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Effectiveness of composite jacket strengthening of reinforced concrete columns under eccentric load after fire exposure

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Dimia Mohammed Salah
ORCID: https://orcid.org/0000-0002-1847-105X
LGC-ROI, Department of Civil Engineering Faculty of Technology University of Batna 2, Batna, Algeria
E-mail: ms.dimia@univ-batna2.dz
Belakhdar Ahmed Rafik
ORCID: https://orcid.org/0000-0003-4286-2349
Mining Laboratory, Civil Engineering Department, Larbi Tebessi University, Tebessa 12002, Algeria
E-mail: ahmedrafik.belakhdar@univ-tebessa.dz
Rabehi Rachid
ORCID: https://orcid.org/0000-0002-9398-7291
Laboratory of Development in Mechanics and Materials (LDMM) - University of Djelfa, Algeria
E-mail: rachid.rabehi@univ-djelfa.dz
Baghdadi Mohamed
ORCID: https://orcid.org/0009-0000-7064-1055
LGC-ROI, Department of Civil Engineering Faculty of Technology University of Batna 2, Batna, Algeria
E-mail: m.baghdadi@univ-batna2.dz
Antonio Marcos de Oliveira Siqueira
ORCID: https://orcid.org/0000-0001-9334-0394
Universidade Federal de Viçosa, Brazil
E-mail: antonio.siqueira@ufv.br
Júlio César Costa Campos
ORCID: https://orcid.org/0000-0002-9488-8164
Universidade Federal de Viçosa, Brazil
E-mail: julio.campos@ufv.br

Abstract

This research presents a numerical study of the behavior of reinforced columns with a square cross section subjected to eccentric stress under the influence of fire. As a first step, the study examined the effects of exposing columns to fire with an increasing temperature up to 600°C for 60 minutes under eccentric loading conditions (e/b = 0, 0.1, 0.15, 0.20). As a second step, the columns were strengthened with a 100-mm concrete jacket and shirts supported by a steel structure consisting of vertical angles and horizontal spreaders to determine the effectiveness of the strengthening in increasing the resistance of these damaged columns. After the fire, this type of reinforcement is considered better than reinforcement with concrete shirts, reinforcement with carbon fiber-reinforced polymers, and others because of its advantages. There are many advantages to the ease and speed of implementation. The results showed that the columns that were repaired and strengthened after the fire with the steel structure casing led to a significant increase in resistance.

It was found that the greater the thickness of the steel structure, the greater the resistance, and that the greater the eccentricity ratio, the lower the resistance as well as the collapse load.

Keywords: Reinforced concrete column. Fire. Eccentricity load. Numerical investigation. Jacket.

1. Introduction

Concrete structures are ubiquitous worldwide, representing some of the most common types of construction. As a result, the examination of how these structures behave and respond to various forces, including the potential for collapse, is of paramount importance. Among the myriad threats that structures face, fires and earthquakes stand out as two of the most formidable challenges. These natural and man-made disasters can have devastating consequences for concrete buildings and infrastructure, making them critical areas of study and concern for architects, engineers, and safety experts. Understanding how concrete structures perform under the duress of fires and seismic events is essential for designing resilient and safe buildings in regions prone to these risks. In general, it is considered that concrete elements in construction perform better during fires than exposed steel members. According to (Zhaodong *et al*., 2018), the main cause of this is concrete's limited thermal conductivity. In 2008, the Concrete Industry conducted a survey concluding that concrete buildings rarely collapse as a result of fire or high-temperature disturbances, which provides additional support for this notion. This year's Grenfell Tower fire also functions as an illustration that supports this conclusion (Qiu *et al*., 2021). Steel jacketing has strengthened structural columns since the 1980s. 1986 debuted the "tubed column," which supports steel jacketing. Enclosing the column in a steel jacket or casing improves its load-carrying capability and structural performance. Since then, steel jacketing has been enhanced as a retrofitting procedure to strengthen and stabilize old columns (Xiang *et al*., 2014; Zhou *et al*., 2019). Currently, the steel jacketing technique is utilized for building worldwide, particularly in the USA, Japan, and Czech Republic. Steel jacketing was initially used for seismic retrofitting and RC column shear strength. Steel jacketing provided passive confinement, like continuous hoop reinforcement. At rectangular RC columns, lateral motion buckled the steel jacketing at the plastic hinge zone. Experiments proved this (Priestley *et al*., 1994).

Also, Xiao (Xiao *et al*., 2003) used stiffeners to prevent plastic hinge buckling. These stiffeners prevented buckling and improved steel jacketing in rectangular RC columns. Cartel developed an angle-and-stirrup steel jacketing method (Cirtek *et al*., 2001a, 2001b). This technology reinforced around 5000 European RC columns. Steel jacketing has emerged to strengthen RC columns, especially in seismic retrofitting. Over time, it has been improved to solve particular issues and increase performance. There are numerous experimental and analytical studies on the restoration of fire-damaged columns (Chen *et al*., 2019; Lai *et al*., 2016).

Concrete-reinforced structures that are exposed to a fire rarely collapse. Resistance recovery following a fire improves reinforced concrete pillars, walls, and columns. This is primarily attributable to the concrete's retained mechanical properties and bearing capacity following the fire duration. A literature study found that a structure's load-bearing capacity falls during heating, reaches a minimum, then recovers in part or completely after chilling (Gernay *et al*., 2015). Variations in load capacity can cause a building to fail during the cooling phase of a fire rather than the high-temperature phase. Material mechanical and thermal inertia property deterioration are the main causes of these discrepancies. Thermal inertia is the tendency of construction materials like steel and concrete to hold heat and postpone cooling. This chilling process lowers the materials' load-carrying capability. Prolonged exposure to high temperatures can also degrade the material's mechanical qualities, such as strength and stiffness. Due to thermal inertia and material degradation, structural failure during a fire's cooling phase is possible, reducing load capacity (Lakhani *et al*., 2019; Gernay *et al*., 2011).

Numerous studies have been conducted to investigate the decrease in load-bearing capacity of reinforced concrete (RC) columns after fire exposure. These studies have explored various parameters to understand their influence on the behavior of fire-damaged columns. The parameters commonly considered include geometric characteristics, support conditions, heating conditions, load levels under fire, etc. By investigating these parameters, researchers aim to gain insights into the behavior of RC columns under fire conditions and develop guidelines for assessing the residual load-bearing capacity of fire-damaged structures (Kodur *et al*., 2013; Li *et al*., 2019; Franssen *et al*., 2001). In their study, Demir *et al*. studied the impacts of post-fire duration on residual rigidity and discovered that it had a greater impact than on residual lateral load capacity (Demir *et al*., 2020). Chen *et al*. found 27% and 38% power losses after two and four hours of heating, respectively. Extended fire exposure slowed the steel bars' strength recovery after cooling (Chen *et al*., 2009).

The researchers concluded in (Ezz-Eldeen *et al*., 2016) through their study that the use of steel structure technology to reinforce the reinforced concrete columns led to an increase in the bearing capacity of the columns subjected to central pressure and that increasing the area of coverage of the steel structure of the reinforced column as well as increasing the cross-sectional area of the vertical angles of the steel structure led to an increase in the load-bearing capacity of the reinforced columns, as well as that by increasing the eccentrically loaded ratio of the reinforced columns and the non-reinforced columns, the resistance of the columns decreases. And in the references (Elsamny *et al*., 2013; Tarabia *et al*., 2014), they concluded that the number of horizontal spacing’s did not significantly affect the bearing capacity of the columns, and this can be attributed to the large spacing between the spacing’s. It also showed the significant effect of increasing the dimensions of the vertical angles on the bearing capacity of the supported column.

In the references (Giménez *et al*., 2009; Belal *et al*., 2015) the researchers concluded that all the tested elements showed a significant improvement in compressive strength and vertical displacement at collapse. Whereas, the value of the collapse load reached by the tested reinforced columns was less than the sum of the values of the collapse loads for the concrete columns, and there was no significant difference in the behavior of the columns supported by the structure and the steel structure calculated theoretically in the case of using epoxy or cement as an adhesive between the steel structure and the surface concrete. A number of studies were conducted to strengthen the columns after the fire, between 2011 and 2013, the University of Manchester conducted a study investigating the mechanical performance of fire-damaged RC columns repaired with fiber-reinforced polymer (FRP) jackets using a constant heat rate of 150°C per hour.

Experiments were conducted to determine how the repair materials and cross-section geometry affect the efficacy of seismic performance and axial-compression (Lamine *et al*., 2023; Benzerga *et al*., 2023; Yaqub *et al*., 2011). In the references (Belakhdar *et al*., 2023; Mohammed *et al*., 2022) investigates the performance and strengthening of reinforced concrete columns after fire exposure by RC jacket. The results show that the axial load carrying capacity of the columns decreases with increasing fire duration, but using a reinforced concrete jacket can improve the post-fire behavior and enhance the axial load capacity. A limited number of studies have tried to estimate the performance of the post-fire capacity of concrete columns under eccentrically loaded conditions (Liu *et al*., 2016). This paper makes a significant contribution to enhancing the reliability and effectiveness of a strengthening technique used to evaluate fire-damaged reinforced concrete (RC) structures, particularly when they are subjected to eccentric loading conditions and are enclosed by a Steel Structure jacket. The factors considered in this research include:

- The bearing capacity of columns after combustion;
- Influence of ratio eccentricity on column behavior during the fire phase (e/b = 0, 0.1, 0.15, 0.20);
- Strengthening the reinforced concrete column after subjected to fire by the RC jacket;

2. Methodology

The central aim of this research project is to examine the response of reinforced concrete (RC) columns to fire exposure. To accomplish this objective, the study utilizes RC columns characterized by cross-sections measuring 0.3 meters by 0.3 meters, a cover thickness of 30 mm, and a height extending to 3 meters. These columns are systematically exposed to parametric fires of different durations, with a specific emphasis on a significant 60-minute fire exposure period. The primary focus of the research is to assess how the load-bearing capacity of these columns is reduced when they are exposed to fire, all while applying axial loading conditions during testing. Following the fire exposure, one of the columns undergoes post-fire repair and strengthening using a technique called composite jacketing. This method involves the application of 10 cm-thick concrete jackets supported by a steel structure consisting of vertical angles and horizontal spreaders, each with a thickness of 10 mm. The SAFIR computer program is used to analyze the structural behavior and response of these columns in fire scenarios. The research aims to provide valuable insights into the behavior of reinforced concrete columns during and after exposure to fire. Ultimately, the findings of this study will contribute to the development of effective fire-resistant structural solutions, which can enhance the safety and resilience of buildings and infrastructure.

3. Development of finite element models

This study replicated reinforced concrete (RC) column post-fire reaction using 2D nonlinear numerical analysis. The SAFIR (Franssen, 2005) computer program was used to simulate the structural behavior of materials and components under fire and high-temperature situations. SAFIR was likely used to complete the investigation on how RC columns react to fire, revealing their structural integrity and performance. This article employs numerical calculations to conduct a nonlinear thermo mechanical analysis of materials susceptible to fire. The program used for these calculations enables the comprehensive assessment of how these materials behave when subjected to the combined effects of temperature and mechanical forces.

This approach allows for a thorough assessment of how these columns respond to fire-induced stresses, providing valuable insights into their behavior and structural integrity in fire conditions. The application supports nonlinear thermo mechanical analysis of materials prone to fire, including concrete, steel, and composite steel structures. The primary aim of this research is to explore the response of reinforced concrete columns when subjected to fire conditions. The emphasis is placed on scrutinizing different elements that impact the behavior of these columns during a fire event. The research uses a square reinforced concrete column that is 300 cm tall and has a cross-section of 30 x 30 cm^2. The longitudinal reinforcement consists of 8Φ12 mm (Figure 1), and there is a 3 cm cover on the longitudinal reinforcement.

The concrete employed in the column exhibits a compressive strength of 25 MPa, and the reinforcement has a yield stress of 400 MPa. For static analysis Before exposing the columns to fire conditions, a structural investigation, likely through static analysis, is performed on control specimens. These control specimens are not exposed to fire and serve as a reference point for evaluating the effects of the fire exposure. The column samples are exposed to a fire for a period of 60 minutes at a temperature of 600 degrees Celsius. This fire exposure likely simulates real-world fire conditions to assess how the columns perform under high-temperature and fire-related stress boundaries. Conditions To replicate real-world conditions, the research columns are constrained at both the bottom and the top during the fire exposure simulation. This means that they are free to move along the Y-axis, representing vertical movement, while having constraints along the Z and X axes, which restrict lateral and horizontal movement. The research aims to provide insights into how reinforced concrete columns behave when subjected to fire, considering factors such as temperature, material properties, and structural design.

The use of the finite element method allows for a detailed and numerical analysis of these behaviors, which can be valuable for designing fire-resistant or fire-protected structures, as shown in Figure 2. The initial boundary condition for concrete defines its properties and behavior at room temperature, affecting its strength, durability, and other properties in engineering and construction applications, typically around 20-25 degrees Celsius (20°C).

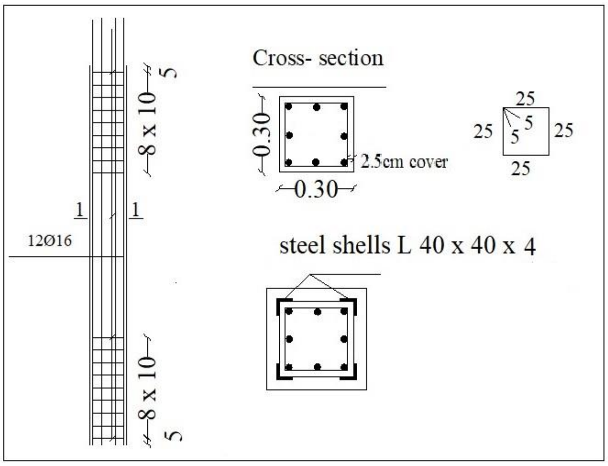

Figure 1 – Geometry and reinforcement details.

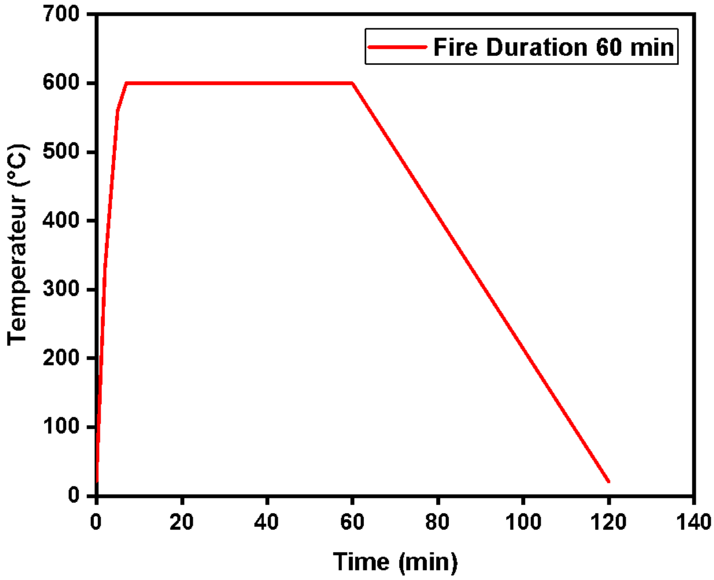

Figure 2 – Temperature-time curve for 600°C exposed columns during a 60-minute fire.

4. Results and discussion

4.1 Temperature evolution

Figures 3 and 4 depict the temperature variations throughout the various stages of a column's exposure to fire and subsequent cooling. Utilizing the Finite Element Analysis (SAFIR FEA) program, the utmost anticipated temperatures were accurately predicted. These temperatures were determined by performing a thermal transmission analysis on a 30 x 30 cm square meter diagonal cross-section extending from point 1 to point 5 in the column. Due to the propagation of the thermal wave, it is crucial to note that the temperatures at different locations within the column do not correspond to the same time; they vary as the heat moves through the structure. This analysis facilitates understanding of the dynamic thermal behavior of the column during and after exposure to a fire.

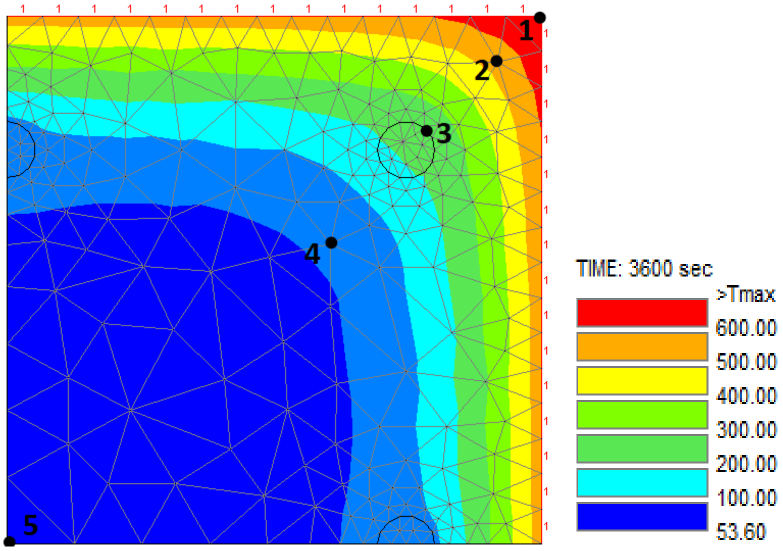

Figure 3 – The predicted section maximum temperature distribution after 60 min (Quarter cross-section with rebar locations).

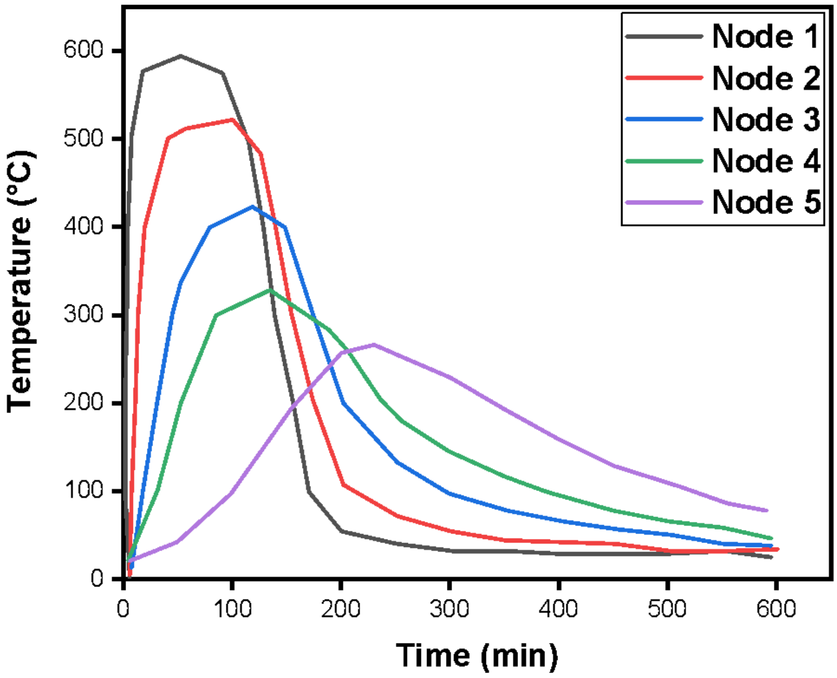

Figure 4 – Temperature evolution within 60 minutes of fire exposure of the cross-section diagonal (from point 1 to point 5).

4.2 Effect of eccentricity ratio (e/b)

As the duration of exposure to fire and the temperature increase, the behavior of concrete undergoes significant changes. Concrete is a widely used construction material, but it is vulnerable to high temperatures, and its structural integrity can be compromised in a fire, there is a noticeable reduction in the load capacity (Pu). At an initial temperature of 20°C, the load capacity stands at 2445 kN. However, as both the eccentricity ratio (e/b) and the temperature rise, the load capacity decreases to 43.2%, 52.88%, 59.60%, and 65.03% of its original value for e/b ratios of 0, 0.1, 0.15, and 0.2, respectively. This pattern underscores the sensitivity of the structural element to increased temperatures and varying degrees of load eccentricity. In the context of fire engineering, these findings emphasize the importance of materials and structural designs capable of withstanding the challenges posed by elevated temperatures and eccentric loading to ensure the safety and integrity of the structure.

Table 1 – Numerical findings of 600°C-exposed RC columns with different eccentricity ratios.

Fire temperature	Eccentricity ratio (e/b)	Load capacity P_u (KN)	Axial deformation Δu (mm) at ultimate load	Lateral deformation (mm)	Reduction in load capacity due to fire
20 °C	0	2445.0	5.00	4.13	-
	0.10	2128.1	7.28	8.76	12.94 (%)
	0.15	1846.1	10.99	9.88	24.49 (%)
	0.20	1597.9	13.32	11.53	34.66 (%)
600 °C	0	1388.0	9.12	15.85	43.23 (%)
	0.10	1152.0	14.20	35.16	52.88 (%)
	0.15	988.0	18.11	42.37	59.60 (%)
	0.20	855.0	20.43	55.60	65.03 (%)

Table 1 contains data related to the behavior of a material or structure under different conditions of temperature, eccentricity ratio (e/b), and various parameters like load capacity, axial deformation, lateral deformation, and reduction in load capacity due to fire. The table presents data at two different temperatures: 20°C and 600°C. As expected, at higher temperatures (600°C), there is a noticeable decrease in load capacity and an increase in deformation compared to 20°C. Eccentricity Ratio (e/b). There are three eccentricity ratio values: 0, 0.1, 0.15, and 0.2. It appears that as the eccentricity ratio increases, both load capacity and deformation tend to increase. Load capacity (Pu) is measured in kilo newton (KN). At 20°C, the load capacity ranges from 2445 KN (at e/b = 0) to 1597.9 KN (at e/b = 0.2). At 600°C, the load capacity decreases significantly, ranging from 1388 KN (at e/b = 0) to 855 KN (at e/b = 0.2). Axial deformation is measured in millimeters (mm). It increases as the eccentricity ratio (e/b) increases and as the temperature increases. Lateral deformation is also measured in millimeters (mm). Similar to axial deformation, lateral deformation increases with higher values of e/b and higher temperatures. Reduction in Load Capacity Due to Fire: The last column indicates the percentage reduction in load capacity due to fire when compared to the load capacity at 20°C and e/b = 0. It shows that as the eccentricity ratio (e/b) increases and the temperature rises to 600°C, the reduction in load capacity due to fire also increases significantly. Overall, this table demonstrates how temperature and the eccentricity ratio affect the load capacity and deformation of a material or structure. Higher temperatures and larger eccentricity ratios lead to reduced load capacity and increased deformation, which is expected in fire-resistant materials or structures. This data can be crucial for designing and assessing the performance of materials in fire-prone environments.

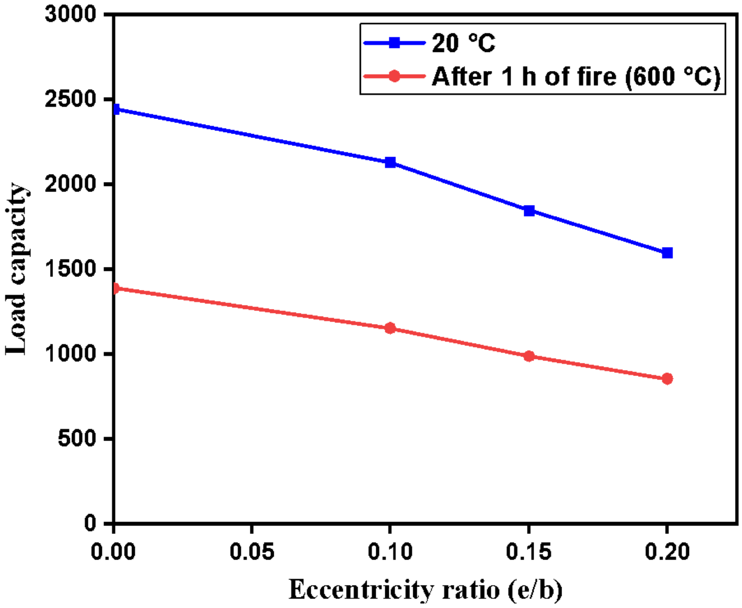

Figure 5 – Diagram of load-eccentricity ratio collapsed (20 and 600 °C).

4.3 Strengthening the RC column after RC jacket fire exposure

Over time, structural components may operate differently from their design. These variances can weaken and degrade their resilience, requiring reevaluation. The eccentricity ratio and resistance to increased temperatures must be considered when designing fire-resistant materials and structures to ensure safety and structural integrity in fires. The eccentricity ratio the distance between a force's application point and an element's center of gravity is crucial to stability and structural behavior analysis. Fire-resistant design requires materials to endure high temperatures to maintain construction integrity and allow safe evacuation and firefighting. The study evaluates high-temperature concrete and steel mechanical and thermal properties. For technical and safety purposes, notably in fire or other heat-related situations, this study examines how certain materials behave at high temperatures. The research seeks to understand how concrete and steel interact in such circumstances to improve structural solutions (Européen, 2004; Eurocode, 2005). The provided data is of utmost importance for the development of a finite element program used in the rehabilitation and strengthening of reinforced concrete (RC) columns and fire-damaged columns. From both a resource conservation and cost-efficiency standpoint, the rehabilitation and strengthening of damaged structures are considered more sustainable alternatives compared to complete demolition and reconstruction. This approach takes into account factors such as time, cost, and materials. In this research, a method known as an RC jacket is employed to reinforce and repair a fire-damaged RC column that endured one hour of exposure to fire on all four sides. The RC jacket essentially involves applying a concrete casing around the existing damaged concrete to improve the structural integrity of the burnt column. The steel used in this process has a yield stress of 500 MPa. The column has a length of 3 meters and a cross-section of 30 cm × 30 cm, as shown in Figure 6. This strengthening process also alters the column's cross-sectional area, thereby affecting its overall mass and stiffness. The primary objective of this research is to evaluate the effectiveness of strengthening concrete jackets supported by a steel structure consisting of vertical angles and horizontal spreaders. The aim is to enhance the resistance of these damaged columns and improve their load-bearing capacity after being exposed to a temperature of 600°C for a duration of 60 minutes. In the context of strengthening concrete columns, intriguing findings emerged. When external strength was maintained at 30 MPa, the load-bearing capacity of the columns exhibited remarkable enhancements of 189.0%, 120.3%, 94.30%, and 80.25% under eccentric compression conditions characterized by varying e/b ratios of 0, 0.1, 0.15, and 0.20. These improvements were particularly notable after a 60-minute fire exposure, with varying jacket thicknesses of 5 cm and 10 cm. The efficiency of the strengthening method was determined through Equation (1), providing a quantifiable means to assess the efficacy of these interventions in bolstering load-bearing capacity under these specific conditions. These findings shed light on the potential of steel jackets to enhance the resilience of concrete columns, offering valuable insights for structural engineering and fire-resistant design.

$$\Delta(\%) = \frac{strengthening\ collapse\ load\ P_{U,C} - Load\ carrying\ capacity\ P_{U,20}(T = 20°C)}{Load\ carrying\ capacity\ P_{U,20}(T = 20°C)} X100 \quad (1)$$

Where: Δ (%): Strengthening efficiency in (%);

P_(u,c): load capacity of column with required strengthening technique;

P_(u,20): load capacity of the reference column.

Table 2 – External Strengthening with concrete of fc,$_{28}$ =30 MPa.

Eccentricity ratio (e/b)	**Strengthening efficiency Δ (%)**	
	5cm	**10cm**
Reference column	-	-
0	86.26	189.0
0.1	71.35	120.3
0.15	64.97	94.30
0.20	53.37	80.25

Table 2 provides insightful data on the efficiency of strengthening concrete columns with a specified strength of 30 MPa at varying eccentricity ratios (e/b) and two different strengthening depths: 5 cm and 10 cm, in comparison to a reference column with no strengthening. Notably, the results demonstrate a clear trend where the efficiency of strengthening decreases as the eccentricity ratio (e/b) increases. At an eccentricity ratio of 0.1, the efficiency remains relatively high at 71.35% for a 5 cm depth and increases to 120.3% for a 10 cm depth, indicating potential over-strengthening in the latter case. However, as the eccentricity ratio reaches 0.15 and 0.20, the efficiency steadily declines, emphasizing the importance of carefully considering both the depth and e/b ratio when designing and evaluating strengthening measures for concrete columns, especially in applications where structural integrity is critical.

The results indicate that the column effectively regains its ultimate strength. Consequently, it can be concluded that the strengthening method employed is successful in rehabilitating and fortifying the damaged column. This approach has proven to be an effective means of enhancing column strength. It appears you're describing Figure 6 illustrating the repair details of reinforced concrete (RC) columns using concrete jackets of varying thicknesses (5 cm and 10 cm) and shirts supported by a steel structure composed of vertical angles and horizontal spreaders. Figure 6 likely displays the cross-sectional view (half section) of these repaired columns after exposure to fire. Such illustrations are essential for visualizing the structural rehabilitation and strengthening techniques used to restore the integrity of fire-damaged RC columns, with the concrete jackets and steel support structure playing a pivotal role in this process.

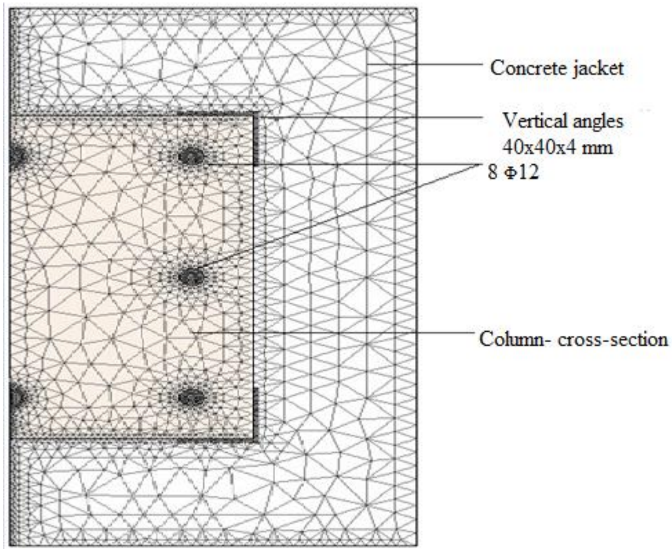

Figure 6 –Repair details of RC columns after fire (half section is shown).

5. Conclusions

The primary purpose of the study was to investigate the effect of 600°C for one hour on the residual load-carrying capacity of structural columns, particularly in the context of post-fire behavior and when these columns are contained by casing under conditions of eccentric pressure. Such a study is essential to understand how structural elements respond to fire and how effective the envelope is in maintaining its load-carrying capacity in non-ideal loading scenarios. Based on the study's primary objective, several conclusions can be drawn:

- Strengthening concrete columns with a 10-cm concrete jacket and steel structure resulted in a notable increase in resistance.
- At 20°C, the load capacity is 2445 KN, and it decreases as the eccentricity ratio e/b (0.1, 0.15, and 0.2) and temperature increase to 12.94, 24.49, and 34.66%, respectively. At a constant temperature of 600°C and varying deflection ratios e/b (0, 0.1, 0.15, 0.2), the load capacity decreased, as the percentages 43.23%, 52.88%, 59.6%, and 65.03% indicate the extent of the fire effect.
- The results showed the importance of taking into account the eccentricity ratio and high temperatures in the design of fire-resistant materials and structures for safety and integrity in fire accidents.
- After one hour, concrete column strengthening is ineffective, and the eccentricity ratio e/b = 0.2 causes fire at high temperatures.

References

Belakhdar, A. R., Dimia, M. S., & Baghdadi, M. (2023). Post-fire behavior of RC columns repaired with square hollow section steel tube and RC concrete jackets. The Journal of Engineering and Exact Sciences, 9(6), 161456-01e. https://doi.org/10.18540/jcecvl9iss6pp161456-01e

Belal, M. F., Mohamed, H. M., & Morad, S. A. (2015). Behavior of reinforced concrete columns strengthened by steel jacket. HBRC journal, 11(2), 201-212. https://doi.org/10.1016/j.hbrcj.2014.05.002

Benzerga, A. L., Amieur, M., & Rabehi, R. (2023, May). Reinforcement of concrete with composite materials based on fiberglass. In International Conference on Contemporary Academic Research (Vol. 1, No. 1, pp. 42-47). https://doi.org/10.59287/iccar.736

Chen, M. T., & Young, B. (2019). Material properties and structural behavior of cold-formed steel elliptical hollow section stub columns. Thin-Walled Structures, 134, 111-126. https://doi.org/10.1016/j.tws.2018.07.055

Chen, Y. H., Chang, Y. F., Yao, G. C., & Sheu, M. S. (2009). Experimental research on post-fire behaviour of reinforced concrete columns. Fire safety journal, 44(5), 741-748. https://doi.org/10.1016/j.firesaf.2009.02.004

Cirtek, L. (2001a). RC columns strengthened with bandage—experimental programme and design recommendations. Construction and Building Materials, 15(8), 341-349. https://doi.org/10.1016/S0950-0618(01)00015-0

Cirtek, L. (2001b). Mathematical model of RC banded column behaviour. Construction and Building Materials, 15(8), 351-359. https://doi.org/10.1016/S0950-0618(01)00014-9

Demir, U., Goksu, C., Binbir, E., & Ilki, A. (2020, August). Impact of time after fire on post-fire seismic behavior of RC columns. In Structures (Vol. 26, pp. 537-548). Elsevier. https://doi.org/10.1016/j.istruc.2020.04.049

Elsamny, M. K., Hussein, A. A., Nafie, A. M., & Abd-Elhamed, M. K. (2013). Experimental study of eccentrically loaded columns strengthened using a steel jacketing technique. International Journal of Civil and Environmental Engineering, 7(12), 900-907.

Eurocode 3, C. E. N. (2005). Design of Steel Structures–Part 1–2: General Rules–Structural Fire Design.

Européen, C. (2004). Eurocode 2: Design of concrete structures—part 1-1: General rules and rules for buildings. London: British Standard Institution.

Ezz-Eldeen, H. A. (2016). Steel jacketing technique used in strengthening reinforced concrete rectangular columns under eccentricity for practical design applications. International Journal of Engineering Trends and Technology (IJETT), 35(5). https://doi.org/10.14445/22315381/ijett-v35p243

Franssen, J. M. (2005). SAFIR: A thermal/structural program for modeling structures under fire. Engineering Journal, 42(3).

Franssen, J. M., & Kodur, V. (2001). Residual load bearing capacity of structures exposed to fire. In Structures 2001: A Structural Engineering Odyssey (pp. 1-12). https://doi.org/10.1061/40558(2001)89

Gernay, T., & Dimia, M. S. (2011). Structural behavior of concrete columns under natural fires including cooling down phase. In International Conference on Recent Advances in Nonlinear Models-Structural Concrete Applications. RAGRAF, Portugal. https://hdl.handle.net/2268/103981

Gernay, T., & Franssen, J. M. (2015). A performance indicator for structures under natural fire. Engineering Structures, 100, 94-103. https://doi.org/10.1016/j.engstruct.2015.06.005

Giménez, E., Adam, J. M., Ivorra, S., Moragues, J. J., & Calderón, P. A. (2009). Full-scale testing of axially loaded RC columns strengthened by steel angles and strips. Advances in Structural Engineering, 12(2), 169-181. https://doi.org/10.1260/1369433097882517

Kodur, V. K. R., Raut, N. K., Mao, X. Y., & Khaliq, W. (2013). Simplified approach for evaluating residual strength of fire-exposed reinforced concrete columns. Materials and Structures, 46, 2059-2075. https://doi.org/10.1617/s11527-013-0036-2

Lai, M. H., & Ho, J. C. M. (2016). A theoretical axial stress-strain model for circular concrete-filled-steel-tube columns. Engineering Structures, 125, 124-143. https://doi.org/10.1016/j.engstruct.2016.06.048

Lakhani, H., & Ožbolt, J. (2019, October). Structural behaviour of Reinforced Concrete (RC) columns under fire. In IOP Conference Series: Materials Science and Engineering (Vol. 615, No. 1, p. 012088). IOP Publishing. https://doi.org/10.1088/1757-899x/615/1/012088

Lamine, B. A., Mohamed, A., & Rachid, R. (2023). Concrete reinforcement using composite fiberglass-based materials. The Journal of Engineering and Exact Sciences, 9(7), 16530-01e. https://doi.org/10.18540/jcecvl9iss7pp16530-01e

Li, W., Wang, T., & Han, L. H. (2019). Seismic performance of concrete-filled double-skin steel tubes after exposure to fire: Experiments. Journal of Constructional Steel Research, 154, 209-223. https://doi.org/10.1016/j.jcsr.2018.12.003

Liu, F., Yang, H., & Gardner, L. (2016). Post-fire behaviour of eccentrically loaded reinforced concrete columns confined by circular steel tubes. Journal of constructional steel research, 122, 495-510. https://doi.org/10.1016/j.jcsr.2016.04.00

Mohammed, H. R., & Said, A. I. (2022). Residual strength and strengthening capacity of reinforced concrete columns subjected to fire exposure by numerical analysis. Journal of the Mechanical Behavior of Materials, 31(1), 212–224. https://doi.org/10.1515/jmbm-2022-0026

Priestley, M. N., Seible, F., Xiao, Y., & Verma, R. (1994). Steel jacket retrofitting of reinforced concrete bridge columns for enhanced shear strength-part 1: Theoretical considerations and test design. Structural Journal, 91(4), 394-405. https://doi.org/10.14359/9885

Qiu, J., Jiang, L., & Usmani, A. (2021). Post-fire Repair of Concrete Structural Members: A Review on Fire Conditions and Recovered Performance. International Journal of High-Rise Buildings, 10(4), 323-334. https://doi.org/10.21022/IJHRB.2021.10.4.323

Tarabia, A. M., & Albakry, H. F. (2014). Strengthening of RC columns by steel angles and strips. Alexandria Engineering Journal, 53(3), 615-626. https://doi.org/10.1016/j.aej.2014.04.005

Xiang, K., & Wang, G. (2014). Experimental Study on Temperature Distribution of Concrete Filled Steel Tube Reinforced Concrete Square Short Columns. Procedia Engineering, 71, 16–21. https://doi.org/10.1016/j.proeng.2014.04.003

Xiao, Y., & Wu, H. (2003). Retrofit of reinforced concrete columns using partially stiffened steel jackets. Journal of Structural Engineering, 129(6), 725-732. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:6(725)

Yaqub, M., & Bailey, C. G. (2011). Cross sectional shape effects on the performance of post-heated reinforced concrete columns wrapped with FRP composites. Composite Structures, 93(3), 1103-1117. https://doi.org/10.1016/j.compstruct.2010.09.012

Zhaodong, D., & Jie, L. (2018). A physically motivated model for fatigue damage of concrete. International Journal of Damage Mechanics, 27(8), 1192-1212. https://doi.org/10.1177/1056789517726359

Zhou, J., & Wang, L. (2019). Repair of fire-damaged reinforced concrete members with axial load: a review. Sustainability, 11(4), 963. https://doi.org/10.3390/su11040963