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CFRP Strengthening of Post-Fire Reinforced Concrete Columns: A Review of Axial Capacity

Manuscript Information

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Abstrak

Paparan kebakaran dapat menurunkan sifat mekanis beton dan baja tulangan secara signifikan sehingga mengurangi kapasitas menahan beban aksial dan keandalan struktural kolom beton bertulang. Carbon Fiber Reinforced Polymer (CFRP) berpotensi menjadi solusi perkuatan. Namun, efektivitasnya dalam memulihkan kapasitas aksial sisa kolom beton bertulang pascakebakaran masih belum banyak dibuktikan. Penelitian ini bertujuan untuk mengevaluasi perkembangan penelitian terkini mengenai perkuatan kolom beton bertulang yang mengalami kerusakan akibat kebakaran menggunakan CFRP serta mengidentifikasi kesenjangan penelitian terkait kondisi paparan kebakaran, konfigurasi perkuatan, dan kinerja struktural sisa. Penelitian ini menggunakan metode Systematic Literature Review (SLR) dengan pendekatan deskriptif-komparatif. Kajian dilakukan terhadap penelitian eksperimental dan numerik terdahulu yang membahas degradasi akibat kebakaran, pengekangan menggunakan CFRP, kapasitas aksial, deformasi, daktilitas, dan mekanisme keruntuhan. Hasil kajian menunjukkan bahwa peningkatan suhu dan durasi paparan kebakaran secara umum menurunkan kapasitas menahan beban kolom beton bertulang. Pengekangan menggunakan CFRP dapat meningkatkan kinerja struktural, sedangkan penambahan jumlah lapisan CFRP berpotensi meningkatkan kapasitas kolom. Namun, efektivitasnya bergantung pada konfigurasi perkuatan dan kondisi termal yang dialami struktur. Bukti penelitian yang tersedia juga menunjukkan bahwa kajian kuantitatif secara langsung mengenai pemulihan kapasitas aksial kolom beton bertulang pascakebakaran masih terbatas. Hal ini disebabkan sebagian besar penelitian lebih berfokus pada elemen balok, hubungan balok-kolom, atau sistem struktur lainnya. Oleh karena itu, diperlukan penelitian eksperimental dan numerik lebih lanjut untuk mengetahui hubungan antara tingkat kerusakan termal, kapasitas aksial sisa, dan konfigurasi CFRP. Kajian ini diharapkan dapat menjadi landasan dalam mengoptimalkan strategi perkuatan menggunakan CFRP serta mengembangkan rekomendasi rehabilitasi yang lebih andal untuk kolom beton bertulang yang mengalami kerusakan akibat kebakaran dalam praktik teknik sipil.

Kata Kunci:
Beton Bertulang, Kolom Pascakebakaran, Kapasitas Aksial, Carbon Fiber Reinforced Polymer, Systematic Literature Review.

Abstract

Fire exposure can significantly deteriorate the mechanical properties of concrete and reinforcing steel, thereby reducing the axial load-bearing capacity and structural reliability of reinforced concrete (RC) columns. Carbon Fiber Reinforced Polymer (CFRP) offers a potential strengthening solution; however, its effectiveness in restoring the residual axial capacity of post-fire RC columns remains insufficiently established. This study aims to evaluate the state of the art of CFRP strengthening for fire-damaged RC columns and identify research gaps related to fire exposure conditions, strengthening configurations, and residual structural performance. A Systematic Literature Review (SLR) was conducted using a descriptive-comparative approach, examining previous experimental and numerical studies on fire-induced degradation, CFRP confinement, axial capacity, deformation, ductility, and failure mechanisms. The reviewed findings indicate that increasing fire exposure temperature and duration generally reduces the load-bearing capacity of RC columns. CFRP confinement can improve structural performance, and increasing the number of CFRP layers may enhance capacity; however, the benefits depend on the strengthening configuration and thermal conditions. The available evidence also reveals that direct quantitative assessments of axial capacity recovery in post-fire RC columns remain limited, as many studies focus on beams, beam–column joints, or other structural systems. Therefore, further experimental and numerical investigations are needed to establish relationships between thermal damage, residual axial capacity, and CFRP configuration. This review provides a foundation for optimizing CFRP strengthening strategies and developing more reliable rehabilitation recommendations for fire-damaged RC columns in civil engineering practice.

Keyword:
Axial Capacity, Carbon Fiber Reinforced Polymer, Fire-Damaged Columns, Reinforced Concrete, Systematic Literature Review.

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INTRODUCTION

The strengthening of post-fire reinforced concrete columns is essential because high temperatures can compromise material integrity and axial load-bearing capacity. Benredjem et al. reported that CFRP strengthening increased axial capacity by approximately 17–58% for normal-strength concrete and 8–29% for high-strength concrete, while ultimate axial deformation increased by 80–280% and 21–125%, respectively, based on 48 specimens that were not exposed to fire (Benredjem et al., 2018). Herarkhi (2026) experimentally demonstrated that FRP materials exhibit different tensile strength and strain-at-failure characteristics, emphasizing the importance of characterizing their mechanical properties to establish reliable parameters for external strengthening applications. Therefore, this study examines the state of the art of CFRP strengthening effectiveness in post-fire reinforced concrete columns, considering thermal damage, material properties, and the number of CFRP layers.

Fire exposure can significantly reduce the axial capacity of reinforced concrete columns due to the degradation of concrete and reinforcing steel. Roudsari and Abu-Lebdeh (2019) reported that exposure to 600°C for 20 minutes reduced column load capacity by approximately 30% and stiffness by up to 34.6%. Carbon Fiber Reinforced Polymer (CFRP) offers a potential strengthening solution through lateral confinement. In experimental tests involving 150 concrete cylinder specimens, Karouche et al. (2022) reported compressive strength increases of 38–66% for low-strength concrete and 11–31% for high-strength concrete. Meanwhile, Cai et al. (2019) highlighted the importance of assessing the residual capacity and reliability of post-fire concrete structures strengthened with CFRP. However, the reported strength improvements in were obtained from concrete cylinders and do not directly establish the effectiveness of CFRP in post-fire reinforced concrete columns. Therefore, this study aims to review the effectiveness of CFRP strengthening in enhancing the axial capacity of post-fire reinforced concrete columns and identify research gaps concerning fire exposure duration, material damage severity, and strengthening configurations.

Fire exposure can significantly degrade reinforced concrete structures through material deterioration, cracking, concrete spalling, and reduced load-bearing capacity (Salehi & Akbarpour, 2020), (Khiali & Rodrigues, 2023). Zhao et al., (2022) reported that exposure to 400°C for 2 hours increased the maximum crack width of CFRP-reinforced concrete beams by 41.7% and reduced their ultimate flexural capacity by 3.9%, while exposure to 600°C resulted in a complete loss of flexural capacity. Meanwhile, Salehi and Akbarpour investigated CFRP strengthening in reinforced concrete frames under fire temperatures ranging from 200 to 1,000°C, demonstrating that strengthening effectiveness depends on temperature and CFRP configuration (Salehi & Akbarpour, 2020). However, the effectiveness of CFRP in restoring the residual axial capacity of post-fire reinforced concrete columns remains an important research area requiring further investigation. Therefore, this study presents a state-of-the-art review of strengthening methods, fire exposure temperatures, residual axial capacity, and factors influencing CFRP effectiveness to identify research gaps and future research directions.

However, these studies focused on composite columns, FRP-confined concrete, and precast connections rather than fire-damaged reinforced concrete columns. Therefore, further research is needed to evaluate CFRP effectiveness in restoring axial capacity and ductility after fire exposure, considering residual concrete strength, reinforcement damage, and CFRP configuration.

Axial Compression Performance

The axial compression performance of post-fire reinforced concrete (RC) columns is strongly influenced by the residual compressive strength of concrete, reinforcement properties, bond–slip behavior, and axial load ratio (Chen & Jiang, 2022). Chen and Jiang demonstrated through numerical analysis that column performance under fire and cyclic loading varies with cross-sectional dimensions, concrete cover, longitudinal reinforcement ratio, and axial load ratio; they also recommended a fire-resistance design time of 2.5 times that required under static loading to limit performance degradation (Chen & Jiang, 2022).

Regarding CFRP strengthening, Wang et al. reported that applying two CFRP layers to post-fire RC beam–column joints increased ultimate bearing capacity by 30.3% and energy dissipation capacity by 26.5% compared with unstrengthened joints (Wang et al., 2023). In complementary experimental research on RC beams exposed to 600 and 800 °C for two hours, Jadooe et al., (2018) found that the load capacity decreased by 5.2% and 32%, respectively, while NSM-CFRP repair improved the flexural capacity of beams exposed to 800 °C. Although these findings demonstrate the influence of fire damage and the potential of CFRP strengthening, the reported improvements concern columns under combined fire and cyclic loads, beam column joints under seismic loading, and beams under flexure not the direct recovery of post-fire column axial

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capacity. Therefore, further investigation is needed to quantify CFRP strengthening effectiveness in restoring the residual axial capacity of post-fire RC columns.

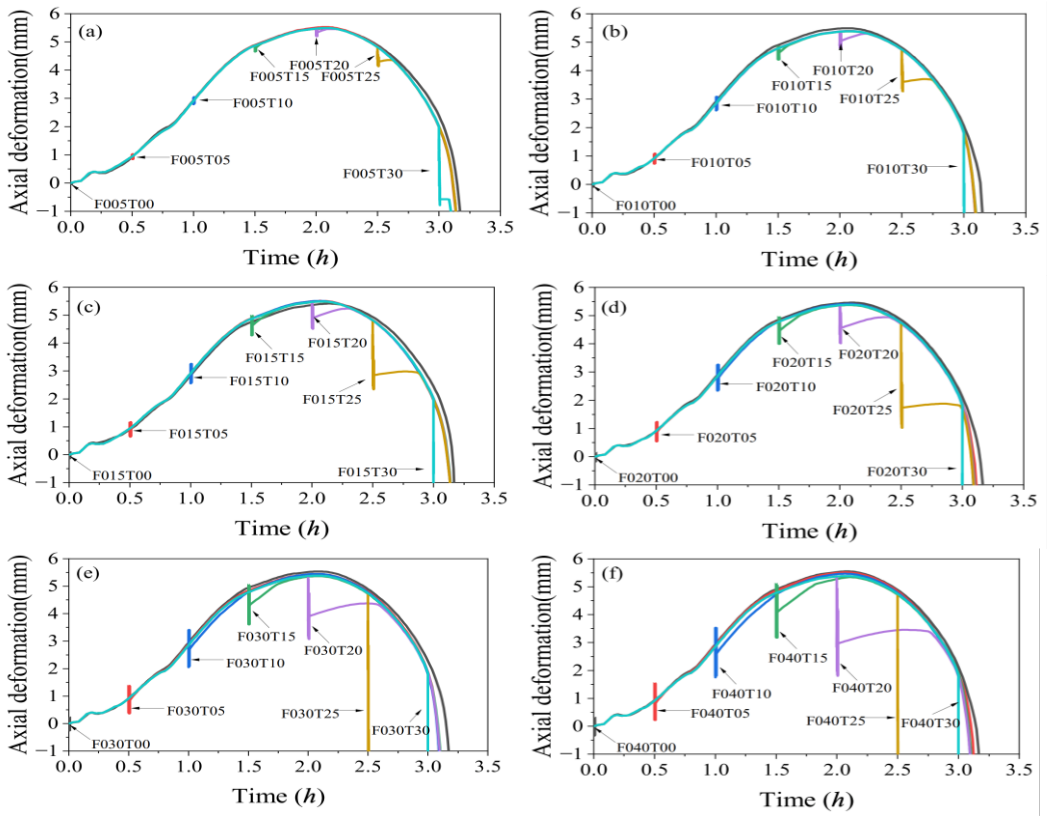


Figure 1. Axial deformation-time curve of different working conditions. (a) A = 0.05; (b) A = 0.10; (c) A = 0.15; (d) A = 0.20; (e) A = 0.30; (f) A = 0.4 (Chen & Jiang, 2022)

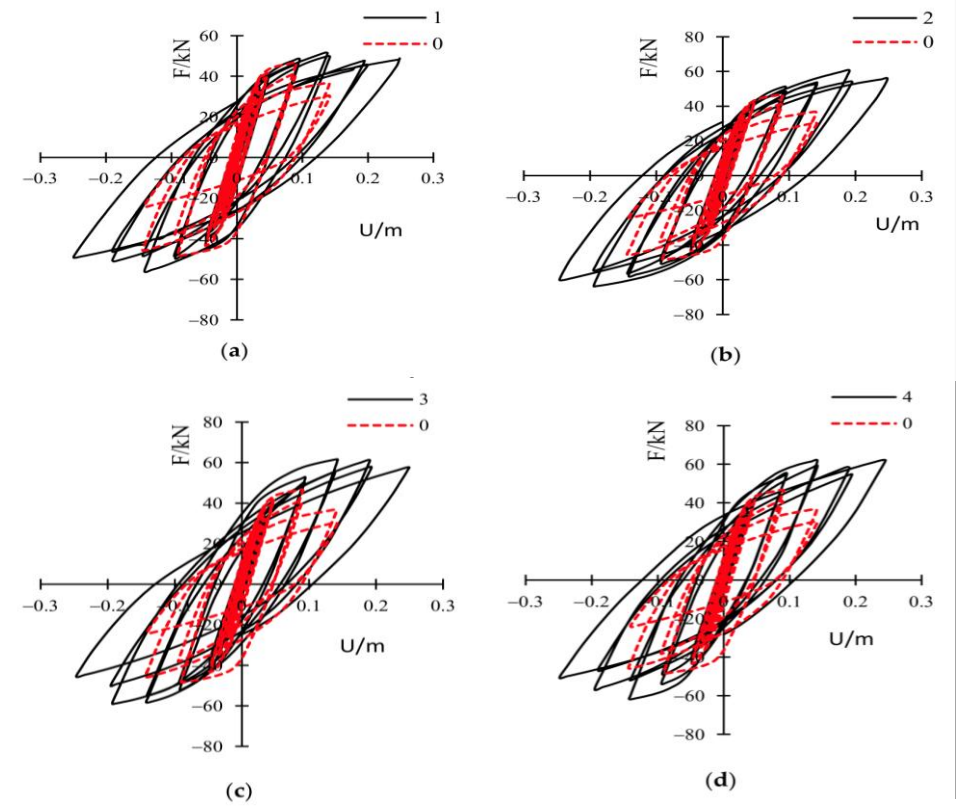


Figure 2. Hysteretic curves of the specimen reinforced with different CFRP layers. (a) 1 layer; (b) 2 layers; (c) 3 layers; (d) 4 layers. (Wang et al., 2023)

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METHODS

This study employs a Systematic Literature Review (SLR) with a descriptive-comparative approach to evaluate the effectiveness of Carbon Fiber-Reinforced Polymer (CFRP) in restoring the axial load-bearing capacity of post-fire reinforced concrete columns. The review process involves identifying, screening, and analyzing relevant publications based on fire exposure temperature and duration, CFRP strengthening configurations, and changes in residual axial capacity. The assessment parameters include concrete compressive strength, ultimate load capacity, axial deformation, ductility, and failure modes, as exposure to elevated temperatures can degrade the mechanical properties of construction materials and reduce the load-bearing capacity of reinforced concrete elements (Khiali & Rodrigues, 2023). Previous research has also identified the axial load ratio, cross-sectional dimensions, concrete cover, and longitudinal reinforcement as important factors influencing column performance under fire-related conditions (Chen & Jiang, 2022). As a comparative reference, a numerical study of post-fire reinforced concrete beam–column joints reported a 30.3% increase in ultimate load capacity when two layers of CFRP were applied; however, this finding concerns the load-bearing performance of beam–column joints under cyclic loading and should not be interpreted as direct evidence of improved axial capacity in columns (Wang et al., 2023). The findings of the reviewed studies are synthesized to identify performance trends, limitations in the available experimental evidence, and research gaps concerning the restoration of axial load-bearing capacity in post-fire reinforced concrete columns.

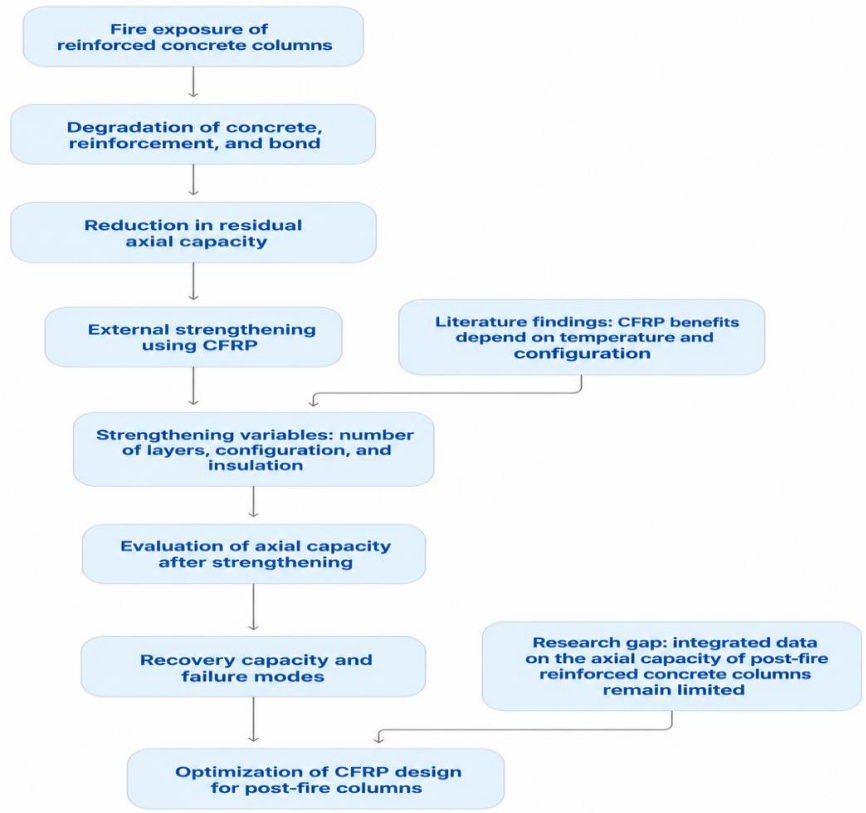


Figure 3. Method

RESULTS AND DISCUSSION

Fire-Induced Degradation of Column Load-Bearing Capacity

Roudsari and Abu-Lebdeh (2019) evaluated four reinforced concrete column models using ABAQUS, considering fire temperatures of up to 600 °C and exposure durations of 10, 15, and 20 minutes. The results indicated that the load-bearing capacity of the columns decreased with increasing fire exposure duration. This finding establishes the importance of assessing the residual load-bearing capacity of thermally damaged columns when evaluating the effectiveness of CFRP strengthening systems. Accordingly, the performance of CFRP-strengthened columns should be assessed relative to their post-fire residual capacity rather than solely against their capacity under ambient conditions (Roudsari & Abu-Lebdeh, 2019).

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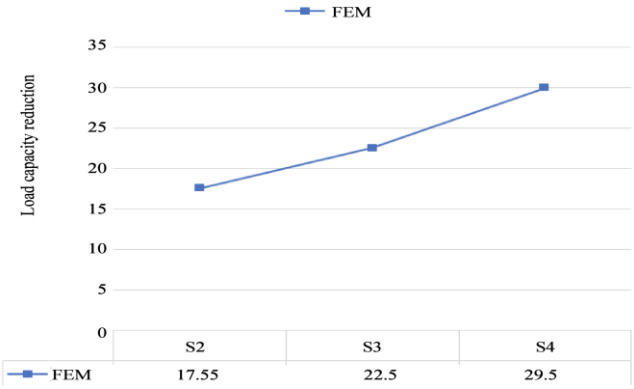


Figure 4. Reduction in load Capacity due to fire

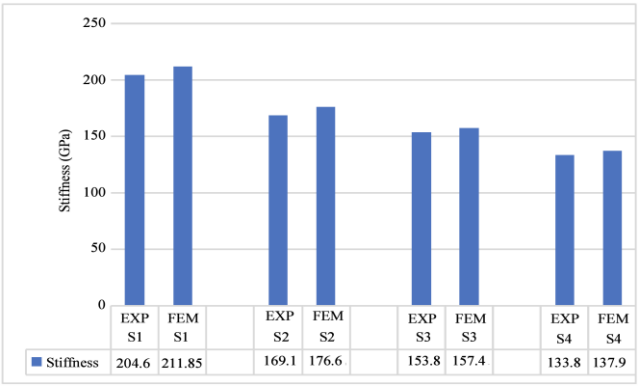


Figure 5. Stiffness at different fire periods

Effect of CFRP Layer Configuration on Column Load-Bearing Capacity

Takla and Tarsha (2020) investigated square reinforced concrete columns confined with multiple CFRP layers and subjected to fire exposure. The analytical results indicated that increasing the number of CFRP layers improved the axial load-bearing capacity of the columns; however, the addition of more than four layers did not produce a significant further improvement. The authors also emphasized the need for adequate thermal protection because polymer-based strengthening materials are susceptible to elevated temperatures. These findings suggest that the number of CFRP layers should be optimized by considering both the required axial load-bearing capacity and the thermal conditions experienced by the strengthened column after fire exposure (Takla & Tarsha, 2020).

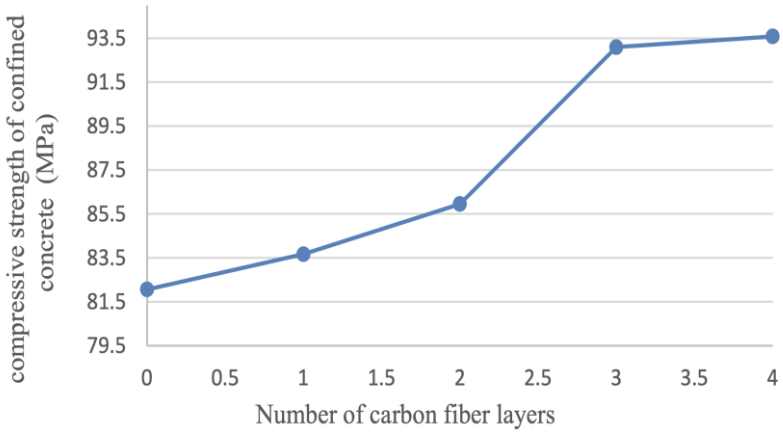


Figure 6. The relationship between the number of carbon fiber layers with compressive strength of confined concrete (fCC)

Table 1. The numerical results as obtained by ANSYS Workbench after thermal-structure analysis

Model	Analytical Failure load after fire (KN)
C79.5-L12	2980.4
C79.5-L12-S8	2940.2
C79.5-L12-S8+1CFRP	2910.6
C79.5-L12-S8+2CFRP	2894.3
C79.5-L12-S8+3CFRP	2857.6
C79.5-L12-S8+4CFRP	2827.1

Effectiveness of FRP in Fire-Exposed Structures Subjected to Lateral Loading

Salehi and Akbarpour (2020) employed finite element analysis to evaluate FRP-strengthened reinforced concrete structures subjected to temperatures ranging from 200 to 1000 °C and lateral loading. The study indicated that FRP exhibited better structural performance at lower fire temperatures. For a particular model incorporating CFRP reinforcement in beams and columns, the reported load capacity at 1000 °C reached 44.3 kN, approximately 550% higher than that of the corresponding model reinforced with steel under the same temperature conditions. However, this result represents the lateral-load response of a structural frame rather

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than a direct measurement of the post-fire axial load-bearing capacity of an individual column. Consequently, the findings provide supporting evidence for the potential benefits of CFRP but cannot be directly interpreted as a quantitative improvement in the axial capacity of post-fire RC columns (Salehi & Akbarpour, 2020).

Performance of CFRP-Strengthened Reinforced Concrete Beam–Column Joints After Fire Exposure

Wang et al., (2023) investigated CFRP-strengthened reinforced concrete beam–column joints through numerical simulations involving post-fire conditions and cyclic loading. The application of two CFRP layers resulted in a 30.3% increase in ultimate load capacity and a 26.5% increase in energy dissipation capacity compared with the unstrengthened post-fire joints. However, these improvements were not consistently maintained as the number of CFRP layers increased. Although the study did not directly quantify the axial load-bearing capacity of the columns, its findings demonstrate that the effectiveness of CFRP strengthening depends on the reinforcement configuration and the governing failure mechanisms of the structural components (Wang et al., 2023).

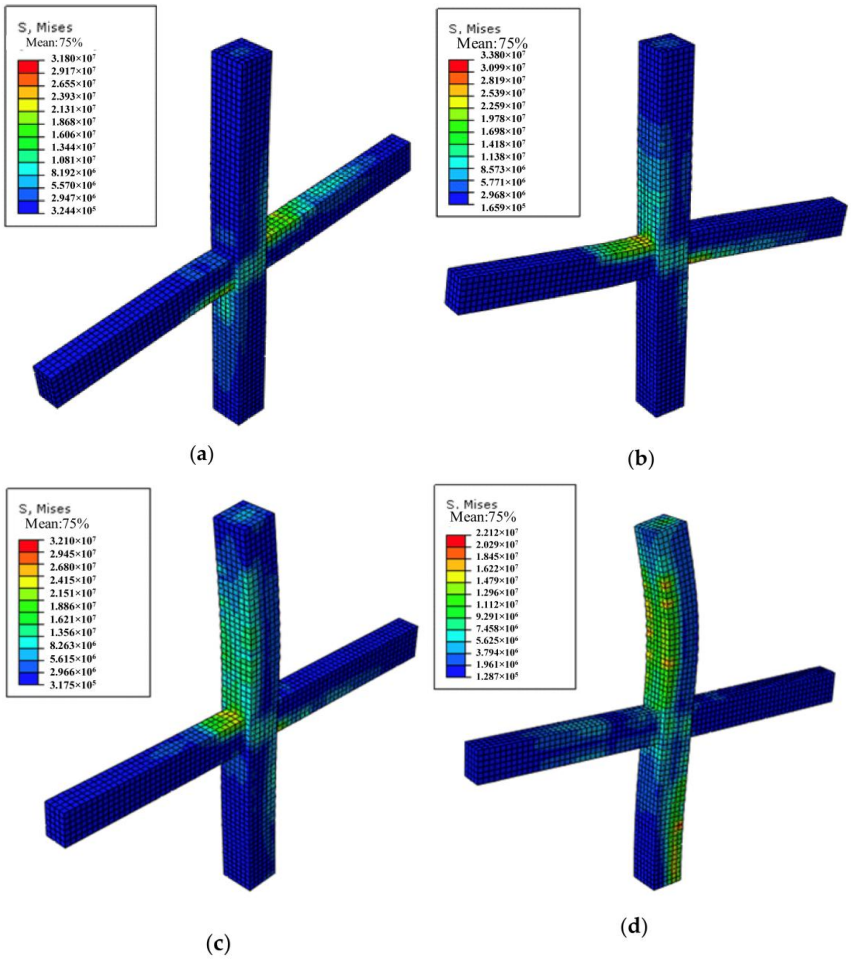


Figure 7. Stress distribution of the specimen subjected to different axial compression ratios.
(a) n = 0.3; (b) n = 0.5; (c) n = 0.7; (d) n = 0.8.

Combined Effects of Fire Exposure and Cyclic Loading on Columns

Chen and Jiang (2022) analyzed reinforced concrete columns subjected to fire exposure in conjunction with cyclic loading. The results indicated that the influence of cyclic loading on column response was relatively limited when the duration of cyclic loading was less than two hours. The study also recommended that the design fire-resistance duration of a column should be at least 2.5 times its fire-resistance duration under static loading. These findings are relevant to the assessment of CFRP-strengthened post-fire columns because residual capacity must be evaluated in conjunction with the loading history and thermally induced material degradation, rather than being determined solely by the maximum temperature experienced during the fire (Chen & Jiang, 2022).

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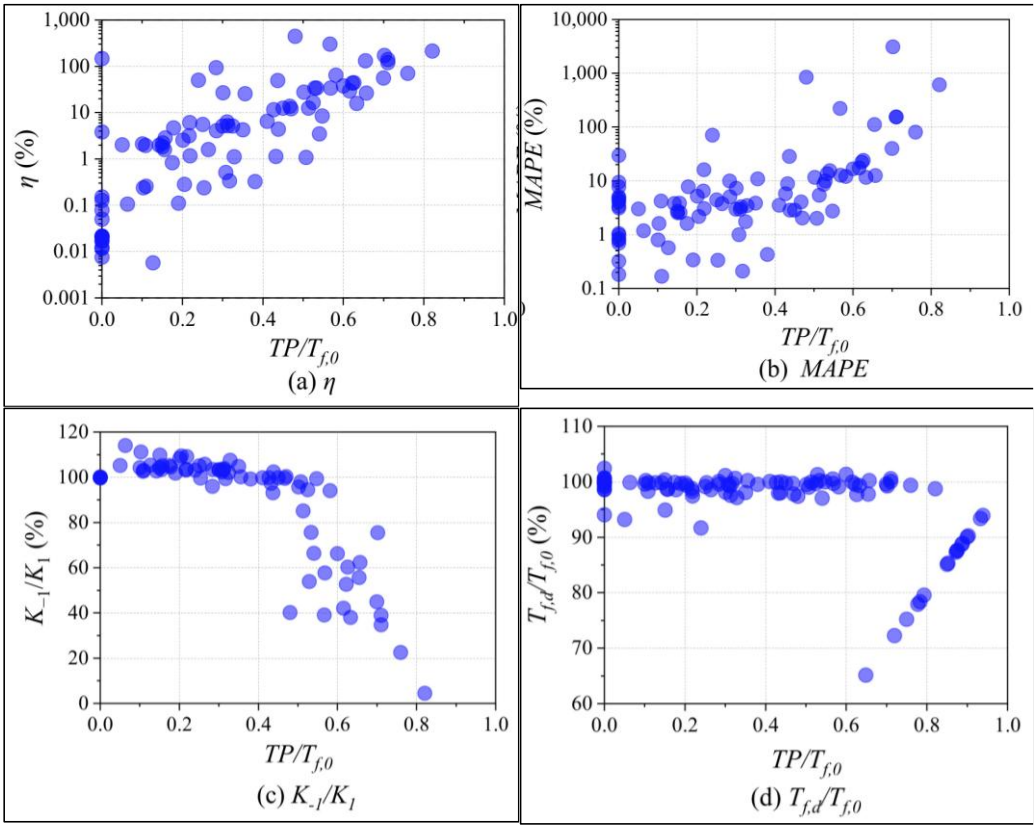


Figure 8. The effect of cyclic load on different columns during fire exposure: (a) cyclic load effect coefficient η; (b) MAPE; (c) stiffness degradation ratio; (d) fire resistance time ratio.

CFRP Strengthening of Post-Fire Concrete Members and Implications for Residual Capacity

Jadooe et al., (2018) experimentally investigated nine reinforced concrete beams strengthened with CFRP laminates using the near-surface-mounted (NSM) technique following exposure to the ISO 834 standard fire. The findings demonstrated that NSM CFRP laminates could improve the stiffness and load-bearing capacity of thermally damaged beams. Although quantitative improvements in the axial capacity of columns were not reported, the study supports the potential application of CFRP as a rehabilitation material for fire-damaged concrete structures. Nevertheless, extrapolation of the findings from beams to columns should be undertaken with caution because flexural behavior and axial compression are governed by different structural response mechanisms and failure modes (Jadooe et al., 2018)

Changes in the Capacity of FRP-Reinforced Concrete Members at Elevated Temperatures

Zhao et al., (2022) conducted flexural tests on seven reinforced concrete beams incorporating glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) reinforcement. Following exposure to 400 °C for two hours, the ultimate capacity of the CFRP-reinforced beams decreased by 3.9% relative to the ambient-temperature condition, whereas the GFRP-reinforced beams experienced an 11.9% reduction. At 600 °C, the flexural capacity of the CFRP-reinforced beams was reported to be completely lost in the authors' residual-capacity assessment. These findings demonstrate that CFRP-based reinforcement systems are also subject to thermal performance limitations and should not be assumed to remain fully effective following exposure to elevated temperatures (Zhao et al., 2022).

Reliability Analysis of CFRP-Strengthened Concrete Structures After Fire Exposure

Cai et al., (2019) developed a reliability-based assessment approach for CFRP-strengthened reinforced concrete beams after fire exposure, accounting for fire duration, concrete cover thickness, and the number of CFRP layers. At a load ratio of 0.2 and a concrete cover thickness of 35 mm, the reported increases in the reliability index for one, two, and three CFRP layers following 120 minutes of fire exposure were 3.30%, 19.70%, and 29.28%, respectively. For a concrete cover thickness of 45 mm, the corresponding increases were 12.93%, 25.26%, and 32.70%. These values represent improvements in the reliability index associated with the flexural capacity of beams and should not be interpreted as percentage increases in the axial load-bearing capacity of columns (Cai et al., 2019).

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Table 2. Efficiency of the postfire reliability index of the CFRP-strengthened RC beams when as=35 mm.

Fire exposure time	1 layer	2 layer	3 layer
30 min	2.28%	14.34%	21.14%
60 min	8.81%	20.19%	25.70%
120 min	3.30%	19.70%	29.28%

Table 3. Efficiency of the postfire reliability index of the CFRP-strengthened RC beams when as=45 mm

Fire exposure time	1 layer	2 layer	3 layer
30 min	6.89%	16.75%	22.38%
60 min	13.45%	23.51%	31.55%
120 min	12.93%	25.26%	32.70%

Implications for the Development of CFRP Strengthening Systems for Post-Fire Columns

Imran and Mahendran (2021) developed finite element models and design equations to predict the axial compressive capacity of CFRP-strengthened tubular steel columns at elevated temperatures. The study indicated that the CFRP adhesive underwent softening within a temperature range of approximately 65–120 °C. Furthermore, CFRP strengthening in the investigated steel columns was reported to become ineffective at temperatures exceeding 225 °C in the absence of adequate thermal protection. The investigated insulation systems achieved fire-resistance durations exceeding 60 minutes for most columns protected with CAFCO 300 and exceeding 120 minutes when intumescent coatings were used. Although the investigated structural members were tubular steel columns rather than reinforced concrete columns, the findings highlight the importance of controlling the temperature at the CFRP–substrate interface and providing appropriate thermal protection when designing CFRP strengthening systems (Imran & Mahendran, 2021).

Synthesis and Research Gaps

Overall, the reviewed studies demonstrate that CFRP has the potential to improve the load-bearing capacity and structural performance of damaged members. However, its effectiveness is governed by several interacting parameters, including fire temperature, exposure duration, number of CFRP layers, concrete cover thickness, and the governing failure mechanism. The available numerical evidence directly addressing reinforced concrete columns remains limited. Although the reviewed column studies identify fire-induced capacity degradation and potential benefits associated with CFRP confinement, they do not provide a sufficiently integrated comparison to establish the improvement in the residual axial load-bearing capacity of post-fire RC columns as a function of temperature, exposure duration, and CFRP configuration.

Accordingly, the study entitled State of the Art on Analysis of CFRP Strengthening Effectiveness on the Axial Capacity of Post-Fire Reinforced Concrete Columns can address this research gap through a systematic evaluation of residual axial capacity, capacity recovery ratio, the influence of CFRP layer configuration, and post-strengthening failure mechanisms. Particular emphasis should be placed on distinguishing direct experimental or numerical evidence for RC columns from findings derived from beams, beam column joints, and steel columns. This distinction is essential to ensure that the resulting synthesis provides a technically reliable basis for assessing the effectiveness of CFRP strengthening in fire-damaged reinforced concrete columns.

CONCLUSION

The reviewed studies show that fire exposure reduces the residual load-bearing capacity of RC columns by degrading concrete and reinforcing steel. CFRP confinement has the potential to improve the axial performance of concrete columns, and the available column-focused evidence indicates that the number of CFRP layers is an important parameter. However, the effectiveness of CFRP after fire depends on the severity of thermal damage, column properties, loading history, strengthening configuration, and thermal protection. Current evidence does not support a single quantitative estimate of axial capacity recovery for post-fire RC columns because the available studies use different specimens, loading conditions, and performance measures.

For engineering practice, the assessment should begin with an evaluation of fire exposure, concrete damage and spalling, reinforcement condition, and the residual axial capacity of the column. CFRP should be selected only after checking the substrate condition, the required confinement, the number and arrangement of layers, and the need for thermal protection at the CFRP–concrete interface. The designer should verify the strengthened column under the relevant axial load and consider deformation and failure mode, not capacity alone. Further experimental and numerical studies should test post-fire RC columns directly and report capacity before fire, after fire, and after strengthening. Such data are necessary to establish reliable design guidance and practical rehabilitation procedures.

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