebar diameter the critical time was practically the same. This may be explained that after a certain diameter of the rebar its lateral expansion can lead to concrete detachment leading to a reduction on the critical times.

Concerning to circular columns (Fig. 6) increasing the column diameter increasing the critical time. For columns of 250 mm diameter it was observed that increasing the diameter of the longitudinal rebars increasing the critical time (Fig. 6 a). The increasing of the stiffness of the surrounding structure seams not having influence on the critical times (Fig. 6 a and b). An increase in axial restraint results in an increase in rotational restraint together. The first reduces the critical time of the columns but the other increase the critical time.

Specimens after test

All tested columns were observed after test in order to identify the cracks and spalling occurred. This visual observation allowed the identification of spalling on the edges of square columns and compressed areas of the columns, exposing in certain cases the steel rebars. During the tests explosive spalling could be heard especially in the first 10 min of the test.

Square cross section columns

Figure 7 illustrates the spalling in the square cross-section columns tested (160 mm x 160 mm). In the Figure it is visible the concrete detachment on the corners and compressed zones of the columns. The columns tested with smaller stiffness of the surrounding structure could deform more and lead to the origin of concrete spalling on the compressed zones (Fig. 7 a). In Figure 7 b) it seems that the spalling was not so critical occurring only along the edges of the columns. This may be justified by the high stiffness of the surrounding structure that avoided the deformation of the columns.

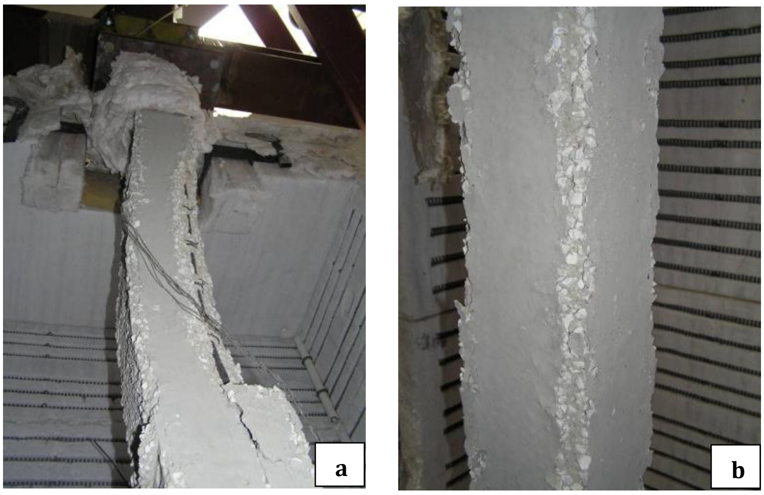


Fig.7 Columns of square cross section (160 × 160mm^2), reinforcement ratio As/Ac=1.23%.

a) Low restraint level. b) High restraint level.

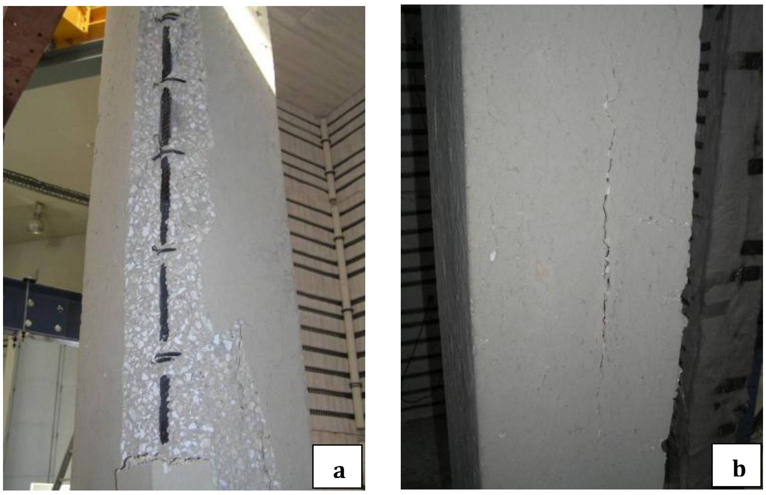


Fig.8 Columns of square cross section (250 × 250mm^2), reinforcement ratio As/Ac=1.27%.

a) Low restraint level. b) High restraint level.

Columns of higher cross-section deformed less in the test and showed at the final less spalling in the surface. However the spalling on the corner of the columns also occurred mainly in the ones built with rebars of higher diameter (Fig. 8). Some macro cracks appeared on the columns along the steel rabars (Fig. 8 b).

These macro cracks are perfectly visible in Figure 9. Some of the columns buckled, however this may have occurred in the later stages of the test (Fig. 9 b). As the furnace is completely closed this phenomenon could only be observed after the test. The use of longitudinal bars of higher diameter in columns inserted in a structure of higher stiffness can have a detrimental effect on the columns behaviour in fire with their possible buckling.

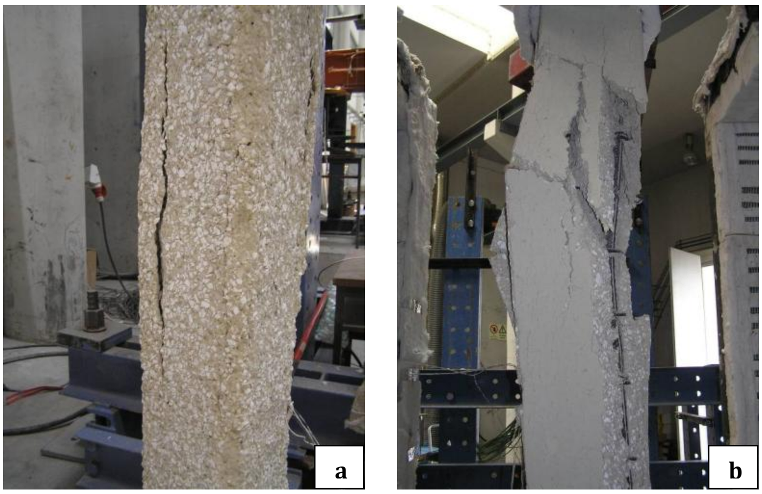


Fig.9 Columns of square cross section (250 × 250mm^2), reinforcement ratio As/Ac=3.14%.

a) Low restraint level. b) High restraint level.

Higher loading levels and steel reinforcement ratio look a higher spalling grade on columns. Bigger and deeper cracks were observed on the column surface.

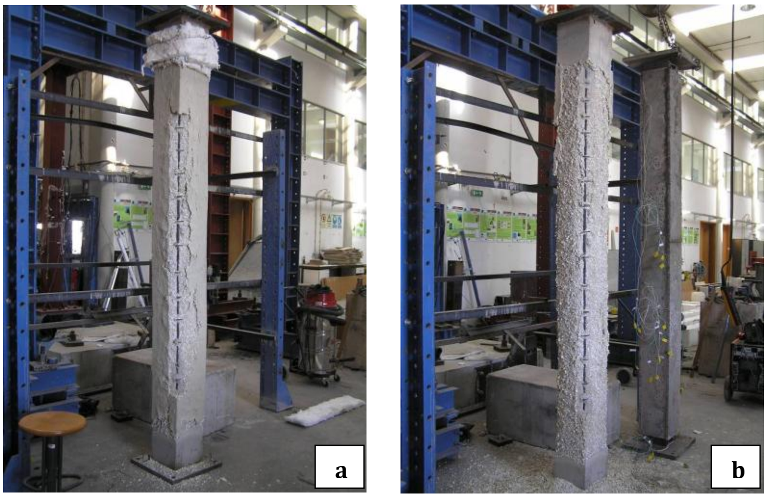


Fig.10 Detachment of concrete over the days after testing

a) Day of the test. b) One day after the test.

After testing, over the days, it was observed the detachment of layers of concrete from the surface of columns (Fig. 10). This detachment was more intense in the early days and reduced over time. The amount of concrete that fell was too large.

Circular cross section columns

Figure 11 shows the spalling on circular columns. The phenomenon was on the surface, not very intense, and there isn't a preferred zone for occurring like in the square cross-section columns which occurred on the corners. Higher steel reinforcement ratios did not mean higher degree of concrete spalling because the rebars were distributed along the column perimeter (Figs. 11 a and b).

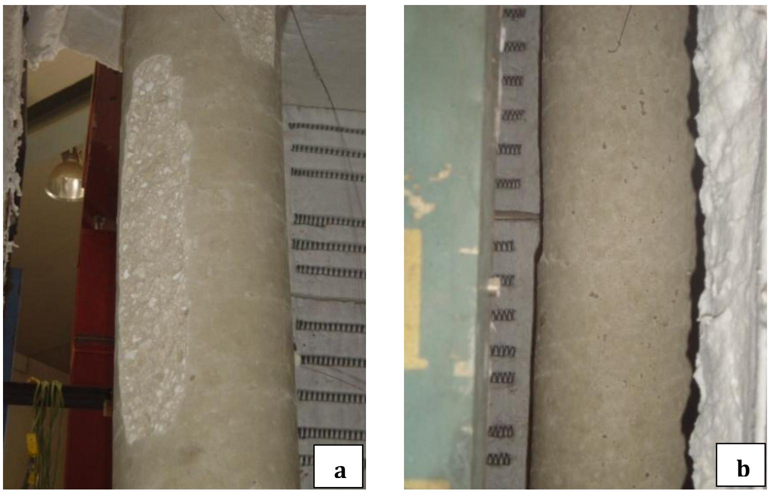


Fig.11 Columns of circular cross section, Ø250mm.

a) Reinforcement ratio As/Ac=1.38%. b) Reinforcement ratio As/Ac=3.84%.

The evolution of the concrete detachment from the column over time after the test was observed in circular columns. As in the square columns this phenomenon was very intense in the first days and reduced over the time. One week after the test didn't fell more concrete from the element (Fig. 12).

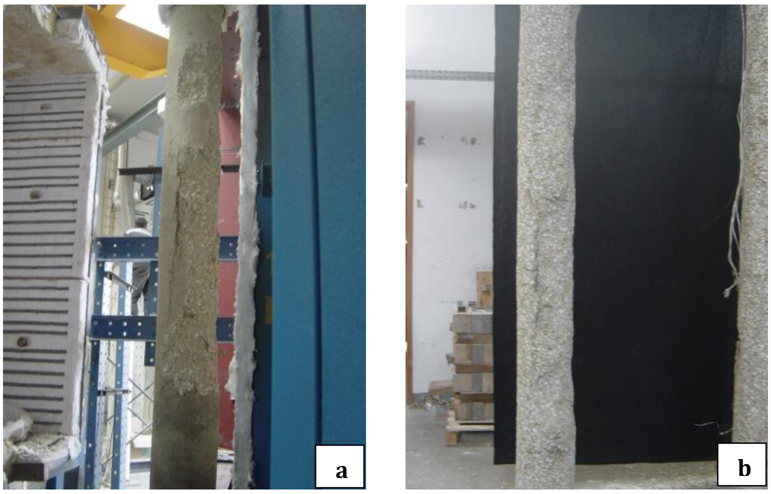


Fig.12 Concrete spalling after testing.

a) Day of the test. b) One day after the test.

CONCLUSIONS

This paper summarized the results of fire resistance tests on square and circular cross-section columns with restrained thermal elongation. The results of this research allow us to conclude the following:

- Increasing the longitudinal reinforcement ratio increases the fire resistance of RC columns.
- Increasing the slenderness of the columns leads to a significant reduction on its fire resistance. That reduction is more significant for columns with lower reinforcement ratio.
- Increasing the restraining level lead to higher restraining forces on the columns.
- Increasing the loading level reduces significantly the fire resistance of the columns. With a higher loading level extensive spalling was observed on columns surface.
- This study showed that spalling can occur either in circular or in square columns, however less intense on the first due to the distribution of steel reinforcement along the perimeter of the column.
- Intense spalling occurs on the corners of the square cross-section columns due to the higher concentration of steel reinforcement on these areas and by cracks may appear along the longitudinal rebars.
- The compressed zones of the columns due to the bending present in general higher degree of spalling.
- Thus, the idea that spalling can only occur on high strength concrete is jeopardized as the concrete of these columns was of small resistance class.

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