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# The role of concrete cover on the load bearing capacity of reinforced concrete beams in fire: a finite element analysis

**J. Szép [1], M. Habashneh[1] and M.M. Rad [1]**

**Department of Structural and Geotechnical Engineering, Széchenyi István University, Győr, Hungary**

## Abstract

This paper investigates how high temperatures affect the load-bearing capacity of reinforced concrete beams using finite element analysis. The study aims to address a critical knowledge gap in the design of concrete buildings that are susceptible to fire and help prevent overall structure failure. The research focuses on uncertainties associated with the distribution of temperature within reinforced concrete beams, with the aim of providing valuable insights that can enhance the safety and reliability of concrete structures under fire conditions. The process of modelling reinforced concrete beams at high temperatures involved the use of reliability analysis, which took into account the uncertainty surrounding the distribution of temperature. To regulate the process, a limit in the form of a reliability index was introduced. To simulate the performance of the considered beams under high temperatures, a finite element model that had been validated was utilized, before being used to investigate the effect of different concrete cover thicknesses and heat distribution scenarios. The findings indicate that increasing the concrete cover can lead to a higher load capacity of the beams, with higher maximum temperatures achieved when heat is applied to all three surfaces of the beams. Moreover, the study considers the effect of uncertainties in temperature distribution, which results in different load capacities for different concrete covers.

**Keywords:** reinforced concrete, elevated temperature, finite element, heat distribution.

# 1 Introduction

The utilization of concrete is extensive in the construction industry because of its strength, durability, and fire resistance. However, high temperatures from fire can cause stiffness reduction and degradation of material properties, leading to the potential failure of structures. Therefore, understanding the performance of concrete when exposed to fire is critical to designing robust buildings and preventing overall failure. As a result, many studies have investigated the behavior of reinforced beams under fire conditions [1,2]. Hlavička et al. [3] analyzed the mechanical characteristics of residual fracture by examining various heating loads.

Researchers have recently shown increasing interest in using finite modelling to accurately simulate the performance of concrete under the effects of fire [4,5]. Borst and Peeters [6] proposed a finite element model at elevated temperatures that incorporates the highly nonlinear material behavior of concrete.

In the case of reinforcing rebars, there have been numerous studies examining the influence of high temperatures on the steel. One such study by Felicetti et al. [7] explored the behavior of steel bars following exposure to high temperatures. Additionally, in his research, Dotreppe [8] showed how temperature affects the mechanical properties of tempered steels.

In order to achieve the goal of developing structural models that satisfy safety and performance requirements, it is important to take into account any uncertainties that may arise from the material properties or applied loading conditions during the design phase in structural engineering [9,10]. Słowik et al. [11] conducted a reliability analysis on reinforced concrete beams, where the experimental results were utilized to evaluate the safety factors of the shear resistance of the designed beams. Also, a computational model that incorporates reliability analysis to simulate the behavior of reinforced concrete beams subjected to elevated temperatures was done by Szép et al. [12].

In this paper, the load bearing capacity of reinforced concrete beams which are subjected to fire is investigated. To achieve this, a finite element analysis was conducted using the commercial software ABAQUS[13], with the model first validated according to the work of El-Hawary et al.[14] before increasing the concrete cover (CC) to examine the behavior of the beams in case of fire. Furthermore, the proposed work focuses on uncertainties that could be associated with the distribution of temperature within the reinforced concrete beams. Our research seeks to address a critical knowledge gap in the design of concrete buildings that are susceptible to fire and help prevent the overall failure of such structures. By analyzing the effect of uncertain elevated temperature and CC on the load-bearing capacity of reinforced concrete beams, this paper aims to provide valuable insights that can enhance the safety and reliability of concrete structures under fire conditions.

## 2 Methods

Models of the reinforced concrete (RC) beams were done by using commercially available software ABAQUS® [13] and employ finite element (FE) analysis. To develop the finite element models, we conducted heat transfer analysis first and then performed stress analysis based on the temperature distribution obtained from the first step.

This proposed work utilized the concrete damaged plasticity model (CDPM) found in the ABAQUS/Standard manual [13] to imitate the concrete material's response to varying temperatures, including ambient and elevated temperatures. Table 1 contains the assumed data for the CDPM, including the softening parameter (K), the ratio of initial equibiaxial compressive yield ($f_{b0}/f_{c0}$), dilation angle, eccentricity, and viscosity parameter (μ).

| Dilation angle | $\mu$ | $f_{b0}/f_{c0}$ | Eccentricity | K |
|---|---|---|---|---|
| 30 | 0.005 | 1.16 | 0.1 | 0.667 |

Table 1: Input data for CDPM

Compression stress-strain curves at elevated temperatures were considered according to Eurocode 1992-1-2 [15] to simulate the concrete material. The thermal expansion coefficients, thermal conductivity, specific heat, and density are crucial parameters for heat transfer analysis which were also calculated using the temperature-dependent thermal equations suggested by Eurocode 1992-1-2 [15].

## 3 Results

This section comprises three parts. First, we validate the model using finite element analysis (FEA) in accordance with El-Hawary et al. [14]. Second, new models for three different concrete covers with fire heat applied to three surfaces are proposed. Finally, a numerical investigation of reinforced concrete beams under uncertainty of the applied heat is considered. The element mesh sizes were chosen carefully to achieve accurate results within a reasonable computational time and was determined to be 15 mm.

To analyse heat transfer within the concrete and steel bars, we used DC3D8 (8-node linear brick element) and DC1D2 (2-node link element), respectively. When modelling the reinforced concrete beam for stress analysis, concrete was modelled using eight-node first-order hexahedral (C3D8) elements and 2-node linear displacement element (T3D2) for steel. We utilized finite element analysis to investigate the nonlinear behavior of the beams and adopted the damage plasticity model for this purpose. Figure 1 illustrates the geometry, cross-section, boundaries, and loading conditions of the first beam which was considered for validation. The geometry of the beams was length=1800 mm, with a cross-sectional area of (120mm × 200mm). The considered material properties of steel reinforcing bars in the case of ambient temperature are considered in Table 2. Noting that at room temperature, the concrete's compressive strength was 25 MPa and its young's modulus (*E*) was 23.5 GPa.

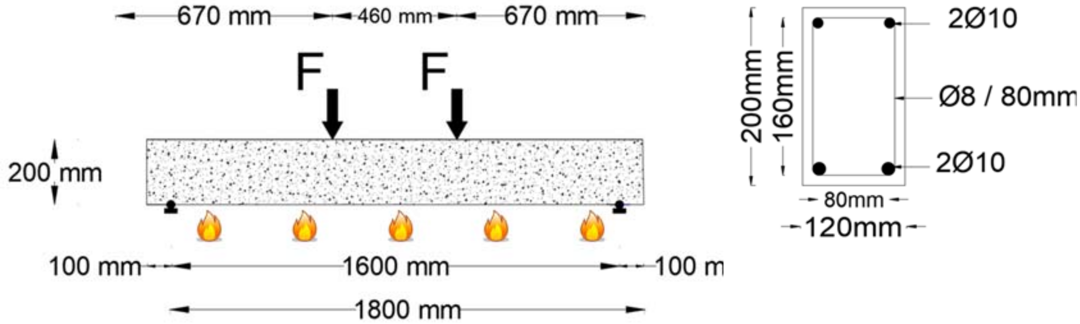



Figure 1. Considered beam with its geometry, cross-section and loading conditions

| Reinforcement | ϕ (mm) | $f_y$ (MPa) | *E* (MPa) |
|---|---|---|---|
| Top reinforcement | 10 | 235 | 200000 |
| Bottom reinforcement | 10 | 358 | 200000 |
| Stirrups | 8 | 235 | 200000 |

Table 2: Considered reinforcement in the case of ambient temperature

The considered model was verified according to El-Hawary et al. [14]. It is worth mentioning that the beam was exposed to fire from the lower part for 120 minutes. Besides, Figure 2 shows the temperature distribution within the cross-section of the considered beam which resulted from the heat transfer analysis in which the temperature was varied from 27 ºC at the top layer to 600 ºC at the bottom layer of the beam.

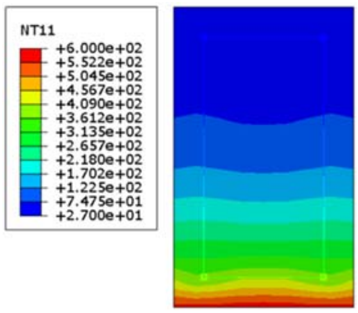
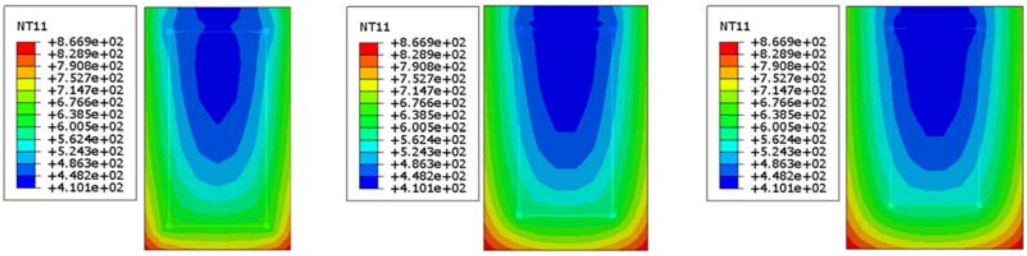



Figure 2. Resulted distribution of temperature

As mentioned earlier, three reinforced concrete beams with concrete covers of 20 mm, 30 mm, and 40 mm, respectively, were considered. It was assumed that the fire heat would be applied to three surfaces of the beams. Figure 3 presents the temperature distribution obtained for each case. It is worth mentioning that when heat is applied to all three surfaces, the maximum temperature achieved is higher than the value obtained when heat is only applied to the bottom surface, as shown in the temperature distribution plots. Moreover, we can observe that as the thickness of the concrete cover increases, the maximum temperature within the cross-section decreases. Table 3 represents the obtained ultimate load values for each case, where the load capacity of the beams increases as the concrete cover increases.




(a) CC=20mm (b) CC =30mm (c) CC =40mm

Figure 3. Temperature distributions according to different concrete cover

| CC (mm) | $F_{ultimate}$ – (kN) |
|---|---|
| 20 | 19 |
| 30 | 22 |
| 40 | 28.8 |

Table 3: Resulted load in the cases of various concrete cover

The last part of this section considers the uncertainties in temperature distributions. As a result, different temperature cases were considered for each of the three surfaces with a variation of 15% from the previously considered distribution. Figure 4 provides an illustration of the technique used for the beams with 20 mm cover. It can be observed that different temperature distribution counters resulted from considering a 15% variation. Using the reliability index ($\beta$) in engineering designs has several advantages. One benefit is that it helps to standardize engineering practices in many different applications of reliability analysis. As a result, various engineering standards, particularly structural standards such as EN1990 [16], provide a wide range of target values for controlling $\beta$.

A nonlinear code was developed by utilizing $\beta$ in which the reliability limit is constructed as:

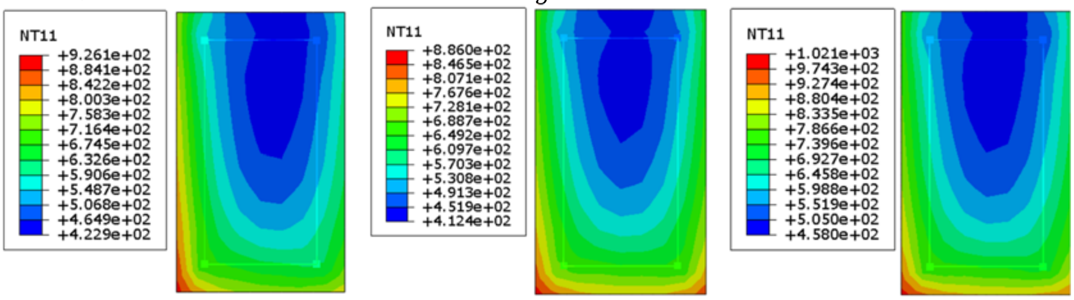
$$\beta_{target} - \beta_{calc} \leq 0 \tag{1}$$

In this context, $\beta_{calc}$ refers to the reliability index calculated for each iteration, and the program will stop running once $\beta_{calc}$ reaches the desired value of reliability index ($\beta_{target}$), as this condition will have been met. The following formulas are employed to calculate $\beta_{target}$ and $\beta_{calc}$:

$$\beta_{target} = -\Phi^{-1}\left(P_{f,target}\right) \tag{2}$$

$$\beta_{calc} = -\Phi^{-1}\left(P_{f,calc}\right) \tag{3}$$

where $\Phi^{-1}$ refers to the inverse of the normal distribution function and $P_f$ is the probability of failure. Consequently, Table 4 shows the obtained ultimate load capacity for the different covers when $\beta_{target} = 3.50$.




(a) first amplitude (b) second amplitude (c) third amplitude

Figure 4. Various temperature distributions when concrete cover = 20 mm

| CC (mm) | $F_{ultimate}$ – (kN) |
|---|---|
| 20 | 20 |
| 30 | 22.6 |
| 40 | 29.3 |

Table 4: Resulted load in the cases of various concrete cover according to the first amplitude

## 4 Conclusions and Contributions

The effect of elevated temperatures on the load-bearing capacity of reinforced concrete beams was investigated. The finite element analysis was conducted using ABAQUS software and the model was validated based on the work of El-Hawary et al. [13]. The study also proposed new models for different concrete covers with fire heat applied to three surfaces and investigated the beams' behavior under uncertainty in the distribution of heat. The results showed that as the thickness of the concrete cover increases, the maximum temperature within the cross-section decreases, and the load capacity of the reinforced concrete beams increases. Additionally, the research revealed that considering a 15% variation in the distribution of temperature results in different temperature distributions that affect the ultimate load capacity of the beams. The findings of this study can help improve the safety and reliability of concrete structures under fire conditions, and the proposed models and techniques can be useful for future research in this area.

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