

PARAMETRIC ASSESSMENT OF FIRE RESISTANCE REQUIREMENTS ON REINFORCEMENT DEMAND IN RC COLUMNS DESIGNED TO EUROCODE 2

ÉVALUATION PARAMÉTRIQUE DES EXIGENCES DE RÉSISTANCE AU FEU SUR LA DEMANDE EN FERRAILLAGE DES POTEAUX EN BA CONÇUS SELON L'EUROCODE 2

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Rania ALLALOU¹, Ferhat FEDGHOUCHE¹¹Laboratoire des Travaux Publics, d'Ingénierie de transport et de l'Environnement (LTPiTE), École Nationale des Travaux Publics Francis Janson (ENSTP), Garidi, Alger, Algérie.

r.allalou@enstp.edu.dz

Abstract- Fire safety is a critical design consideration for reinforced concrete (RC) columns, as their failure can trigger the progressive collapse of structures such as buildings and bridges. While Eurocode 2 provides design methods, the quantitative impact of specifying different fire resistance durations (R-ratings) on the final reinforcement design is not well-documented in practical guides. This paper addresses this gap by conducting a parametric and comparative analysis. Three common column cross-sections (rectangular, square, and circular) are designed for fire resistance requirements ranging from R60 to R240 using the tabulated method of EN 1992-1-2. The results reveal a highly non-linear relationship between fire duration and reinforcement requirements. Furthermore, the study highlights a critical vulnerability of the circular section, which is shown to be impossible to design for high requirements (R240), emphasizing the major influence of geometry on fire performance. This study provides valuable design charts and critical insights that can assist structural engineers in making informed decisions about the significant structural and economic implications of fire resistance requirements.

Keywords: Fire resistance, Reinforced concrete, Column, Eurocode 2, Parametric analysis, Structural design.

Résumé- La sécurité d'incendie est une considération de conception critique pour les poteaux en béton armé (BA), car leur défaillance peut déclencher la ruine progressive de structures telles que les bâtiments et les ponts. Bien que l'Eurocode 2 fournisse des méthodes de conception, l'impact quantitatif de la spécification de différentes durées de résistance au feu (classes R) sur le dimensionnement final du ferrailage n'est pas bien documenté dans les guides pratiques. Cet article comble ce manque en réalisant une analyse paramétrique et comparative. Trois sections transversales de poteaux courantes (rectangulaire, carrée et circulaire) sont dimensionnées pour des exigences de résistance au feu allant de R60 à R240 en utilisant la méthode des valeurs tabulées de l'EN 1992-1-2. Les résultats révèlent une relation fortement non linéaire entre la durée d'exposition au feu et le ferrailage requis. De plus, l'étude met en évidence une vulnérabilité critique de la section circulaire, qui s'avère impossible à dimensionner pour des exigences élevées (R240), soulignant l'influence majeure de la géométrie sur la performance au feu. Cette étude fournit des abaques de conception et des analyses critiques précieuses qui peuvent aider les ingénieurs en structure à prendre des décisions éclairées concernant les implications structurelles et économiques significatives des exigences de résistance au feu.

Mots - clés : Résistance au feu, Béton armé, Poteau, Eurocode 2, Analyse paramétrique, Conception structurelle.

1-Introduction

In most civil engineering structures, from buildings to bridges, reinforced concrete (RC) columns are the primary vertical load-bearing elements [1]. We know that if these columns fail during a fire, they can trigger the progressive collapse of the entire structure [2], which makes their fire safety design critical. Severe fires are a real risk in many scenarios—such as in tunnels, underground car parks, or from a vehicle fire beneath a bridge—and can generate temperatures exceeding 1000°C [3]. Under these extreme conditions, the materials themselves degrade significantly. As documented in, the compressive strength of concrete and the yield strength of steel both drop dramatically [4].

The European standard for concrete structures [5], provides a comprehensive framework for structural fire design. It offers several approaches with varying levels of complexity: advanced calculation models, simplified calculation methods, and a prescriptive tabulated method [6]. The tabulated method is widely used in practice in common design due to its simplicity, as it provides minimum member dimensions and reinforcement cover for standard fire resistance classes without requiring explicit thermo-structural analysis. This approach is often considered conservative, a point highlighted by [7] in their study on bridge deck slabs.

Numerous studies have explored the fire behavior of concrete structures. For instance, [8] improved the Eurocode concrete model by including the effects of transient creep. Others have focused on the performance of specific structural elements, such as high-performance concrete columns. [9]. More recently, a comprehensive state-of-the-art review by Wang [10] synthesized the results of 148 tests and confirmed that cross-sectional geometry is one of the most influential parameters on the fire resistance of RC columns. However, while the methods themselves are well-documented, there is a lack of published quantitative studies that systematically investigate the sensitivity of the final reinforcement design to the specified fire resistance duration, particularly for columns.

Engineers in the preliminary design phase often lack clear guidance on the highly non-linear structural and economic implications of choosing a higher R-rating. This choice can lead to a dramatic increase in reinforcement requirements, as the design must account not only for material degradation but also for significant second-order effects, such as fire-induced bending moments in columns. [11].

Therefore, the objective of this paper is to conduct a parametric and comparative analysis to quantify the impact of fire resistance duration on the reinforcement required for RC columns. This study investigates three common cross-sections: rectangular, square, and circular, with dimensions and loading conditions representative of those found in civil engineering structures. The aim is twofold: firstly, to develop design charts that illustrate the highly non-linear trade-offs between fire safety levels and steel reinforcement economy. Secondly, and more critically, it aims to assess the influence of geometry on structural fire performance, highlighting a significant design vulnerability for the circular column when using prescriptive code methods.

2- Methodology

To quantify the impact of fire resistance duration on the reinforcement of RC columns, we conducted a parametric and comparative analysis. Our approach is based on Method A (the tabulated method) from Eurocode 2. [5].

2.1- Case Studies

We selected three common column cross-sections, with dimensions that are representative of those typically found in medium-span reinforced concrete bridge structures:

- Case 1: A rectangular column with dimensions $b=300$ mm and $h=600$ mm.
- Case 2: A square column with dimensions $b=h=600$ mm.
- Case 3: A circular column with a diameter $D=500$ mm.

For all three cases, the material properties were kept constant: a concrete strength class of C25/30 ($f_{ck} = 25$ MPa, with siliceous aggregates) and reinforcing steel with a characteristic yield strength of $f_{yk} = 500$ MPa (Class B or C).

2.2- Fire Design Method and Assumptions

The design was performed using Method A, as described in Section 5 of EN 1992-1-2 [5]. This prescriptive approach relies on a key assumption regarding the fire exposure scenario, which dictates how the physical phenomenon is modeled.

For this study, we adopted the unsymmetrical exposure scenario (one-sided fire). This choice is fundamental because it generates a unilateral thermal gradient, causing the column to bow ("thermal bowing") and thus inducing a significant second-order bending moment. This phenomenon is accounted for in our model by applying an explicit combined bending and compression load case (N+M) [11]. In contrast, a symmetrical scenario (4-sided fire) would only lead to a reduction in the axial compression capacity, which is generally less demanding.

We chose this conservative scenario as it is representative of critical real-world cases (e.g., facade columns, bridge piers). The specific technical assumptions for the application of Method A are as follows:

- The temperature-time curve follows the standard ISO 834 fire.
- The axis distance 'a' for each fire resistance duration was determined from Table 5.2a of the standard, by selecting the values from column 5, which correspond to a column exposed on one side with a load level of $\mu_{fi} = 0.7$.

2.3- Loading Conditions

To isolate the effect of the fire duration, the design internal forces under fire conditions were kept constants for all analyses, based on the accidental load combination specified in Eurocode 0. The design internal forces were:

- Axial Force, $N_{Ed,fi} = 0.4$ MN.
- Bending Moment, $M_{Ed,fi} = 0.28$ MN·m.

2.4- Parametric Analysis

The primary variable in this study is the fire resistance requirement. The analysis was performed for five distinct standard durations: R60, R90, R120, R180, and R240. For each combination of geometry and fire duration, the minimum required total reinforcement area (A_s) was calculated. This area was then expressed as a reinforcement ratio ($\rho = A_s / A_c$, where A_c is the gross concrete cross-sectional area).

3- Results

The analysis was conducted on the three column cross-sections. The results of the parametric analysis for the rectangular and square sections are presented first, followed by the analysis of the critical case of the circular section.

3.1- Parametric Analysis of Rectangular and Square Sections

The quantitative results of the parametric analysis for the rectangular and square columns are summarized in Tab.1 and visualized in Fig. 1.

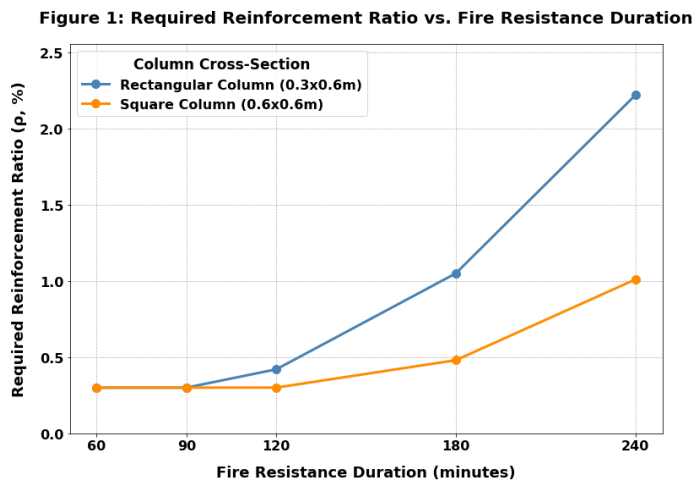
Table1 : Required Reinforcement Ratio (ρ , in %) for Different Fire Resistance Durations.

Tableau 1 : Ratio de Ferrailage Requis (ρ , en %) pour Différentes Durées de Résistance au Feu.

Fire Resistance	Axis Distance 'a' (mm)	Rectangular Column (0.3x0.6m)	Square Column (0.6x0.6m)
R60	25	0,30	0,30
		% (minimum) 4 Ø14	% (minimum) 8 Ø14
R90	25	0,30	0,30
		% (minimum) 4 Ø14	% (minimum) 8 Ø14
R120	35	0,42 %	0,30
		4 Ø16	% (minimum) 8 Ø14
R180	55	1,05 %	0,48 %
		8 Ø20	8 Ø20
R240	70	2,22 %	1,01 %
		10 Ø25	8 Ø25

Figure 1: Required Reinforcement Ratio vs. Fire Resistance Duration for Rectangular and Square Columns.

Figure 1 : Ratio de Ferrailage Requis vs. Durée de Résistance au Feu pour les Poteaux Rectangulaire et Carré.



From these data, several factual observations can be made: 1) Existence of an Initial Plateau: For fire resistance requirements up to R90 for the rectangular column and up to R120 for the square column, there is no impact on the final design. The reinforcement required for the fire condition does not exceed the regulatory minimum reinforcement ($\rho_{\min} \approx 0.30\%$), which therefore remains the governing design criterion. 2) A Critical Inflection Point: Beyond this plateau, the steel demand increases exponentially. For the rectangular column, the reinforcement ratio is multiplied by a factor of more than 7 (from 0.30% to 2.22%) when increasing the requirement from R90 to R240. 3) Significant Influence of Geometry: The square cross-section demonstrates significantly greater robustness. The "take-off" point for its reinforcement curve is delayed until R180. At the R240 requirement, the steel ratio needed for the rectangular column (2.22%) is more than double that required for the square column (1.01%) to resist the same internal forces.

3.2- Critical Case: Design Failure of the Circular Section

The analysis of the circular section ($D=500$ mm) for the highest fire resistance

requirement (R240) revealed a design failure. The results are presented in Tab.2.

Table 2: Design Results for the Circular Column at R240.

Tableau 2 : Résultats du dimensionnement pour le poteau circulaire à R240.

Parameter	Required Value	Maximum Allowed Value (EC2)	Rebar Arrangement	Status
Steel Area A_s	92.9 cm ²	78.5 cm ²	Required: 19 Ø25 Max. plausible: 16 Ø25	FAILURE
Reinforcement Ratio ρ	4.73%	4.00%	-	FAILURE

The required reinforcement ratio to ensure fire stability ($\rho = 4.73\%$) exceeds the maximum technological limit allowed by Eurocode 2 ($\rho_{\max} = 4.00\%$). Therefore, the design of this column is not feasible under the tabulated method without modifying its dimensions.

4- Discussion

The presented results reveal clear trends with significant implications for the design of reinforced concrete columns subjected to fire. The following discussion aims to interpret these findings by contextualizing them within the fundamental principles of structural fire behavior and existing literature.

4.1- The Threshold Effect and Exponential Reinforcement Increase

The existence of an initial plateau, where fire design has no impact, is an important finding. It signifies that for moderate fire resistance requirements (R60-R90), the inherent robustness and the minimum reinforcement requirements of Eurocode 2 for ambient temperature design are often sufficient. However, the inflection point observed around R120 marks a paradigm shift.

The exponential growth in reinforcement beyond this threshold can be explained by the combination of two penalizing

phenomena. The first is the accelerated material degradation at elevated temperatures, a phenomenon extensively documented by [4]. The second is a direct consequence of the Eurocode's tabulated method: to protect the reinforcement during longer fires, the code mandates a significant increase in the axis distance 'a'. This increased cover reduces the internal lever arm of the cross-section, making it mechanically less efficient at resisting the bending moment, as emphasized by fundamental fire design principles [11]. It is this "double penalty"—weaker materials and a geometrically less efficient section—that causes the dramatic increase in the required reinforcement.

4.2- Comparative Efficiency of Rectangular and Square Geometries

Our analysis has quantitatively demonstrated that the square cross-section is structurally more robust under fire than the rectangular one. The required steel ratio for the square column is approximately half that of the rectangular column at R240. This superior performance is consistent with studies on heat transfer in concrete elements. A more massive and less slender section, such as the square column, possesses a greater thermal inertia, which slows the penetration of heat towards the core of the element [5]. Furthermore, to resist the fire-induced bending moment, a wider section provides better mechanical efficiency by maintaining a larger effective compression zone.

4.3- Critical Vulnerability of the Circular Section

The design failure of the circular column for the R240 requirement is the most critical finding of this study. It demonstrates that a cross-section, while perfectly valid at ambient temperature, can become impossible to design under the prescriptive rules of Eurocode 2's Method A. This vulnerability is explained by the lower mechanical efficiency of the circular geometry in resisting fire-induced combined bending and compression. Unlike a square section, the material is less effectively distributed to create an optimal internal lever arm. This finding is consistent with research

showing that the fire resistance of RC columns is highly sensitive to the cross-sectional shape, especially under eccentric loading [12]. Furthermore, it aligns with large-scale statistical analyses, such as that of [10], which rank 'section shape' among the parameters with a significant influence. Our study, however, takes this a step further by demonstrating that, within the framework of the Eurocode's tabulated method, this geometrical parameter can be the direct cause of a design failure. This result highlights a potential design risk that could be overlooked, particularly in architectural projects where circular columns are often favored for aesthetic reasons.

4.4- Implications for Design and Engineering Practice

These findings have direct implications for engineering practice. A) Preliminary Design: The design charts presented in this paper can serve as a decision-making tool during the preliminary design phase, addressing a need identified by [13] who emphasizes the importance of simplified and practical approaches. B) Design Optimization: The study suggests that for requirements exceeding R120, it may be more structurally sound to increase the cross-sectional dimensions rather than passively increasing the reinforcement ratio. This aligns with the general philosophy of fire design, where increasing cover and dimensions is considered the most effective protective measure [6]. C) Limitations of Prescriptive Design: The failure of the circular case highlights the limits of tabulated methods [7]. For potentially vulnerable geometries or high fire resistance requirements, it becomes imperative to turn to a more refined analysis using Eurocode 2's advanced calculation methods, which can account for complex phenomena like transient creep [8], and could lead to an optimized and feasible design.

5- Conclusion

This paper presented a parametric and comparative analysis of the impact of fire resistance duration on the required reinforcement for reinforced concrete columns,

using the tabulated method from Eurocode 2. The study is based entirely on the prescriptive tabulated method from Eurocode 2 (Method A), a simplified and often conservative approach. The study quantified the highly non-linear relationship between these two parameters and led to the following key findings: 1) A threshold effect was identified: For moderate fire resistance requirements (up to R120), the regulatory minimum reinforcement is often sufficient, and the impact of the fire design remains limited. 2) An exponential increase in reinforcement is observed for high requirements: Beyond this threshold, the steel demand grows dramatically, especially for the rectangular section, due to the combined effect of material degradation and the reduction in the mechanical efficiency of the cross-section. 3) Cross-section geometry is a critical performance factor: The square section was found to be significantly more robust than the rectangular one. More importantly, the circular section demonstrated a critical vulnerability, leading to a design failure for the R240 requirement under the code's prescriptive rules.

In conclusion, this study provides practical design charts that illustrate the considerable structural and economic implications of high fire resistance requirements. Furthermore, it highlights the limitations of prescriptive approaches and emphasizes that the choice of geometry is a first-order design parameter for ensuring the fire safety of reinforced concrete columns.

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