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Fire Tests and Calculation Methods for Circular Concrete Columns

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Abstract. The introduction sets the scene of the present paper, i.e. the extensive research works performed at the University of Liege in order to derive acceptable calculation methods for the fire design of concrete columns. It is explained that all previous works have been based on square or rectangular cross sections, for which corner spalling was observed very often, whereas circular section are nowadays becoming more and more popular.

In order to examine the influence of the circular shape on the behavior under fire conditions, an experimental research study has been performed recently at the University of Liege. This paper describes the test procedure, the observations made, and the values obtained for the fire resistance. Theoretical methods have been developed for a quick, safe, and efficient design of concrete columns under fire conditions. These methods have been applied successfully to the recently tested circular columns.

Key words: concrete, columns, fire resistance, fire tests, calculation method, spalling, circular section

1. Introduction

The behavior of reinforced concrete columns under fire attack is generally satisfactory. However, sudden spalling is sometimes observed; in such cases, failure may occur prematurely and fire resistance may be reduced substantially. Despite this phenomena, concrete columns must be properly and safely designed under fire conditions. Different approaches can be used in order to design a concrete structure in case of fire:

- Experimental tests has been the first method to be used, but it is limited to simple elements, and it is time consuming and expensive.
- Numerical modelling is nowadays the most sophisticated tool that is available.
- Simple calculation methods are necessary for application to most simple cases in everyday practice.

In fact, the three approaches are related, not so much for their application, but certainly during the creation of the different tools, see Figure 1: numerical modelling relies on experimental tests for validation, whereas simple calculation methods are based on the knowledge gained from numerical modelling, and are also supposed to yield results that are in good agreement with experimental results.

It is not easy to simulate the behavior of concrete structures under fire conditions, and moreover consulting engineers do not always have the required kind of numerical tool at their disposal. In order to proceed to a quick and efficient design, it is important to elaborate simplified methods based on analytical formulations. These types of methods

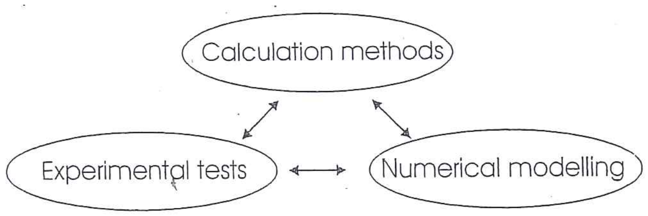

Figure 1. Relationship between the 3 approaches for design.

are also proposed in FIP-CEB Recommendations [1], and in the European prestandard ENV 1992-1-2 (Eurocode 2-1-2) [2], but they are more appropriate to beams and slabs than to columns.

This is why, in everyday practice, the design of simple concrete columns submitted to fire is traditionally realized by using tabulated data. This procedure has been appearing for a long time in the FIP/CEB Recommendations dealing with this matter. More recently, the European Commission for Standardisation (CEN) has published Eurocode 2-Part 1-2, in which various tables of this type are proposed to the designers.

Several research studies have been performed in Belgium, and more particularly at the University of Liege, on the fire resistance of concrete columns. It has been quickly realized from comparisons with results of experimental tests that the tabulated data proposed in ENV 1992-1-2 was not satisfactory and, furthermore, had a tendency to yield unsafe results, see Figure 2.

These research studies were thus undertaken in order to improve the calculation methods for the design of concrete columns under fire situations.

In one of them [3], the main parameters affecting the behavior of reinforced concrete columns at elevated temperatures, and their influence on the fire endurance have been

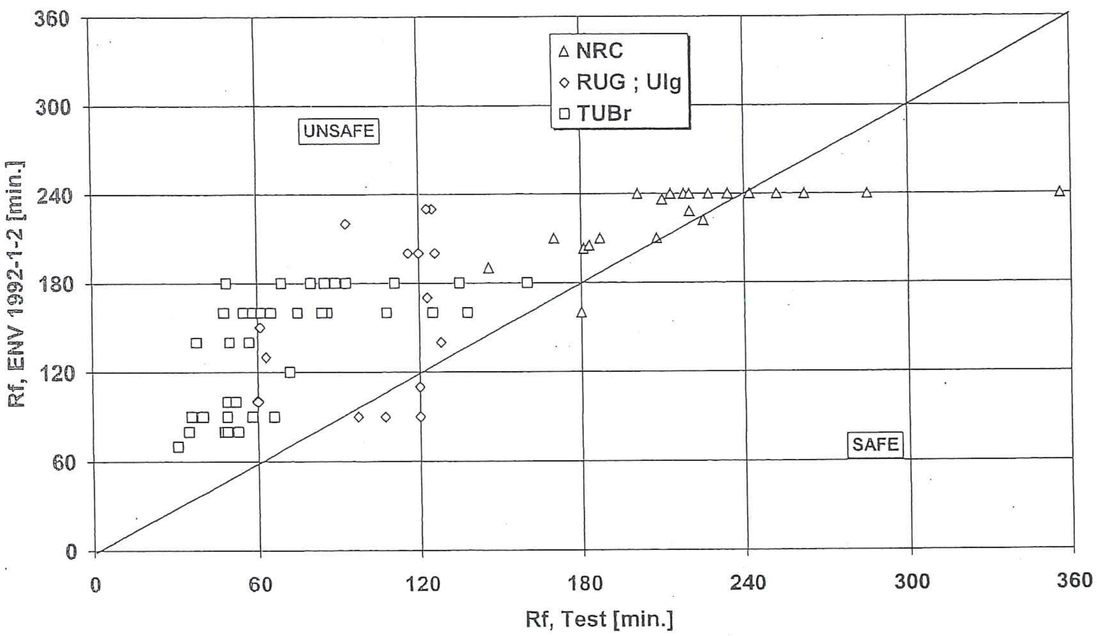

Figure 2. Comparison between test and ENV 1992-1-2.

examined. This experimental study has been performed at the Universities of Liege and Ghent in Belgium.

As a result, two alternative simplified calculation methods were developed in Liege for the determination of the fire resistance of column subjected to the standard ISO fire. To this purpose, not only the test results from Liege and Ghent have been used [3], but also experimental results from the Technical University of Braunschweig [4], and from the N.R.C. Fire Research Station in Ottawa [5]. These two methods are briefly described in [6], while the second (more elaborate) one is developed in detail in [7].

Another experimental investigation has been subsequently performed at the University of Liege on the spalling of concrete columns [8, 9]. With this study and the experimental results obtained in the preceding research works [3], it has been possible to derive conclusions regarding various parameters influencing this phenomenon.

As a whole, 21 test results from N.R.C., 39 from Braunschweig, 24 from Ghent, and four from Liege were considered in these research works, i.e. a total of 88 test results on full scale columns. Yet, all the preceding tests and studies have been made on columns with square or rectangular cross sections. Due to the development of new types of framework, circular concrete columns are now cheap and easy to build, and they are progressively more and more used. However very few tests under fire conditions have been made on columns with this type of cross section.

In order to examine the influence of the circular shape on the behavior of concrete columns at elevated temperatures, an experimental study has been performed recently at the University of Liege. The two main questions for which an answer was sought are:

1. Are the circular sections less prone to spalling, due to the fact that there is no corner in a circular section, and that corner spalling in the rectangular sections is usually the first observed spalling?
2. Are the calculation methods that have been developed for rectangular sections still valid in the case of a circular section?

This paper describes first the elements tested, the experimental procedure and the observations made during the tests. Conclusions are drawn regarding spalling phenomena and design methods for circular concrete columns.

2. Experimental Program

2.1. Description of Specimens

Four columns with circular cross section (diameter 300 mm) and a length of 2100 mm have been tested. Two columns are reinforced with 6 ϕ 20 longitudinal bars ($A_s/A_c = 2.67\%$) and two with 6 ϕ 12 ($A_s/A_c = 0.96\%$). For each specimen the transversal reinforcement is realized with ϕ8 circular stirrups with a spacing of 100 mm until 400 mm from the supports, and a spacing of 200 mm in the central part. The concrete cover is $c = 30$ mm on the stirrups and $c = 38$ mm on the main bars, i.e. for the longitudinal bars an axis distance $a = 44$ mm for ϕ 12 bars and $a = 48$ mm for ϕ 20 bars. The material qualities are C 60 siliceous for concrete and S 500 for the steel reinforcing bars.

2.2. *Experimental Procedure*

The columns have been tested in one of the furnaces of the Fire Test Laboratory. The length of the columns was limited by the height of the furnace.

The concrete characteristics have been evaluated according to the Belgian standards. Quality C 60 was obtained without adding ultra fine particles.

Each column was simply supported at the ends, which give a slenderness of 28. The furnace is provided with an external frame specially designed to apply forces. Specimens are loaded by means of two double-effect (compressive and tensile) hydraulic jacks. Several thermocouples were placed in each column before the casting of the concrete in order to measure the temperature evolution.

The temperature in the furnace varied according to standard ISO 834 (very similar to the ASTM E119). The elongation of the columns and the temperature in the thermocouples were recorded every minute during the tests. The compression force was applied first and measured continuously in order to check that its variation during the fire test was negligible. The column aspect was examined basically every 15 minutes, unless spalling was noticed.

2.3. *Test Results*

The test results are summarized in Tables 1 and 2.

3. Simplified Calculation Methods for Design

As already mentioned, two alternative simplified calculation methods have been developed. The first one is a very simple model [6] which gives values well in agreement with experimental results. Referring to the classification of EC2-1-2 [2], it can be considered as a level 1 method (same as tabulated data). The basic equation is given hereafter.

$$R_f = 120\left(\frac{R_{f,\eta}+R_{f,a}+R_{f,L}+R_{f,b}+R_{f,n}}{120}\right)^{1.8} \tag{1}$$

TABLE 1
Load Applied and Fire Resistance Obtained for the Four Columns

Column	Main reinforcement	Load applied (kN)	Load applied/ Design strength N_{ud}	Fire resistance (min)
C1	6 ϕ 12	1260	0.59	156
C2	6 ϕ 12	1770	0.83	131
C3	6 ϕ 20	1450	0.57	187
C4	6 ϕ 20	1900	0.75	163

TABLE 2
Main Observations During the Tests

Column	Time (min)	Observations
C1	25	sloughing off of concrete in many places of the external layer
C2	20	large cracks (mainly longitudinal)
	29	sloughing off of concrete of almost the whole external layer
C3	34	large cracks at the bottom of the column
		a few moments later sloughing off of concrete at the same place
	60	significant increase of the damage
C4	30	large cracks at the bottom of the column
		a few moments later sloughing off of concrete at the same place
	38	significant increase of the damage

where

$$R_{f,\eta} = 83(1.00 - \eta_{fi}), \qquad \eta_{fi} = N_{d,fi}/R_d, \tag{2}$$

$$R_{f,a} = 1.60(a - 30), \qquad a = \text{axis distance in mm}, \tag{3}$$

$$R_{f,L} = 9.60(5 - L), \qquad L = \text{buckling length in m}, \tag{4}$$

$$R_{f,b} = 0.09b, \qquad b = \text{Dimension of the section in mm}, \tag{5}$$

$$R_{f,n} = 12 \qquad \text{if more than 4 longitudinal, bars are present, 0 otherwise.} \tag{6}$$

This method has been used to evaluate the fire resistance of the four circular columns. As can be seen in Table 3, it gives values in good agreement with experimental results, though a little bit too conservative. Figure 3 shows a graphic presentation of the comparison between results obtained with this method and the experimental test results.

The second model [6, 7] is more elaborate and can be considered as a simplified calculation method (level II according to EC2-1-2). This method has been applied to the four circular columns; the approach and the results are presented hereafter.

In this model, the ultimate load capacity of the heated column is expressed as a fraction of the plastic crushing load of the section:

$$\mathrm{N_u(t)} = \chi^{\mathrm{MN}}(\lambda)\mathrm{N_{pl}(t)}, \tag{7}$$

TABLE 3
Fire Resistance Values (Method 1)

Column	Theoretical fire resistance Method 1 (min)	$R_{f,m1}/R_{f,\text{test}}$
C1	126	0.81
C2	91	0.70
C3	141	0.76
C4	113	0.70

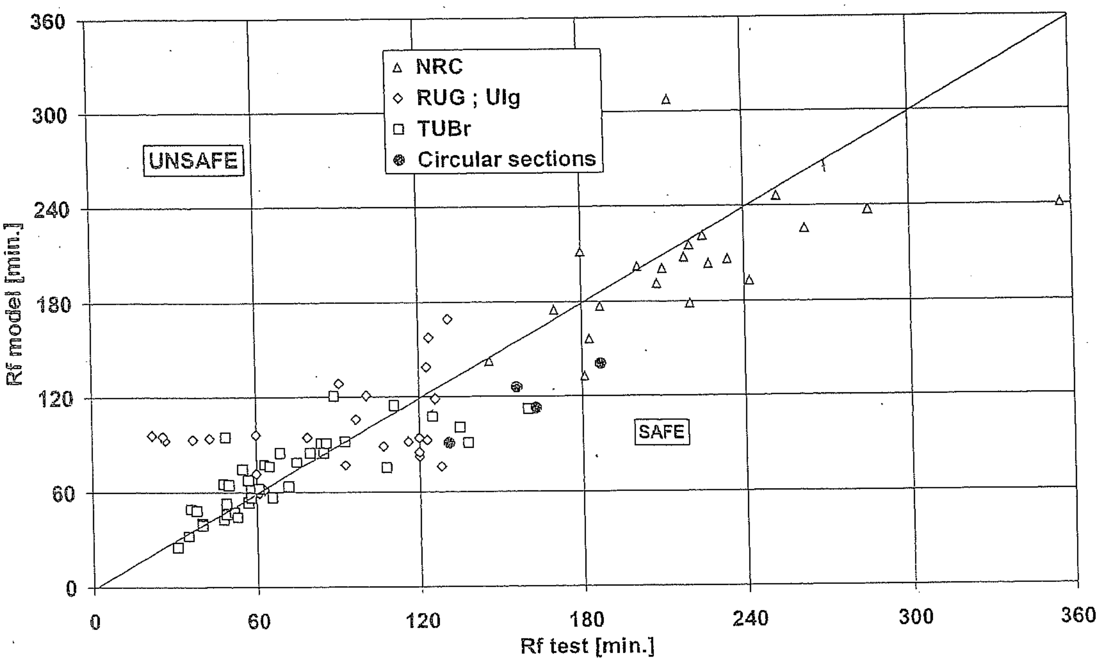

Figure 3. Comparison between test and method 1.

with t: time

λ: slenderness ratio at 20°C.

$N_{pl}(t)$ is the plastic load of the section at time t:

$$N_{pl}(t) = \gamma(t)(\beta_1(t)N^c_{pl} + \beta_2(t)N^s_{pl}), \tag{8}$$

with N^c_{pl} the plastic load of the concrete core at 20°C; N^s_{pl} the plastic load of the steel reinforcement at 20°C; $\beta_1(t)$ and $\beta_2(t)$ represent the diminution of the plastic loads with time. $\gamma(t)$ is a function which takes into account spalling of concrete occurring at the beginning of the fire:

$$\gamma(t) = 1 - 0.3t \geq 0.85 \tag{9}$$

$\chi^{MN}(\lambda)$ is the buckling coefficient:

$$\chi^{MN}(\lambda) = \frac{\chi(\lambda)}{\varphi(\lambda)} \tag{10}$$

$\chi(\lambda)$: buckling coefficient for an axial load; $\varphi(\lambda)$: non linear amplification term due to the eccentricity of the load.

When applying the values proposed in [7] to the circular columns, it was observed that the theoretical results were too conservative. The analysis of the discrepancies between theoretical and experimental results led to the following considerations:

— Despite the particular shape of the columns, surface spalling was observed in the four tests, see Figure 4. This means that the reduction coefficient $\gamma(t)$ of Equation (9) taking account of spalling should also be applied for circular columns.
— The calibration of Equations (7) to (10) has been based on test results on columns with a rectangular cross-section and with a length situated between 3 and 4 m for almost all the elements. A new calibration for a length of approximately 2 m was realized. This led to the following new formulation for the buckling coefficient $\chi(\lambda)$ appearing in Equation (10), the amplification coefficient $\varphi(\lambda)$ remaining unchanged.

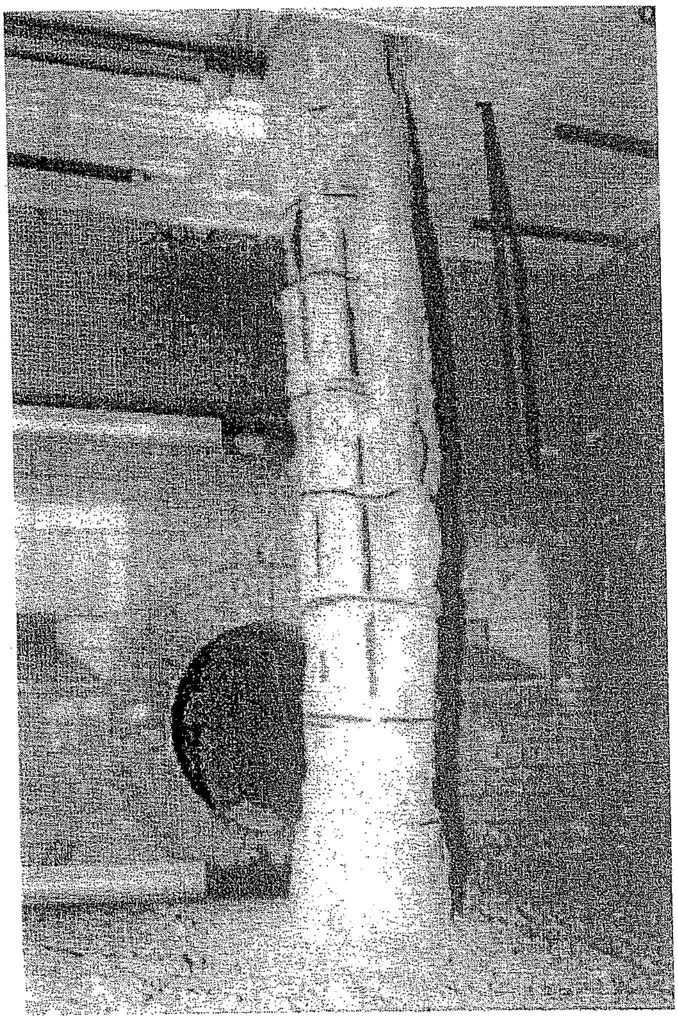

Figure 4. Spalling in column C1 as observed after the test.

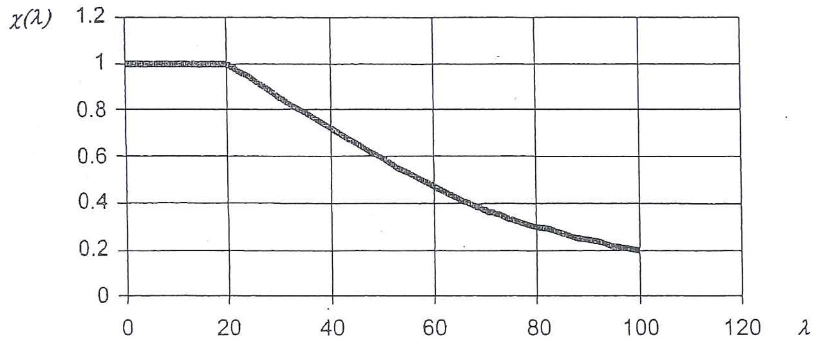

Figure 5. Buckling coefficient versus slenderness ratio.

Figure 5 shows a graphic presentation of Equations (11) to (13)

$$\chi(\lambda) = 1, \qquad \lambda \le 20, \tag{11}$$

$$\chi(\lambda) = \left[1 + \frac{70-\lambda}{200}\right] \cdot 0.80 \cdot \left(\frac{20}{\lambda}\right)^{0.7(\frac{\lambda}{70})(\frac{225-c}{200})^5}, \qquad 20 < \lambda < 70, \tag{12}$$

$$\chi(\lambda) = 0.80 \cdot \left(\frac{20}{\lambda}\right)^{0.7(\frac{\lambda}{70})(\frac{225-c}{200})^5}, \qquad 70 < \lambda, \tag{13}$$

in which c: concrete cover (to the longitudinal reinforcement).

In order to show the adequacy of this new formulation, the ratio N_u (formula)/N_u (test) has been calculated for the four columns. N_u (formula) is the maximum axial load according to the theoretical formulation, and N_u (test) is the load applied during the test. The fire resistance is the one measured during the test.

It can be noticed that the new formulation leads to safe, though rather conservative, values for design purposes, see Table 4. Additional studies will be performed to examine whether a particular formulation should be derived for N_{pl}, Equation (8), in case of circular columns.

4. Conclusions

1) Observations made during experiments show that surface spalling was noticed between 20 and 60 minutes of fire test. The circular shape of the cross-section does not prevent the occurrence of this phenomenon.

TABLE 4
Comparison Between Theoretical (Method 2) and Experimental Results

Column	N_u (formula)/N_u (test)
C1	0.79
C2	0.65
C3	0.58
C4	0.50

2) No explosive spalling occurred with the high strength concrete C 60 used here. This corroborates research studies made previously [7, 8, 10]. This type of spalling is essentially observed in concrete densified by means of ultra fine particles such as silica fume.
3) The diameter of the longitudinal reinforcement $\phi 12$ or $\phi 20$ had no significant influence on surface spalling.
4) Despite surface spalling phenomena, the values obtained for the fire resistance are relatively high. An increase of the load level leads to a significant decrease of the fire resistance.
5) Two simplified calculation procedures developed previously at the University of Liege have been used to evaluate the ultimate capacity of the four columns at elevated temperature. In order to take account of the short length of the specimens, a new formulation has been proposed for the buckling coefficient used in the second method.
6) With this new formulation, both methods lead to acceptable and safe values for design purposes.

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